

Design and Implementation of an Autonomous Passive Infrared and Real-Time Clock-Controlled Off-Grid Photovoltaic Street Lighting System

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Abstract—Conventional public street lighting (PSL) operates continuously at full intensity, regardless of surrounding activity, wasting energy and relying fully on the grid. This study designed and tested an autonomous off-grid photovoltaic (PV) PSL prototype of 100 Watt-peak (Wp) integrated with a Passive Infrared (PIR) HC-SR501 motion sensor and a Real-Time Clock (RTC) DS3231 module to apply two-level lighting during 17:00 to 05:00 Western Indonesian Time (WIB). The PIR sensor reliably detected objects up to 350 cm (100 percent success), but not at 400 cm or 450 cm, indicating an effective detection range well below its 7 m nominal rating rather than a lamp-actuation fault. The RTC consistently matched lamp transitions to the 17:00 and 05:00 schedule over three days of observation. The system load was 210.07 Wh per day, 28.03 percent lower than conventional always-on operation (291.87 Wh per day), while the PV array produced 255.50 Wh per day (Peak Sun Hours (PSH) 3.65 h, 70 percent efficiency), giving a 45.43 Wh per day (21.63 percent) reserve and 82.22 percent utilization efficiency. The 12 V 12 Ah Valve-Regulated Lead-Acid (VRLA) battery yielded an autonomy day of only 0.55 day (approximately 13.2 h), barely above one night and far below common off-grid design practice (2 to 3 days), so increasing battery capacity to about 22 to 44 Ah is recommended. Motion-sensing and time-based scheduling together deliver a meaningful efficiency gain, although the storage capacity still needs to be enlarged for reliability during consecutive poor-weather days.

Keywords—*Arduino Uno, energy efficiency, off-grid photovoltaic system, PIR sensor, public street lighting, RTC DS3231.*

I. INTRODUCTION

Public lighting (PSL) is vital for nighttime mobility and safety, especially in poorly lit areas, such as parks and rural roads. Energy-efficiency evaluation of road and street lighting installations remains an active research concern, with recent studies proposing and comparing multiple quantitative indicators for assessing road-lighting efficiency [1]. Conventional PSL is typically not adaptive; it supplies full-intensity light continuously, regardless of the surrounding activity, wasting energy when an area is quiet and accelerating lamp degradation, while heavy dependence on the grid limits PSL expansion in infrastructure-poor rural areas. This aligns with Indonesia's 23% renewable-energy-mix target for 2025 [2], making autonomous solar PSL a strategic solution. Off-grid photovoltaic (PV) systems are promising because they convert solar radiation into stored electrical energy via a solar charge controller (SCC) without emissions [3]; however, small-scale off-grid battery capacity is limited and prone to over-discharge without a power-

management strategy [4], making microcontroller-based control essential.

Prior work has explored varied sensing approaches, including vehicle motion sensing based on passive infrared (PIR) and light-dependent resistor (LDR) technologies [5], Long Range (LoRa)-based PIR telemetry [6], an automated wiper-and-blower panel-cleaning system with IoT monitoring (3.17–9.81% power-output recovery after cleaning) [7], motion/vibration-based dimming reducing consumption by up to 86% [8], [9], and fog-sensing or lithium-battery alternatives [4], [10]. Recent reviews of IoT-enabled street lighting confirm that PIR- and real-time clock (RTC)-type sensing is now common practice, while identifying quantitative energy-balance validation and storage-reliability sizing as recurring gaps in the field [11], [12]. Consistent with this, none of [4]–[10] report a full energy balance (production vs. load), a battery-autonomy calculation, or a sensitivity analysis of their own design assumptions—each demonstrates that a PIR- or LDR-triggered lighting scheme works, but not how large the battery or panel must be for a stated reliability target, nor how sensitive that sizing is to real-world variability in traffic or weather conditions. Therefore, the contribution of the present study is not the PIR+RTC sensing combination itself, which is methodologically common, but a replicable quantitative sizing and reliability-analysis framework—energy balance, battery-capacity sensitivity, and benchmarking—layered on top of it, aimed at moving PIR-based PSL research from working demonstrations toward design guidance that a practitioner can size a deployment against.

This study used an Arduino Uno controller with a DS3231 RTC (± 2 ppm, approximately ± 1 min/year) to strictly bound the lamp operation to 17:00–05:00 WIB and a PIR HC-SR501 (nominal range 7 m) to trigger a two-level dimming scheme: Lamp 1 only (dim/standby) when quiet and both lamps (bright) when motion is detected. The objectives of this study were (1) to design and realize the PV/PIR/RTC PSL prototype, (2) to evaluate PIR and RTC functional performance, and (3) to analyze the system energy balance, PV output profile, component power consumption, utilization efficiency, and battery autonomy, benchmarked against design practice and similar studies. Building on the distinction drawn above, the main contribution of this study is the quantitative sizing and reliability analysis framework itself—battery capacity sensitivity, PV efficiency and motion-trigger sensitivity, and systematic benchmarking



against prior PIR-based PSL research—rather than the sensor combination in isolation.

II. RESEARCH METHODS

A. Design and System Architecture

This study follows an engineering design-research approach: design, prototyping, testing, and quantitative-descriptive analysis of a laboratory-scale PSL pole tested outdoors. The independent variables are the object distance from the PIR sensor, PV measurement time, and lamp mode; the dependent variables are the sensor logic response, per-component voltage/current, and system power/energy. Control is centered on an Arduino Uno; a 12 V Valve-Regulated Lead-Acid (VRLA) battery, charged via an SCC from the PV panel, supplies the system and is stepped down to 5 V (LM2596) for the microcontroller and sensors. The architecture comprises four blocks—power supply, input, processing, and output (Fig. 1)—where the RTC and PIR feed the Arduino Uno, which drives two independent relay channels controlling the 12 V 12 W DC LED lamps.

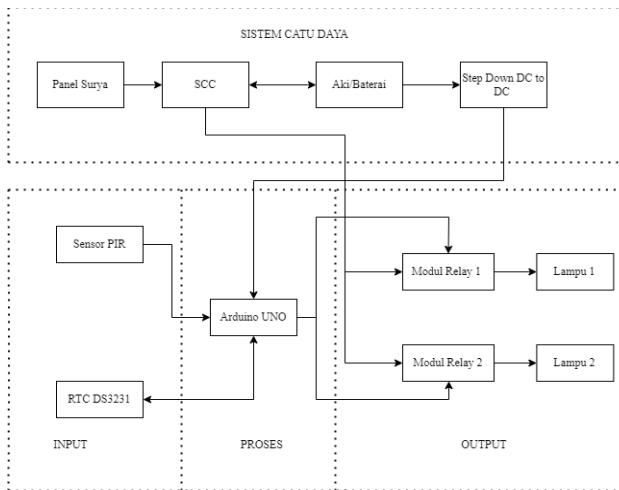


Fig. 1. System block diagram.

The electrical wiring (Fig. 2) routes the PV panel to the SCC for battery charge management, steps 12 V down to 5 V for the Arduino Uno, and switches 12 V loads to lamps 1 and 2 via two single-channel relays based on the Arduino logic. Mechanically, the pole (5 cm cross-section) carries a 40 cm, $\pm 25^\circ$ -inclined arm supporting the PV panel and both LED lamps, with the PIR sensor housed below the lamps to optimize the scan angle. SCC and battery were separated into insulated enclosures (35×25×20 cm, 18×8×30 cm, and 20×14×18 cm, respectively) at the pole base.

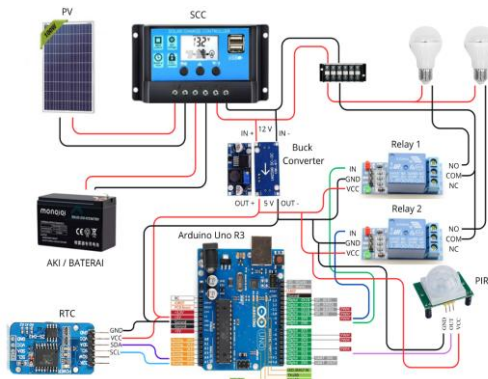


Fig. 2. Wiring diagram.

B. Control Logic and Construction

The Arduino IDE firmware (Fig. 3) reads the RTC time to bound the operation to 17:00–05:00 WIB, defaults to Lamp 1 only, and on PIR motion activates both lamps under a 15 s non-blocking, retriggerable timer—resetting to 15 s on new motion before Lamp 2 turns off. This retriggering underlies the Lamp-2 duty-cycle assumption used in Section III.E. Construction comprised continuity checks on all modules, enclosure assembly, power-circuit wiring (PV-SCC-battery), load/relay/PIR wiring and calibration, and multimeter verification of switching logic.

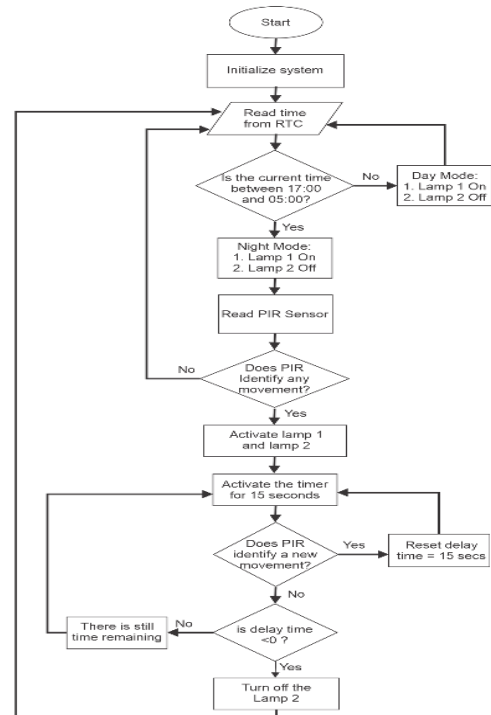


Fig. 3. Control-logic flowchart.

C. Test Instruments, Procedures, and Data Analysis

Testing used a digital multimeter (0.01 V / 0.01 A display resolution) and a Network Time Protocol (NTP)-synced smartphone as the time reference in an open prototype area. (1) PIR test: a person moved along a path perpendicular to the sensor axis at 50–400 cm (50 cm steps), recording the sensor output and lamp status. (2) RTC test: lamp on/off times were visually compared to the smartphone reference at 17:00 and 05:00 WIB over three consecutive days. (3) PV test: panel V/I were logged 09:00–14:00 WIB at 15-min intervals (21 points). (4) Component test: V/I for the Arduino, RTC, PIR, both relays, and both lamps were logged at seven nighttime instants, under both single- and dual-lamp conditions (14 rows). Data were analyzed via descriptive statistics (PV power profile), comparative analysis (standby vs. detection vs. conventional mode), energy-balance analysis (PV production vs. load), a battery-capacity sensitivity analysis for autonomy day, and benchmarking against prior studies to validate derating or Depth of Discharge (DoD) assumptions.

III. RESULTS AND DISCUSSION

A. PIR HC-SR501 Sensor Test

To evaluate the PIR sensor's performance, a detection range test was conducted, with the results summarized in Table I. The PIR sensor produced a HIGH output (motion detected) at all seven tested distances from 50 to 350 cm (100% success within this range), with both lamps actuating correctly throughout. However, at 400 cm and 450 cm, the sensor consistently produced a LOW output (no motion detected), and Lamp 2 remained off at both distances, exactly as the control logic dictates when no PIR trigger is present. This places the sensor's confirmed effective detection range at approximately 350 cm, well short of its 7 m (700 cm) nominal rated range.

TABLE I. PIR SENSOR RESPONSE VS. OBJECT DISTANCE

Dist. (cm)	50	100	150	200	250	300	350	400	450
Response	HIG H	HIG H	HIG H	HIG H	HIG H	HIG H	HIG H	LO W	LO W
Lamp 1	On	On	On	On	On	On	On	On	On
Lamp 2	On	On	On	On	On	On	On	Off	Off

Because the PIR's own output signal, not the lamp actuation circuitry, determined the system behavior beyond 350 cm, this was properly characterized as a sensor-range limitation rather than a hardware or wiring fault, and no relay or driver-circuit redesign was required. A substantial gap between a manufacturer's nominal detection range and measured real-world performance is not unusual for low-cost PIR modules; possible contributing factors include the ambient thermal contrast between the moving subject and background, sensor mounting angle, and datasheet ranges being measured under idealized conditions rather than outdoor deployment. Distinguishing between these factors requires dedicated controlled testing, which is outside the scope of this study. The practical implication is that pole spacing and coverage planning for this system should be based on the confirmed effective range of approximately 350 cm rather than the manufacturer's 7 m rating; where a longer detection range is required, on-site verification with the specific deployment sensor or a supplementary sensor with a longer confirmed range is recommended before finalizing pole placement.

B. RTC DS3231 Module Test

Lamp on/off times were compared to an NTP-synced smartphone at 17:00 and 05:00 WIB over three consecutive days. Transitions consistently matched both reference times with no visually observed deviation, indicating reliable schedule-keeping. This test was performed at a minute resolution; second-level quantitative time-drift logging was not performed and is acknowledged as a limitation, although it is consistent with the DS3231's ± 2 ppm (approximately ± 1 min/year) datasheet accuracy. Long-term quantitative validation is recommended as future work.

To bound this limitation quantitatively rather than leave it open-ended: at the DS3231's rated ± 2 ppm accuracy, the maximum drift is $2 \times 10^{-6} \times t$, giving approximately 0.17 s/day, 5.2 s/month, and 63 s (≈ 1.05 min) over a full year of continuous operation—consistent with the approximately 1 min/year figure already cited. Relative to the 12-hour (17:00–

05:00) operating window, even a full year of uncorrected drift is less than 0.15% of the window length, so the lamp schedule would still switch within approximately 1 min of the intended time after a year without resynchronization. The DS3231 was deliberately chosen over simpler RTC ICs (e.g., the DS1307) specifically because its integrated temperature-compensated crystal oscillator (TCXO) holds this ± 2 ppm bound across its operating temperature range, whereas an uncompensated RTC can drift substantially more as outdoor pole-top temperatures swing between day and night.

Independent microcontroller-based implementations of the DS3231 report comparable sub-minute-per-year timekeeping accuracy in practice, corroborating this datasheet-derived bound [13]. This datasheet-derived bound cannot substitute for the field-measured drift a reviewer might reasonably expect, but it indicates that the qualitative three-day check is unlikely to be masking a practically significant scheduling error; periodic resynchronization—e.g., via the IoT connectivity proposed in future work—remains good practice for unattended multi-year deployment regardless.

C. PV Panel Output Test

The output power of the 100 Wp PV panel was measured at 15-minute intervals between 09:00 and 14:00 WIB. The statistical summary of these measurements is presented in Table II, while the corresponding fluctuation of the PV output power profile is visually illustrated in Fig. 4. Output ranged 31.79–99.45 W (mean 69.61 W, SD 18.17 W); the sharp dip at 12:15 WIB (vs. approximately 80 W nearby) indicates transient cloud shading, typical of uncontrolled outdoor PV measurement. Such environmental variability underscores the importance of utilizing cumulative Peak Sun Hours (PSH) for realistic energy yield calculations, rather than relying on peak instantaneous wattage.

TABLE II. PV PANEL TEST SUMMARY (09:00–14:00 WIB, 15-MIN INTERVALS, N = 21)

Statistic	Value
Power range	31.79 - 99.45 W
Mean power ($\pm$ SD)	69.61 $\pm$ 18.17 W (CV $\approx$ 26%)
Total energy (Σ)	365.47 Wh
Peak Sun Hours (PSH)	3.65 h
Lowest reading	31.79 W at 12:15 (transient cloud cover)

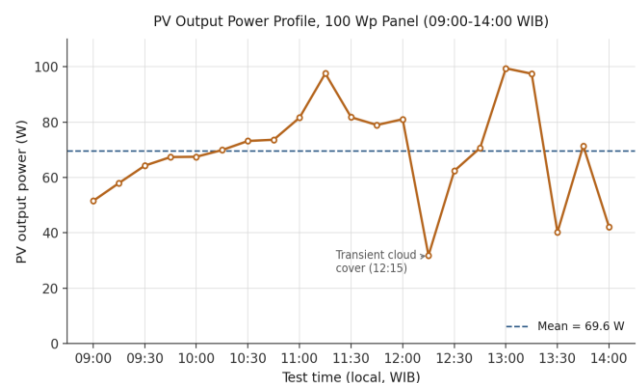


Fig. 4. PV output power profile.

Daily PV energy production is calculated as follows:

$$E_{PV} = P_{PV} \times PSH \times \eta \quad (1)$$

Substituting the measured parameters yields $E_{PV} = 100 \times 3.65 \times 0.7 = 255.50$ Wh/day. The 70% efficiency assumption remains optimistic relative to Lima Flores et al. [3], who measured a considerably higher 90–93% efficiency for a small (250 W) grid-connected micro-inverter operating at high altitude—illustrating that measured inverter efficiency depends strongly on system type, scale, and installation conditions, and that the present 70% figure should ultimately be validated against the specific hardware used here. The EPV estimate should thus be validated via longer-term (≥ 1 month) production monitoring across weather conditions.

D. System Energy Balance and Discussion

Power was computed as $P = V \times I$ for each component and instant, resulting in 14 measured rows in total. Table III shows the representative points from these measurements.

TABLE III. MEASURED POWER BY COMPONENT AND MODE (REPRESENTATIVE INSTANTS, W)

Time	Mode	Ard uino	RT C	PIR	Relay 1	Relay 2	Lamp 1	Lamp 2
17:00	L1 only	0.25 4	0.01 0	0.25 0	0.354	0	11.99 1	0
17:00	L1+ L2	0.26 4	0.01 0	0.29 5	0.359	0.354	12.03 7	12.01 1
19:00	L1+ L2	0.26 3	0.01 1	0.29 0	0.353	0.353	11.68 2	11.65 6
04:00	L1+ L2	0.25 3	0.01 0	0.27 9	0.342	0.342	11.01 7	11.00 5
04:30	L1+ L2	0.24 9	0.01 0	0.27 4	0.342	0.342	10.89 4	10.88 1

Battery voltage declined steadily overnight, from 12.90 V (17:00) to 12.26 V (04:30)—a 0.64 V (5.33%) drop, well above the deep-discharge threshold (approximately 11.5–11.8 V), supporting the 80% Depth of Discharge (DoD) assumption used below. With only Lamp 1 on, standby power is $P_{standby} = P_{lamp1} + P_{Arduino} + P_{PIR} + P_{RTC} = 12.506$ W, so the daily standby energy is:

$$E_{standby} = P_{standby} \times t \quad (2)$$

Substituting the values gives $E_{standby} = 12.506 \text{ W} \times 12 \text{ h} = 150.07$ Wh/day. With both lamps on, $P_{detection} = 24.618$ W. Based on the 15 s retriggerable timer (Fig. 3), Lamp 2's cumulative on-time is assumed to be approximately 5 h/day ($t_{detection}$) which around 1,200 trigger events/night; the actual value depends on site traffic and should be validated by logging real trigger counts:

$$E_{load} = E_{standby} + (P_{lamp2} \times t_{detection}) \quad (3)$$

Thus, the total load is $E_{load} = 150.07 + (12 \times 5) = 210.07$ Wh/day. Without PIR control, both lamps stay on continuously, resulting in $P_{conventional} = 24.323$ W and $E_{conventional} = 291.87$ Wh/day. Therefore, the energy savings (ΔE) can be calculated as:

$$\Delta E = E_{conventional} - E_{load} \quad (4)$$

This yields $\Delta E = 291.87 - 210.07 = 81.80$ Wh/day (28.03% savings), which is illustrated in Fig. 5. These savings not only reduce the required daily energy generation but also alleviate the overnight cyclic stress on the battery bank. Over a multi-year deployment, operating at this reduced load is expected to optimize the initial capital expenditure and extend the operational lifespan of the storage system.

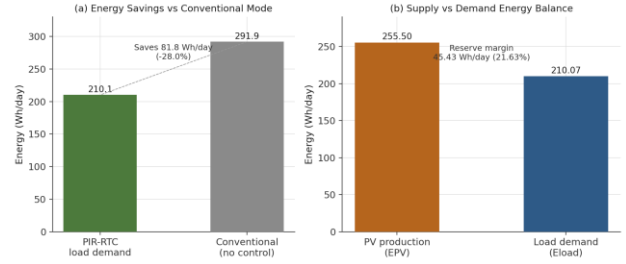


Fig. 5. (a) savings vs. conventional mode; (b) PV supply vs. load demand.

This 28.03% saving is moderate compared to Fokui and Wandji [9] (up to 86%, vibration-sensor PSL), because Lamp 1 here stays at full brightness in standby (only Lamp 2 is switched), whereas [9] dims fully when idle—pulse-width modulation (PWM) dimming of Lamp 1 is a promising upgrade. Comparing supply and demand:

$$E_{margin} = E_{PV} - E_{load} \quad (5)$$

$$\eta_{system} = \frac{E_{load}}{E_{PV}} \quad (6)$$

This provides an $E_{margin} = 255.50 - 210.07 = 45.43$ Wh/day (21.63% reserve) and a system utilization efficiency of $\eta_{system} = \frac{210.07}{255.50} = 82.22\%$.

E. Battery Capacity and Autonomy Day

Battery capacity is $C_{bat} = 12 \text{ V} \times 12 \text{ Ah} = 144$ Wh. At an 80% Depth of Discharge (DoD), the usable energy is $E_{usable} = 115.2$ Wh, which gives the Autonomy Day (AD) calculation:

$$AD = \frac{E_{usable}}{E_{load}} \quad (7)$$

Substituting the values yields $AD = 115.2/210.07 = 0.55$ day (approximately 13.16 h). This barely exceeds one 12-h night with no real safety margin. A recent review of stand-alone PV/wind system sizing by Kafando et al. [14] found that two to three days of autonomy are generally adopted, with studies reporting ranges from 2–9 days depending on load criticality. However, the review noted that this practice is rarely justified quantitatively and rarely distinguishes public-safety loads such as PSL from ordinary residential loads. Even at the lower end of this range, the existing 12 Ah battery falls far short, as depicted in Fig. 6. A charging-current check ($I_{max} = P_{PV}/V_{mp} = 100/18$, approximately 5.56 A) confirmed that the 10 A SCC operated safely with an approximate 44% margin, allowing future expansion up to 180 Wp on the same SCC.

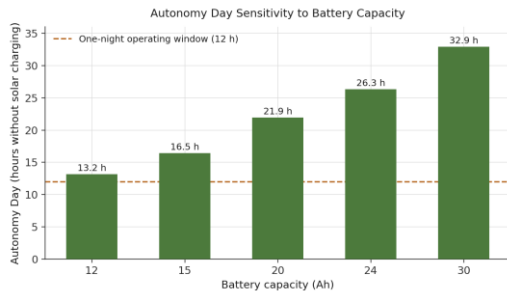


Fig. 6. Autonomy Day sensitivity to battery capacity.

TABLE IV. BATTERY-CAPACITY SENSITIVITY

Capacity (Ah)	12	15	20	22 ^a	24	30	44 ^b
AD (day)	0.55	0.69	0.91	1.01	1.10	1.37	2.01
AD (hours)	13.2	16.5	21.9	24.2	26.3	32.9	48.3

^a Target for full 1-day autonomy; ^b Target for a 2-day minimum standard [14]. A capacity of approximately 22 Ah reaches one full day, and approximately 44 Ah is needed to reach standard practice, motivating the 20–44 Ah recommendation below, which is sized to the desired reliability level.

F. Comparison with Prior Studies

As outlined in Table V, this study is comparatively stronger in quantitative energy-balance and autonomy analysis, which most comparators omit; like [5], [6], [8], however, its single PIR sensor cannot distinguish object type (human/animal/vehicle), a shared limitation.

TABLE V. BENCHMARKING AGAINST SIMILAR PSL STUDIES

Study	Sensor	Panel	Key feature / energy result
This study	PIR + RTC	100 Wp	Full energy balance + AD sensitivity; 28.03% savings
Sánchez Sutil & Cano-Ortega [6]	PIR	-	LoRa telemetry focus, no energy balance
Zaki & Abdullah [7]	-	-	Automated wiper + IoT cleaning; 3.17–9.81% power recovery
Sinappan et al. [5]	PIR + LDR	-	Vehicle-motion dimming; ~50% energy savings, no RTC
Singha Roy et al. [10]	LDR + fog (inferred)	-	IoT cloud monitoring; ESP32-based testbed, simulated environment

Overall, the PIR+RTC control cuts daily energy use by 28.03% with a PV supply margin of 21.63%, but autonomy day (0.55 day) sits far below standard PV practice (2–3 days) [14], so reliability under consecutive overcast weather remains a concern despite good normal-weather performance. The 70% efficiency and 5 h/day detection assumptions should be validated with longer monitoring and real trigger logging, and the confirmed approximately 350 cm effective PIR range (versus its 7 m nominal rating) should inform pole-spacing decisions in future deployments.

G. Sensitivity Analysis of Assumptions

The energy-balance figures above rest on two assumptions flagged earlier as needing validation: a 70% PV derating efficiency and a 5 h/day cumulative Lamp-2 detection time. Both were adopted rather than measured directly because the prototype’s single-session

instrumentation (a handheld multimeter, logged manually) could only sustain a 5-hour daytime PV window and a manually observed three-night RTC/PIR check; continuous multi-week logging of PV output and actual PIR trigger counts would require a dedicated data logger, which was outside the scope of this capstone-scale prototype and is listed as future work. To make the resulting uncertainty explicit rather than hidden inside a single point estimate, Tables VI and VII recompute the energy balance across the plausible range of each assumption using the already-measured $P_{standby}$, P_{lamp1} , P_{lamp2} , and PSH values; no new experimental data is introduced.

Specifically, regarding the derating efficiency assumption, Table VI demonstrates that at the pessimistic end of the literature range (60%), the daily margin collapses to approximately 4.25% of the load—a thin buffer that would leave the system vulnerable to even brief overcast periods, whereas at the optimistic end (72%), the margin approaches 25%. The true value likely varies day-to-day with panel soiling, temperature, and irradiance, which is precisely why the 70% baseline should be treated as a planning assumption to be replaced with logged data, not as a guaranteed figure.

TABLE VI. SENSITIVITY OF PV ENERGY PRODUCTION AND MARGIN TO THE DERATING EFFICIENCY ASSUMPTION

η^a (%)	60	67	70 (baseline)	72
EPV (Wh/day)	219.00	244.55	255.50	262.80
Emargin (Wh/day)	8.93	34.48	45.43	52.73
Margin (% of Eload)	4.25	16.42	21.63	25.11

^a $\eta = 60\%$ is treated as a conservative derating allowance; $\eta = 67\%$ and 72% are illustrative sensitivity-range points; $\eta = 70\%$ is the baseline assumption in this study. For context, Lima Flores et al. [3] measured a considerably higher 90–93% efficiency for a small (250 W) grid-connected micro-inverter at high altitude, underscoring that measured inverter efficiency varies substantially with system type and scale.

Regarding the assumed nightly motion-trigger duration, Table VII illustrates that site traffic therefore matters: a quieter location ($t_{detection} \approx 3$ h/night) would improve both the PV margin and the autonomy day, while a busier one ($t_{detection} \approx 10$ h/night, i.e., roughly 2,400 trigger events) would erase the PV margin entirely (a projected 14.57 Wh/day deficit) and shorten the autonomy day to approximately 10.2 h—under a single 12-hour night. This confirms the manuscript’s earlier recommendation that actual trigger counts be logged on site before the 5 h/day assumption is relied upon for deployment sizing and shows that the assumption is not merely a numerical nicety but can change the sign of the energy margin.

TABLE VII. SENSITIVITY OF DAILY LOAD AND AUTONOMY DAY TO THE ASSUMED NIGHTLY MOTION-TRIGGER DURATION

$t_{detection}$ (h)	3	5 (baseline)	7	10
Eload (Wh/day)	186.07	210.07	234.07	270.07
Emargin (Wh/day) ^a	69.43	45.43	21.43	−14.57
AD (day)	0.62	0.55	0.49	0.43
AD (hours)	14.86	13.16	11.82	10.24

^a E_{margin} computed at the 70% efficiency baseline ($E_{PV} = 255.50$ Wh/d).

H. PWM Dimming Feasibility for Autonomy Extension

The previously mentioned future-work suggestion—PWM-dimming Lamp 1 during quiet (no-motion) hours instead of leaving it at full brightness—can be evaluated mathematically with the hardware already characterized in Table III, without new experiments [15]. Let $d \in [0,1]$ be the PWM duty (approximated as proportional to Lamp 1's average power) applied only during the $(12 - t_{\text{detection}})$ quiet hours, while Lamp 1 remains at full power alongside Lamp 2 during the $t_{\text{detection}}$ bright hours. With $P_{\text{other}} = P_{\text{Arduino}} + P_{\text{PIR}} + P_{\text{RTC}} = 0.514$ W running continuously regardless of dimming, the daily load becomes:

$$E_{\text{load}}(d) = P_{\text{Lamp1}}[t_{\text{detection}} + d(12 - t_{\text{detection}})] + 12P_{\text{other}} + P_{\text{Lamp2}} \times t_{\text{detection}} \quad (8)$$

With $P_{\text{Lamp1}} = 11.991$ W, $P_{\text{other}} = 0.514$ W, $P_{\text{Lamp2}} = 12$ W, and the baseline $t_{\text{detection}} = 5$ h, the effect of PWM-dimming on the daily load and autonomy day is evaluated in Table VIII. The scenarios range from $d = 1.0$ (no dimming, the as-built baseline) to $d = 0.0$ (Lamp 1 fully off whenever no motion is present, the extreme case), together with one combined scenario pairing moderate dimming with the battery upgrade already recommended above.

PWM dimming alone provides a real but bounded improvement: even the extreme case of switching Lamp 1 off completely whenever no motion is present only raises the autonomy day from 0.55 to approximately 0.91 day (approximately 21.9 h)—a 66% improvement, but still short of a single full day and well below the 2-day minimum standard [14]. Mathematically, the existing 12 Ah battery cannot reach the 2-day standard through dimming alone, because Lamp 2's detection-mode load and the continuous control electronics already account for the majority of unavoidable consumption once $t_{\text{detection}}$ is nonzero. Dimming is nonetheless a worthwhile complement rather than a substitute for battery upsizing: pairing a moderate $d = 0.3$ duty with the already-recommended 22 Ah battery raises the autonomy day from 1.01 day (Table IV, no dimming) to approximately 1.40 day for the same battery investment, and a comparable multiplier would apply at 44 Ah. Future prototypes should therefore treat PWM dimming and battery sizing as complementary levers rather than alternatives.

TABLE VIII. EFFECT OF PWM-DIMMING DUTY (LAMP 1, QUIET HOURS) ON DAILY LOAD AND AUTONOMY DAY

d (quiet-hour duty)	1.0 (baseline)	0.5	0.3	0.2	0.0 (Lamp 1 off)	0.3 + 22 Ah ^a
E_{load} (Wh/day)	210.07	168.09	151.30	142.91	126.12	151.30
AD (day)	0.55	0.69	0.76	0.81	0.91	1.40
AD (hours)	13.16	16.45	18.27	19.35	21.92	33.51

^a Combines $d = 0.3$ dimming with the 22 Ah battery from Table IV ($E_{\text{usable}} = 211.2$ Wh) rather than the as-built 12 Ah.

IV. CONCLUSION

The PIR HC-SR501 achieved 100% detection success up to 350 cm but failed to detect motion at 400 cm and 450 cm—a sensor-range limitation, not a circuit-level fault, placing its confirmed effective range well below the 7 m nominal rating. The RTC DS3231 kept lamp transitions aligned to the

17:00/05:00 schedule over three days of qualitative observation; quantitative time-drift logging is a noted limitation. PIR+RTC power management cut daily load to 210.07 Wh/day, 28.03% (81.80 Wh/day) below conventional always-on operation. The 100 Wp panel produced 255.50 Wh/day (PSH 3.65 h, 70% efficiency—an optimistic assumption meriting longer validation), covering demand with a 21.63% margin and 82.22% utilization efficiency. The 12 Ah battery gave only a 0.55-day (approximately 13.16 h) autonomy, well short of the 2–3 days norm for standalone PV [14]; approximately 22 Ah is needed for one full day and approximately 44 Ah for the 2-day minimum.

A quantitative bound on RTC drift (approximately 63 s/year at the DS3231's rated ± 2 ppm) confirms that the three-day qualitative check is unlikely to conceal a practically significant scheduling error, though periodic resynchronization remains advisable for multi-year deployment. Sensitivity analysis shows that the energy margin ranges from approximately 4% to 25% of the load across the literature's 60–72% efficiency range and can turn negative if the nightly motion-trigger duration exceeds approximately 8 h—underscoring that both assumptions should be replaced with logged data before deployment sizing. PWM-dimming Lamp 1 during quiet hours mathematically extends the autonomy day from 0.55 to at most approximately 0.91 day using the existing 12 Ah battery, a meaningful but insufficient gain on its own, confirming that dimming should complement, not replace, the recommended battery upgrade.

Future work should: (1) size the battery to 20–44 Ah per the desired reliability target; (2) add current/voltage sensors with a data logger for continuous charge and RTC-drift monitoring; (3) apply PWM dimming to Lamp 1 (not just on/off switching of Lamp 2), which the analysis above shows can extend the autonomy day by up to approximately 66% in the extreme case, though not to the 2-day standard by itself; (4) log actual PIR trigger counts on site to replace the 5 h/day assumption; (5) monitor PV production daily over a full month across weather conditions; and (6) add IoT connectivity for remote monitoring of battery status, lamp faults, and RTC resynchronization.

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