



Design and Performance Analysis of a Solar Powered Smart Street Lighting System

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Abstract

This methodology paper presents the design and analytical performance evaluation of a stand-alone solar-powered smart street lighting system intended for roads, campuses and locations where grid extension is costly or unreliable. The proposed system combines a photovoltaic (PV) module, battery storage, a charge controller, a high-efficiency LED luminaire, a microcontroller, a light-dependent resistor (LDR), and a passive infrared (PIR) motion sensor. The design objective is to maintain useful nighttime illumination while reducing energy consumption through scheduled dimming and demand-based brightness control. A step-by-step sizing procedure is developed from the nightly load profile, peak-sun-hours, component derating, allowable battery depth of discharge and required autonomy. For a representative 30 W LED lamp, the calculated smart-lighting profile requires approximately 252 Wh per night, compared with 372 Wh for an equivalent full-brightness LED system including control losses. A 150 W PV module, 12 V/150 Ah battery and 20 A controller provide a practical design margin. The calculated energy reduction is about 32%, while usable battery energy supports approximately 3.2 nights of operation without solar input. The results indicate that integrating PV generation with LED lighting and sensor-based control can substantially improve the energy efficiency and autonomy of street lighting, provided that local solar resources, battery aging, temperature and lighting standards are considered in final implementation.

Introduction

Street lighting is essential for road visibility, pedestrian safety and night-time activity, but conventional installations can impose a continuous energy and maintenance burden. High-pressure sodium (HPS) lamps have historically dominated road lighting, whereas LED luminaires offer controllability, improved directional light distribution and lower electrical demand. Experimental comparison of HPS and LED public-lighting technologies has shown that LED systems can provide an effective alternative when photometric performance and visual

conditions are considered rather than lamp wattage alone (Rodrigues et al., 2011). Later work emphasized that LED street lighting should be treated as a complete system involving optical design, electronic drivers, thermal management and appropriate quality criteria (Ciriminna et al., 2015).

Solar-powered street lighting further reduces dependence on grid electricity by generating energy locally during the day and storing it for night use. This configuration is attractive in remote roads, rural communities, campuses and new developments because it can avoid trenching

and long cable runs. Masoud (2015) demonstrated the relevance of combining PV generation and LED lamps in a street-lighting case study, while Galita (2015) developed a stand-alone solar LED streetlight in which automatic brightness control was used to reduce unnecessary consumption. Daud and Khader (2014) also showed that PV-powered street lighting can be integrated with electronic control and communication for switching and supervision.

The term smart street lighting refers to more than automatic dusk-to-dawn switching. A smart system senses ambient light or road use, processes the information and adjusts the luminaire output to the actual need. Wireless and sensor-based systems have been proposed to support dynamic control, monitoring and maintenance (Elejoste et al., 2013). Adaptive algorithms have also demonstrated meaningful energy savings: Escolar et al. (2014) reported savings close to 35% for adaptive control relative to rigid lighting behavior, while Lau et al. (2015) showed that traffic-aware control can reduce energy use substantially in simulated road networks while preserving useful illumination. These studies motivate a design that combines the independence of a stand-alone PV system with the controllability of LED lighting.

The aim of this paper is therefore to develop a clear methodology for designing and evaluating a solar-powered smart street lighting unit using components and approaches supported by literature available up to 2016. The objectives are: (i) to establish the functional architecture; (ii) to determine the nightly energy demand under a smart dimming schedule; (iii) to size the PV array, battery and charge controller; (iv) to define sensor and control logic; and (v) to quantify energy savings, generation margin and battery autonomy through analytical performance calculations. The paper does not claim results from a fabricated field prototype; instead, the Results section reports a reproducible design-case analysis that can be used as the basis for later experimental validation.

Literature Review

Research prior to and during 2016 shows a convergence of three technologies: efficient LED road lighting, stand-alone photovoltaic supply and context-aware control. Rodrigues et al. (2011) compared LED and HPS luminaires experimentally and highlighted the importance of photometric performance under roadway lighting conditions. This supported the move away from evaluating streetlights solely by

installed wattage. Ciriminna et al. (2015) reviewed the broader prospects of LED street lighting and argued that high-quality LED deployment can contribute to electricity savings and lower environmental impact.

The second research stream concerns intelligent control. Elejoste et al. (2013) developed a deployable LED street-light control architecture using wireless communication and environmental awareness, emphasizing reduced installation costs and the value of real-time context. Escolar et al. (2014) used adaptive behavior rules in a simulated smart-lighting environment and reported approximately 35% energy savings compared with fixed behavior. Lau et al. (2015) extended this idea to traffic-aware operation, using networked sensing to adjust brightness in response to vehicles and pedestrians. These studies support the use of dimming rather than simple binary ON/OFF operation.

The third stream focuses on integrating solar supply with street lighting. Daud and Khader (2014) presented a PV source for street lighting with GSM-based supervision, illustrating how local generation and electronic control can be combined. Masoud (2015) evaluated solar-powered LED street lighting in a university case study and identified energy and economic advantages relative to conventional HPS-based infrastructure. Galita (2015) developed a smart solar-powered LED streetlight using automatic daylight control and time-dependent brightness settings. Ling et al. (2016) later described a photovoltaic hybrid LED street-lighting system that combined a PV panel, battery, charge controller, LED array, microcontroller and communication hardware, closely resembling the multi-component architecture required for practical smart lighting.

PV and battery sizing is critical because an undersized system causes loss of lighting during low-irradiance periods, whereas an oversized system raises cost and battery replacement burden. Khatib et al. (2016) reviewed PV-array and storage-battery sizing methods for stand-alone systems and stressed that design criteria must account for meteorological data, reliability and component sizing methodology. Ibrahim et al. (2016) further demonstrated that battery-model accuracy can materially affect optimized PV and storage capacities and life-cycle cost. Consequently, the present methodology uses conservative derating, limited battery depth of discharge and an autonomy check instead of sizing the system from lamp wattage alone.

A gap remains between many smart-lighting studies, which concentrate on control algorithms, and many PV studies, which concentrate on energy sizing without explicitly modelling adaptive road-lighting demand. The contribution of the present methodology is to connect these two dimensions in a single transparent design procedure: first define a safe dimming schedule

and motion override, then calculate the resulting load, then size the PV and battery to the controlled load, and finally evaluate energy saving and autonomy. This sequence is especially useful for preliminary design because every assumption can be replaced with measured local data during implementation.

Table 1. Selected Literature Supporting the Proposed Design (2011–2016)

Study	Focus	Key contribution	Use in this paper
Rodrigues et al. (2011)	LED vs HPS	Photometric/technology comparison	LED selection rationale
Elejoste et al. (2013)	Smart control	Wireless, context-aware LED management	Sensor/control architecture
Daud & Khader (2014)	PV streetlight	PV supply with remote supervision	Stand-alone system concept
Escolar et al. (2014)	Adaptive dimming	~35% simulated savings	Dimming strategy benchmark
Masoud (2015)	Solar LED	PV–LED street-light case study	PV/LED integration
Lau et al. (2015)	Traffic-aware lighting	Demand-responsive brightness	Motion override concept
Khatib et al. (2016)	PV sizing	Review of array/battery methods	Sizing equations and margins
Ibrahim et al. (2016)	Battery model	Sizing sensitivity to battery modelling	SOC/autonomy caution

Methodology

Step 1: Define System Requirements

A single autonomous street-light unit is considered. The design target is a 30 W LED luminaire operating for 12 h per night. Ambient-light sensing prevents daytime operation, and a PIR sensor temporarily overrides dimmed levels when a pedestrian or vehicle is detected. The nominal DC bus is 12 V. To keep the analysis reproducible, an average of 5 peak-sun-hours (PSH) per day and an overall PV derating factor of 0.75 are assumed. The selected battery is limited to 50% depth of discharge (DOD) to reduce deep cycling. These assumptions should be replaced by local irradiance, temperature and lighting-standard data in a site-specific design (Khatib et al., 2016; Ibrahim et al., 2016).

Step 2: Establish the Smart Lighting Load Profile

The controller uses four scheduled brightness levels with a motion-triggered full-output override: 100% for the first 5 h after dusk, 60% for the next 2 h, 30% for the following 4 h, and 60% for the final 1 h before dawn. This profile reflects the principle that lighting demand is generally lower during low-traffic periods, while the PIR sensor restores full brightness when activity is detected. Similar adaptive and traffic-aware approaches have been shown to reduce

energy consumption in prior smart-lighting studies (Escolar et al., 2014; Lau et al., 2015).

$$E_{LED} = \Sigma(P_{LED} \times f_i \times t_i) = 30(1.0 \times 5 + 0.6 \times 2 + 0.3 \times 4 + 0.6 \times 1) = 240 \text{ Wh/night} \quad (1)$$

An additional 12 Wh/night is allocated to the microcontroller, sensors and driver/control losses, giving a design load of 252 Wh/night. A fixed 30 W LED operating at full output for 12 h with the same 12 Wh control allowance would require 372 Wh/night.

Step 3: Size the PV Module

The minimum PV rating is determined from nightly energy demand, available PSH and the system derating factor. The derating factor represents combined losses due to temperature, wiring, charge conversion, dust, module mismatch and non-ideal operating conditions.

$$P_{PV,min} = E_{load} / (PSH \times \eta_{derate}) = 252 / (5 \times 0.75) = 67.2 \text{ W} \quad (2)$$

A practical design should not select a module exactly at the calculated minimum because seasonal irradiance and battery recharge requirements must be considered. Therefore, a commercially common 150 W PV module is selected. At 5 PSH and 0.75 derating, the expected useful daily energy is 562.5 Wh, providing a nominal energy margin of about 310.5 Wh/day

under the design irradiance condition. This conservative oversizing is consistent with the need for reliable stand-alone operation discussed by Khatib et al. (2016).

Step 4: Size the Battery

Battery capacity is determined from the daily load, required autonomy, nominal voltage, allowable DOD and discharge efficiency. For two days of required design autonomy, 12 V nominal voltage, 50% DOD and 90% discharge efficiency:

$$C_{\text{bat}} = (E_{\text{load}} \times N_{\text{aut}}) / (V_{\text{bat}} \times \text{DOD} \times \eta_{\text{bat}}) \\ = (252 \times 2) / (12 \times 0.50 \times 0.90) = 93.3 \text{ Ah} \quad (3)$$

The calculated minimum is rounded upward and additional aging/weather margin is added; hence a 12 V, 150 Ah deep-cycle battery is selected. Its usable energy at 50% DOD and 90% discharge efficiency is approximately 810 Wh. Battery behavior strongly influences stand-alone PV sizing, and inaccurate battery modelling can lead to significant differences in optimized capacity and cost (Ibrahim et al., 2016).

Step 5: Select Charge Controller and Protection

For a 150 W module on a nominal 12 V system, the approximate charging current is 12.5 A.

Applying a 1.25 design factor gives 15.6 A; therefore a 20 A charge controller is selected. A controller with low-voltage disconnect, overcharge protection and temperature compensation is preferred. The circuit should also include PV-side and battery-side overcurrent protection, reverse-polarity protection, weatherproof connectors and an enclosure suitable for outdoor service.

Step 6: Implement Sensing and Control Logic

At daytime illumination above a selected LDR threshold, the lamp remains OFF and the PV module charges the battery. At dusk, the lamp follows the scheduled PWM dimming profile. During dimmed periods, a PIR event commands 100% brightness for a preset interval (for example, 30–60 s) and then returns the lamp to the scheduled level. Battery voltage is continuously checked; if it falls below the low-voltage threshold, the controller restricts brightness or turns the lamp OFF to prevent excessive discharge. This layered control combines the environmental awareness described by Elejoste et al. (2013) with the demand-responsive principle of Lau et al. (2015).

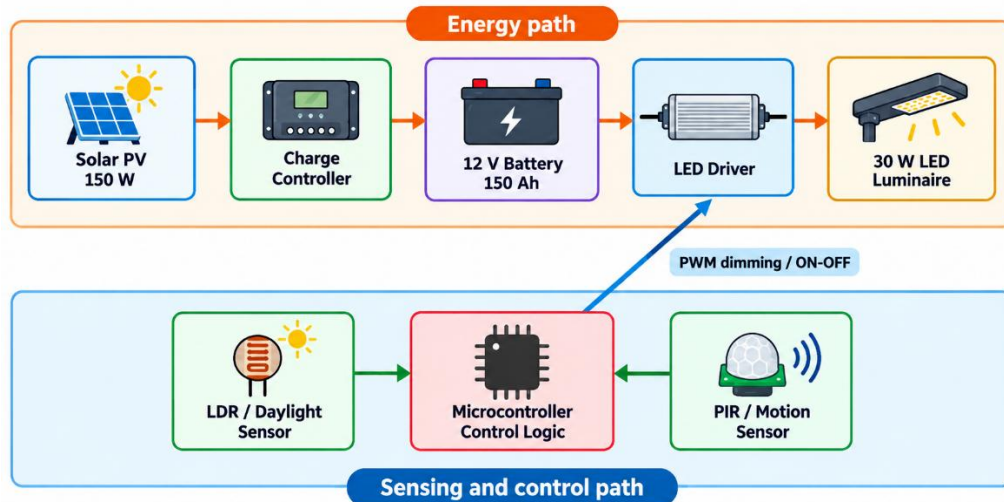


Figure 1. Functional architecture of the proposed solar-powered smart street lighting system.

Step 7: Performance Evaluation Procedure

Performance is evaluated using four indicators: (1) nightly energy consumption, (2) energy saving relative to a fixed full-brightness LED baseline, (3) daily PV energy margin at the assumed PSH, and (4) battery-only autonomy. Energy saving is calculated as $(E_{\text{baseline}} -$

$E_{\text{smart}})/E_{\text{baseline}} \times 100$. Battery autonomy is calculated from usable stored energy divided by the smart nightly load. A sensitivity check is also made for 3, 4 and 5 PSH/day to show how solar resource affects recharge margin. The resulting values are analytical design estimates rather than field measurements.

Table 2. Proposed Design Parameters

Parameter	Design value	Rationale
LED luminaire	30 W, 12 V DC	Efficient roadway-lighting load
Night duration	12 h	Representative design night

Smart load	252 Wh/night	Scheduled dimming + controls
PV module	150 W	Margin above 67.2 W minimum
Solar resource	5 PSH/day	Design assumption; site-specific replacement required
PV derating	0.75	Aggregated practical losses
Battery	12 V, 150 Ah	>2-day required autonomy with margin
Allowed DOD	50%	Battery-life protection
Charge controller	20 A	>15.6 A factored current
Sensors	LDR + PIR	Day/night detection and activity override

Results

The calculated results show that the smart schedule reduces the luminaire energy from 360 Wh/night at continuous full brightness to 240 Wh/night. Including an equal 12 Wh control allowance in both cases gives 252 Wh/night for the smart system and 372 Wh/night for the fixed-output LED baseline. The resulting total energy reduction is 32.3%. This value is close to the scale of savings reported by Escolar et al. (2014) for adaptive control and is consistent with the broader conclusion from prior work that contextual dimming can materially reduce street-light energy demand.

At 5 PSH/day, the 150 W PV module produces an estimated 562.5 Wh/day after the 0.75 derating factor. After supplying the 252 Wh nightly load, the nominal daily surplus is 310.5 Wh. At 4 PSH/day, expected useful PV energy decreases to 450 Wh/day, still leaving a 198 Wh margin. At 3

PSH/day, the useful PV energy is 337.5 Wh/day, leaving only 85.5 Wh/day, which implies slower recovery after a cloudy sequence. This illustrates why solar street-light design must be based on local seasonal irradiance rather than annual average values alone (Khatib et al., 2016).

The 12 V/150 Ah battery stores 1,800 Wh nominally. Restricting operation to 50% DOD and applying 90% discharge efficiency gives 810 Wh of usable design energy. Dividing by 252 Wh/night yields approximately 3.21 nights of battery-only operation. The selected battery therefore exceeds the two-night design-autonomy target. In actual service, low temperature, battery aging, high PIR activity and controller self-consumption would reduce this value; hence state-of-charge monitoring and conservative low-voltage protection are necessary.

Table 3. Calculated Performance of the Proposed Design

Performance indicator	Baseline condition	/	Calculated value	Interpretation
Nightly energy	Fixed 30 W LED		372 Wh/night	Reference including control allowance
Nightly energy	Smart schedule		252 Wh/night	Reduced by dimming
Energy saving	Smart vs fixed		32.3%	Lower nightly demand
PV output	5 PSH/day		562.5 Wh/day	310.5 Wh nominal margin
PV output	4 PSH/day		450 Wh/day	198 Wh nominal margin
PV output	3 PSH/day		337.5 Wh/day	85.5 Wh nominal margin
Usable battery energy	50% DOD, $\eta=0.90$		810 Wh	Protected usable storage
Battery-only autonomy	No solar input		3.21 nights	Exceeds 2-night target

From a functional perspective, the proposed architecture also improves operating flexibility. Daylight sensing eliminates unnecessary daytime lighting, while motion override allows reduced background illumination without preventing full output when road users are present. These capabilities follow the direction of earlier smart street-lighting platforms (Elejoste et al., 2013; Lau et al., 2015) and solar-integrated designs (Galita, 2015; Ling et al., 2016). Nevertheless, the analytical results should be validated with illuminance measurements, battery SOC logging,

measured PV energy and seasonal field trials before deployment.

Conclusion and Discussion

This paper developed a step-by-step methodology for a solar-powered smart street lighting system using literature available up to 2016. The proposed architecture integrates a PV module, charge controller, battery, LED driver, microcontroller, LDR and PIR sensor. The design method begins with the controlled lighting load rather than the lamp nameplate rating, then sizes the generation and storage subsystems using peak-sun-hours, derating, autonomy and DOD

constraints. For the representative design, a 30 W LED controlled by a four-stage dimming schedule requires approximately 252 Wh/night, and a 150 W PV module with a 12 V/150 Ah battery provides a practical energy and autonomy margin. The calculated 32.3% energy reduction demonstrates the value of smart dimming, while the 3.21-night battery-only autonomy indicates that storage can cover short periods of poor weather under the stated assumptions. The findings align with prior research showing that LED technology, adaptive control and PV supply are complementary rather than independent design choices (Masoud, 2015; Escolar et al., 2014; Khatib et al., 2016). The system also offers a modular route for rural and campus lighting where grid expansion is undesirable. The main limitation is that the reported results are analytical design estimates. A complete implementation should conduct road-surface illuminance and uniformity tests, verify PIR detection zones, log PV and battery energy over different seasons, evaluate battery degradation and confirm compliance with applicable road-lighting standards. Future work can also add wireless fault reporting and remote monitoring, as demonstrated in earlier intelligent street-lighting studies (Daud & Khader, 2014; Elejoste et al., 2013). Thus, the proposed methodology is best understood as an engineering design framework for prototype development and subsequent experimental validation.

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