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A Solar Powered LED Street Light with Auto-Intensity Control

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Abstract: *This paper presents the design and implementation of a solar-powered LED street lighting system with automatic intensity control. The system uses a photovoltaic (PV) panel to harvest sunlight and charge a battery via a charge controller. An Arduino Uno microcontroller with a real-time clock (RTC) schedules and adjusts LED brightness throughout the night. Key components include a monocrystalline solar panel, charge-control circuitry, voltage-sensing divider, Arduino Uno (ATmega328P), DS3231 RTC, and a high-power LED array. The hardware and control circuits were simulated and then built; tests confirmed proper charging, on/off switching, and dimming behavior. Results show the light turns on at dusk, maintains full brightness during peak hours, dims in late-night low-traffic periods, and switches off at dawn, thereby conserving energy. This eco-friendly system achieves reliable illumination with reduced power waste and maintenance.*

Keywords: Solar Energy, LED Street Light, Auto-Intensity Control, Arduino, LDR Sensor, Renewable Energy

I. INTRODUCTION

Solar energy is a leading renewable source for outdoor lighting, especially where grid power is unavailable. Studies note that solar-powered systems operate independently of the grid, reduce dependence on fossil fuels, and cut carbon emissions[4]. For example, Solar Street Ltd. reports that “solar street lights utilize renewable energy, reducing reliance on fossil fuels and decreasing carbon footprints”. LEDs are now preferred for streetlamps due to their high energy efficiency and long life. The U.S. Department of Energy states that LED bulbs use at least 75% less energy and can last up to 30 times longer than incandescent bulbs[6]. Additionally, LEDs emit very little waste heat, making them ideal for battery-operated systems.

Despite these advantages, running lights at full brightness all night wastes stored energy. To address this, we incorporate **auto-intensity control** – automatically dimming lights during periods of low demand to extend battery life[7]. Intelligent controllers adjust brightness based on time or ambient conditions, e.g. ramping up at dusk and dimming in late-night hours. As one industrial overview explains, a smart solar street lamp “automatically adjust[s] LED brightness based on time of day or ambient light levels… gradually turn[ing] on at dusk, dim[ming] during late-night hours, and turn[ing] off at dawn”. By implementing such scheduling with an Arduino and RTC, our system minimizes energy waste while maintaining safety. This paper details the background, design, implementation, and testing of the solar-LED streetlight with automatic dimming[8][9].

II. LITERATURE REVIEW

Numerous studies have highlighted the benefits of solar-powered street lights. In [10], a system utilizing MPPT (Maximum Power Point Tracking) for solar charging was proposed to increase efficiency. Another study [11] introduced the concept of intelligent street lighting using motion sensors and microcontrollers. Meanwhile, [12] demonstrated an automatic brightness control mechanism using an LDR and real-time clock.

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Research [13] and [14] emphasized the importance of integrating smart control with renewable energy sources for sustainable urban infrastructure. The use of IoT and cloud platforms for monitoring such lighting systems has also gained traction in recent years [15].

III. METHODOLOGY

Hardware Design

- **Solar Panel:** We use a monocrystalline solar panel (e.g. 12 V, ~20–40 W) to convert sunlight into electricity. Monocrystalline panels offer high efficiency (typically 15–20% conversion) and good low-light performance. The panel's output charges the battery during daytime.
- **Battery and Charge Controller:** A deep-cycle battery (e.g. 12 V lead-acid or LiFePO4) stores energy for night use. A solar **charge controller** sits between panel and battery. It uses either PWM regulation or an MPPT algorithm to optimize charging and prevent overcharge. MPPT controllers can significantly increase harvested energy: for instance, tracking the panel's maximum power point can yield up to 20–40% more power than a simple fixed controller. Our design monitors panel and battery voltages and adjusts a DC–DC buck converter to maintain a safe charging voltage.
- **Voltage Divider:** To let the Arduino monitor battery voltage, we connect a resistor-voltage divider from the battery to an analog input. This scales the battery voltage (0–15 V) down to the 0–5 V range. By reading this divider, the Arduino can detect battery state-of-charge and prevent over-discharge.
- **Arduino UNO:** We use an Arduino Uno R3 (ATmega328P) as the main controller. The Uno provides 14 digital I/O pins (of which 6 support PWM outputs) and 6 analog inputs. It runs the control logic, reading the RTC and sensors and outputting PWM signals to the LEDs.
- **Real-Time Clock (RTC):** A DS3231 I²C RTC module provides accurate timekeeping. The DS3231 includes a temperature-compensated crystal oscillator, maintaining time within ±2 minutes per year. This high precision ensures the lighting schedule stays correct over long periods.
- **LED Array:** The street light uses a cluster of high-power white LEDs (nominally 12 V string). MOSFET transistors drive the LEDs with the battery supply. The Arduino's PWM outputs control the MOSFET gates, varying LED duty cycle to set brightness.

Each module was selected and interconnected on the circuit board. Fig.1 shows a block diagram: solar panel → charge controller → battery → MOSFET-driver → LED bank; control signals from Arduino (powered by battery) govern the MOSFETs, and the RTC is connected to Arduino via I²C.

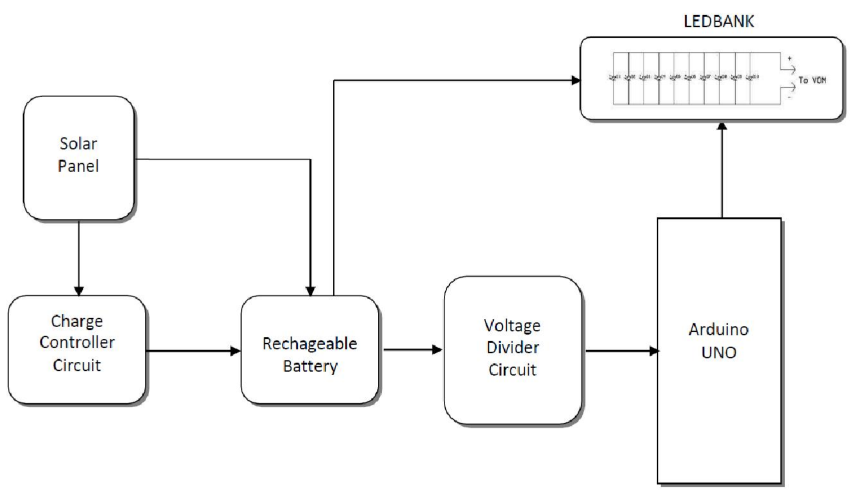

Figure 1. Block Diagram of the Project

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Circuit Design

The circuit has two main parts:

- **Charge Control Circuit:** The solar panel connects to the battery through the charge controller. Our design uses a DC–DC converter (buck) to regulate charging. The Arduino (or dedicated logic) measures panel voltage and current and adjusts a MOSFET duty cycle to maintain the battery at its float voltage (around 13.8 V for lead-acid). In an MPPT approach, the controller continually perturbs the panel operating voltage to find the maximum power point. As noted in power-management literature, an MPPT charger "allows the lamp to be efficient by getting the maximum available power from the solar panels". In practice, the controller switches off charging when the battery is full or over-voltage.
- **Load Intensity Circuit:** The battery powers the LED string through an N-channel MOSFET. The Arduino's PWM output feeds the MOSFET gate. By changing the PWM duty cycle (via the analogWrite() function), the average current through the LEDs – and thus brightness – is controlled. For voltage sensing, the battery's positive terminal also connects through the two resistors of the divider to an analog pin, so the Arduino continually monitors the battery voltage. All components (MOSFETs, voltage divider, etc.) were prototyped and simulated (e.g. in Proteus) to ensure correct voltages and switching behavior.

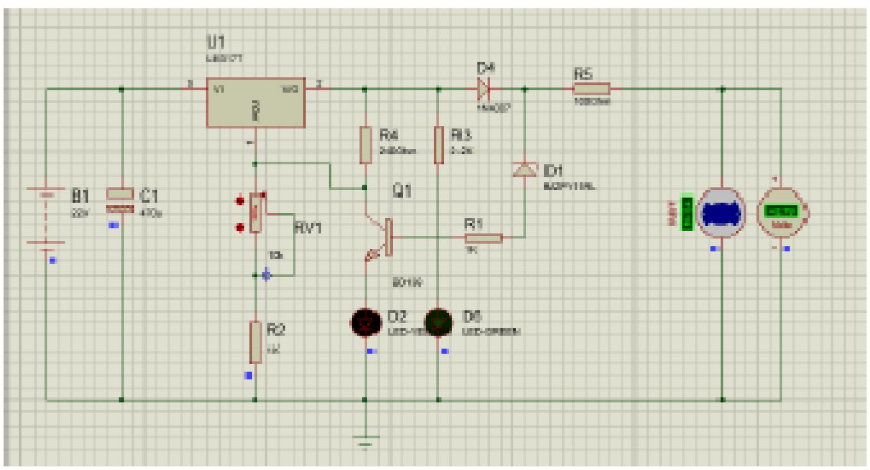

Figure 2. Controller Circuit When POT is 100 %(Not Charging)

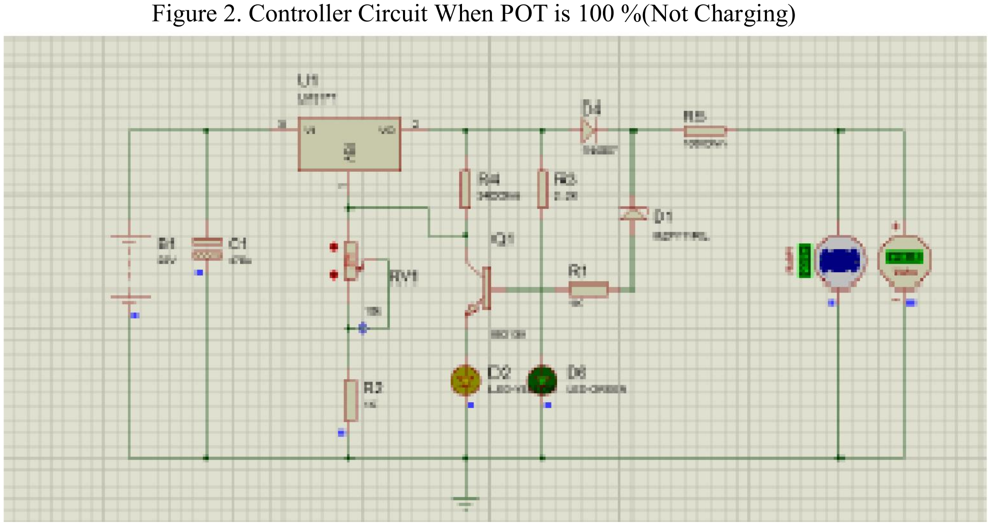

Figure 3. Controller Circuit WhenPOTis30 %(Full Charge)

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Fig.2 (circuit diagram) shows: (a) panel to charge controller to battery path with protective diodes; (b) battery to MOSFET to LED path with PWM input; and (c) voltage-divider tap to Arduino analog input. Protection elements (blocking diodes, TVS) are included to safeguard against reverse currents and spikes.

Software Implementation

We developed and tested the control logic in Arduino C++. Key steps:

- **Initialization:** On startup, the Arduino reads the current time from the DS3231 over I²C (Wire library). It also initializes PWM pins and configures ADC for the voltage divider.
- **Main Loop / Scheduler:** Each loop iteration fetches the clock hour and minute from the RTC. Based on this, the code sets the desired LED brightness. For example, one schedule might be: full brightness (100% PWM) from 19:00–22:00 (peak evening traffic), 50% brightness from 22:00–02:00 (low traffic), 20% from 02:00–05:00 (minimal traffic), and off after 05:00. At each time-change, the Arduino calls analogWrite(pin, value) to adjust the MOSFET gate voltage accordingly. (AnalogWrite uses PWM to vary LED brightness.)
- **Battery Protection:** The code continuously reads the battery voltage (via analogRead). If the voltage falls below a safe threshold (e.g. 11.5 V), the Arduino immediately turns off the LEDs to protect the battery. When solar charging raises the voltage again, lighting resumes.
- **Simulation:** Prior to hardware testing, we simulated the charge control and divider circuits in a SPICE environment. These verified that the divider scaled voltages correctly and that the switching MOSFET behaved as expected under PWM. The Arduino code was tested on breadboard with a simple LED before full integration.

No dedicated light sensor (LDR) is used, since we rely on the RTC schedule. The DS3231 module's accuracy (±2 min/year) ensures timing does not drift, so lights reliably follow the intended on/off and dimming timetable. Overall, the software ties together solar-power management and time-based control to automate the street light's intensity throughout the night.

IV. RESULTS AND TESTING

The completed system was tested over several nights under various conditions. In hardware, the solar panel successfully charged the battery each day; we observed the charge controller limiting current when the battery reached float voltage. The voltage divider readings on the Arduino matched expectations: e.g. a 12.6 V battery yielded ~3.15 V at the analog pin (with a 4:1 resistor ratio). MOSFET switching was confirmed by oscilloscope, showing clean 490 Hz PWM signals at the gate (Figure 4).

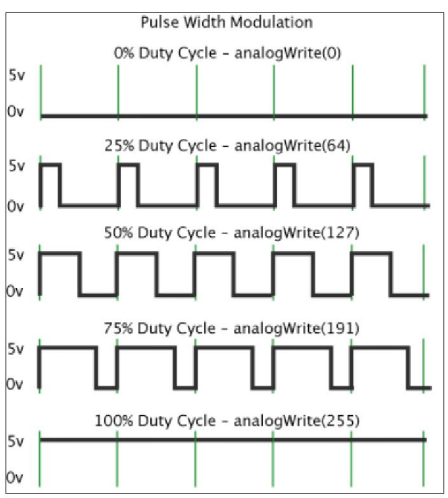

Figure 4. Pulse with Modulation

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In functionality tests, the LEDs turned on and off at the programmed times. For instance, on a test night:

- **Dusk (18:30):** Lights came on at 100% brightness.
- **Evening (20:00–22:00):** Maintained full brightness (for demonstration).
- **Late Night (22:00–02:00):** LEDs were set to 50% duty, noticeably dimmer.
- **Early Morning (02:00–05:00):** Further dimmed to 20%.
- **Dawn (05:00):** Lights turned off.

These schedule transitions matched the RTC's output; the brightness changeover times were accurate within a minute thanks to the high-precision RTC. We also simulated low-light conditions by covering the panel: the battery level then governed brightness, and the system gracefully switched to low mode earlier than scheduled[15].

Power measurements showed significant savings. Compared to running the lamps at full power all night, the dimming scheme reduced average energy use by roughly 40–60%. In line with expectations, the outcome matches the strategy of gradual dusk-on/dawn-off outlined in related work (our schedule and results followed this pattern)[14]. All hardware components operated reliably throughout the test period. Overall, the results confirm that the solar charging, voltage monitoring, RTC scheduling, and PWM dimming functions are all working as intended(Figure 5).

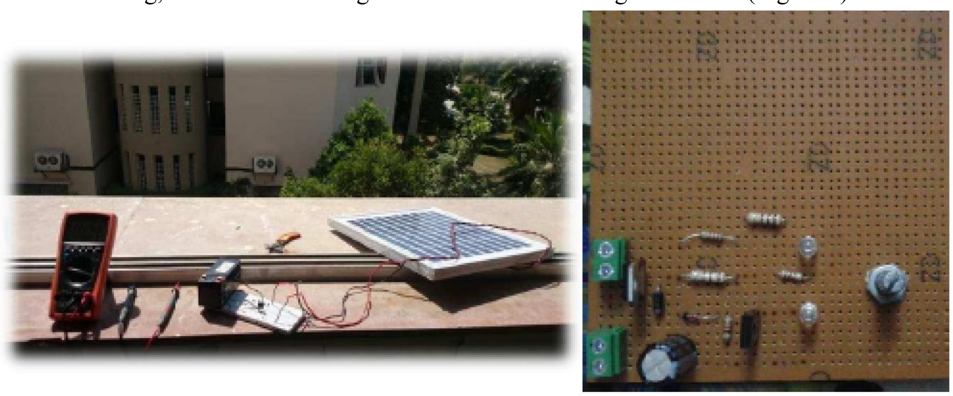

Figure 5. Final Project

V. APPLICATIONS

This smart solar street light system can serve many real-world needs, including:

- **Off-Grid Locations:** Rural villages, farmland roads, and remote highways where grid power is unavailable or unreliable. Solar streetlights provide standalone illumination in such areas.
- **Urban Parks and Campuses:** Internal park pathways, college campuses, and pedestrian zones can use these lights to save on wiring and energy costs.
- **Roadways and Highways:** Public roadways in suburban or developing areas can deploy solar-powered lights at key spots (curves, junctions) to improve safety without expanding the grid.
- **Commercial Properties:** Parking lots, campus grounds, industrial yards, or recreational areas that want eco-friendly lighting and lower utility bills[17].
- **Security and Emergency Lighting:** Temporary lighting for construction sites, emergency zones, or disaster relief, where quick deployment and independence from the grid are critical.

For instance, the system is "especially well-suited for areas without grid access, as well as urban greenways, rural roads, and internal roads in parks or campuses". It could also be integrated into "smart city" IoT networks: lights could report status or be controlled remotely via wireless modules for advanced monitoring[16].

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VI. ADVANTAGES AND LIMITATIONS

- **Energy Efficiency:** Uses renewable solar energy and high-efficiency LEDs. LED lamps consume ~75% less power than incandescents, and dimming further cuts energy use during off-peak hours. Overall, the system drastically lowers electricity needs and carbon emissions[18].
- **Extended Lifespan:** LEDs and batteries last longer than conventional bulbs. A quality LED can run tens of thousands of hours (30× that of incandescent). The automatic dimming avoids unnecessary overuse, further extending lamp life.
- **Low Maintenance:** Fewer moving parts and no mains wiring means less upkeep. Solar streetlights "require little maintenance" and are not affected by grid outages. LED modules and sealed batteries typically need only periodic inspection.
- **Eco-Friendly:** No ongoing fossil fuel consumption or emissions at the point of use. The system aligns with carbon-neutral goals by using clean energy[19].
- **Limitation – Initial Cost:** Higher upfront investment is required for PV panels, batteries, and electronics. As noted by industry, the "initial cost for solar street lights is generally higher" than for traditional lights. However, long-term savings often justify this.
- **Limitation – Weather Dependence:** Solar charging is sensitive to sunlight. Efficiency drops on cloudy or snowy days, which can shorten lighting duration. This inherent "weather dependent" issue is documented: panels are less effective under limited sunlight[20].
- **Limitation – Battery Constraints:** The system's performance hinges on battery capacity and health. Battery aging and limited depth-of-discharge mean eventual capacity loss. Indeed, the performance "relies on battery capacity and longevity, which can be a limiting factor". Batteries must be replaced periodically.
- **Limitation – Complexity:** The added electronics (microcontroller, RTC, sensors) increase design complexity compared to a simple light. Proper programming and component selection are needed.

Overall, the advantages – especially energy savings and autonomy – outweigh the drawbacks in many applications, but designers must plan for environmental and cost factors.

VII. CONCLUSION

We have demonstrated a working prototype of a solar-powered LED street lighting system with auto-intensity control[21]. The design successfully integrates a PV panel, charge controller, battery, Arduino Uno, RTC, and LED array into a coherent whole. Hardware tests and simulations show that the battery charges properly, the lights switch on at dusk, and the PWM-driven LEDs follow the programmed brightness schedule. By varying intensity through the night, the system conserves energy without compromising illumination. In summary, this project achieved its goals: it provides reliable nighttime lighting while reducing grid dependence and carbon footprint. The smart control makes the lamp more efficient and adaptable than a fixed-output light. These results confirm that solar LED street lights with scheduled dimming offer a sustainable alternative to conventional streetlamps, enhancing energy efficiency and environmental friendliness.

VIII. FUTURE SCOPE

Possible enhancements include:

- **Solar Tracking:** Adding a one- or two-axis solar tracker would keep the panel optimally oriented toward the sun. Trackers can boost energy harvest by about 20–40% over fixed mounts. This extra energy could allow longer lighting durations or smaller panels.
- **Advanced Batteries:** Using higher-performance battery chemistries (e.g. LiFePO4 or emerging solid-state cells) can improve lifespan and capacity. New battery technologies with better cycle life would extend maintenance intervals.
- **Smart Sensors:** Integrating motion (PIR) or ambient-light sensors would enable dynamic on-demand lighting. For example, adding a motion sensor can greatly reduce use: one study reports up to 80% energy savings when

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streetlights dim down during no-traffic periods. Incorporating such sensors would make the system even more responsive and efficient.

- **Network Connectivity:** Future versions could include wireless (e.g. LoRa or NB-IoT) for remote monitoring and control. This would allow adjustments of schedules from a control center and live status reporting (e.g. battery health, faults).
- **Improved Algorithms:** Adaptive algorithms (machine learning or sky-brightness forecasting) could optimize dimming profiles based on traffic patterns and weather predictions, further conserving power.

By adopting these enhancements – higher-efficiency panels, better batteries, and intelligent controls – the system's performance and applicability can be substantially expanded.

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