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Applicability of AC/DC Solar Hybrid Street Lighting: A Comparative Study on Reliability and Sustainability in Industrial Parks

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***Abstract*: As Philippine industrial parks transition toward "Green Industry" standards, the demand for lighting infrastructure that balances high operational reliability with decarbonization has intensified. Traditional High-Pressure Sodium and grid-tied LED systems contribute significantly to Scope 2 greenhouse gas emissions due to the nation's coal-heavy electrical grid, while standalone solar street lighting often suffer from a "reliability gap" during the monsoon season, where energy harvest can drop. This study evaluates the applicability of an AC/DC Solar Hybrid Street Lighting System as a resilient middle-ground solution. Utilizing a descriptive-comparative quantitative research design, the study compares the four street lighting systems based on Operational Reliability (Uptime %) and Sustainability (Carbon Footprint). According to the study's findings, the AC/DC hybrid system strikes the ideal balance needed for industrial safety on both sustainability and reliability, while standalone solar maximizes sustainability. The hybrid model, which uses solar DC as the main source and an AC grid fail-safe, guarantees almost zero downtime while significantly lowering indirect carbon emissions, giving developers a solid framework to comply with "Green Industry" regulations without sacrificing operational security.**

***Keywords*: AC/DC Solar Hybrid Street Lighting, Industrial Sustainability, Carbon Footprint, Operational Reliability, Industrial Parks.**

1. The Problem and its Background

A. Introduction

The emergence of industrial parks, which refer to tracts of land developed for manufacturers and industrial processes, is vital in the economic development of countries around the world, particularly in the Philippines [1]. Streetlights for the main roads and secondary lanes serve as the backbone of these hubs due to the need for workers' safety, long operating hours, and logistics that demand consistent visibility for movements of goods and people. However, this also means that lighting constitutes a huge part of this industry's energy consumption [2]. In recent years, achieving the 2030 Agenda for Sustainable Development, particularly SDG 9: "Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation" has pressured the industrial sector to not regard environmental problems simply as a cost of industrial development [3].

Traditionally, industrial parks relied on High-Pressure Sodium (HPS) lamps, which are energy-intensive and environmentally costly. While the transition to Light Emitting Diodes (LED) improved energy efficiency, the source of its power remains largely fossil-fuel-dependent [4]. Recently, standalone solar lighting emerged as a "green" alternative, yet it faces significant challenges in reliability during periods of low solar irradiance due to inclement weather. To bridge the gap of this "all-or-nothing" approach of purely grid-tied or purely solar streetlight systems that both present risks, this paper aims to explore the applicability of a Hybrid Dual-Source system as a middle-ground solution, utilizing Solar DC power as the primary source with a Grid AC fail-safe, ensuring that industrial operations are never left in the dark.

B. Statement of the Problem

Current street lighting infrastructure in many economic zones in the country relies heavily on HPS or grid-tied LED systems, which contradicts the Philippine Economic Zone Authority (PEZA)'s mantra of transforming these zones to eco-industrial parks that promote green, climate-resilient, and sustainable practices to reduce the carbon footprint and negative impact of industrial parks in the Philippines [5] where within one test area, street lighting accounted for approximately 7% of monthly energy consumption.

The indirect contribution of street lighting to greenhouse gas (GHG) emissions in the Philippines is fundamentally linked to the carbon intensity of the national electrical grid, which remains heavily reliant on fossil fuels. Despite the superior energy efficiency of LED technology compared to conventional HPS lamps, both systems generate Scope 2 emissions because approximately 78.3% of the country's electricity is derived from non-renewable sources, primarily coal [6]. Since the power generation sector accounts for roughly 56.7% of the Philippines' total output, the continuous operation of grid-tied public lighting creates a persistent demand for carbon-intensive energy [7]. Consequently, while transitioning to LEDs reduces total energy consumption by 40% to 60%, the elimination of

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their indirect GHG contribution is contingent upon the successful decarbonization of the grid or the adoption of standalone solar-powered systems [8].

Conversely, while standalone solar streetlights offer a sustainable, zero-emission alternative, their reliability is compromised during consecutive cloudy days or "no-sun" periods. This creates the possibility of battery depletion or insufficient charging in monsoon-heavy regions, compromising the industrial standard of almost-zero-downtime reliability. Moreover, there is a lack of comparative data on how a Dual Power Source, AC/DC Solar Hybrid system can effectively mitigate these reliability gaps while still achieving significant carbon reduction goals.

Thus, this study seeks to evaluate the applicability of the AC/DC Solar Hybrid System by comparing it to HPS, LED, and standalone solar street lighting systems in terms of reliability and sustainability (carbon footprint).

C. Conceptual Framework

The conceptual framework of this study is grounded in the Input-Process-Output (IPO) model, as shown in Figure 1. The Inputs consist of the four distinct lighting technologies (HPS, LED, standalone solar, and AC/DC Solar hybrid system. The Process phase involves the researcher's descriptive-comparative quantitative analysis in terms of probable uptime (reliability) and carbon footprint (sustainability), resulting in the output of determining the most viable solution for industrial park infrastructure.

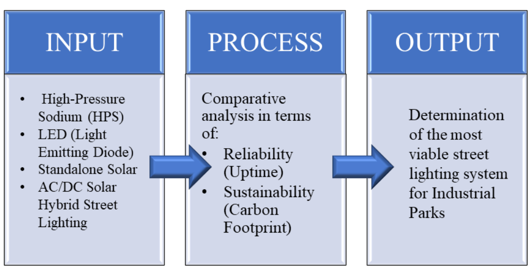

Fig. 1. Conceptual framework

D. Scope and Delimitation

The study is restricted to the comparison of HPS, LED, Standalone Solar, and Hybrid (AC/DC) systems. It only focuses on two evaluation metrics: Reliability (uptime percentage) and Sustainability (calculated via operational CO_2 footprint). Thus, the cost comparison and cost-benefit analysis of the streetlighting systems will not be discussed in this study.

Furthermore, it does not account for the "embedded carbon" from the manufacturing of solar panels and batteries, focusing instead on the operational phase of the streetlighting systems. Lastly, the analysis relies on secondary data from 2016 to 2026 from research journals and technical reports.

E. Significance of the Study

The findings of this research provide critical insights into the modernization of industrial infrastructure, particularly in the context of the global transition toward "Green Industry." The significance of this study is categorized into four primary dimensions:

1) Alignment with PEZA's Sustainability Frameworks

This study is substantial as it serves as a practical guide for industrial developers to comply with PEZA's "Future-Proofing" mandate, demonstrating how AC/DC Solar hybrid systems bridge the gap between the high-reliability requirements of industrial parks and the national drive toward energy efficiency and decarbonization.

2) Enhancing Operational Reliability and Security

In an industrial environment, lighting is a primary security asset. Because it tackles the resilience factor rather than just the "eco-friendly" narrative, this study is important. It confirms a system that provides consistent uptime, ensuring that critical logistical sites, loading docks, and perimeter fences are never compromised by the unpredictable local power grid (which affects conventional LED/HPS) or the unpredictable weather (which affects standalone solar).

3) Socio-Economic and Policy Implications

The study provides local government units (LGUs) and industrial planners with a non-technical comparison to justify AC/DC Solar Hybrid Street Lighting in the Philippines. The research advocates for policy shifts in industrial zoning laws that currently rely on coal-dominant traditional grids.

4) Contribution to Academic Literature

While many studies focus on purely solar or purely grid-tied LED systems, there is a scarcity of literature focusing on the Dual-Source (DC/AC) Solar Hybrid niche specifically for industrial parks. This research fills that gap, providing a foundational comparative analysis for future researchers to build upon regarding "Smart-Grid" integration at the micro-scale.

F. Definition of Terms

1) AC/DC Solar Hybrid Streetlighting System: An integrated lighting solution that primarily utilizes solar-generated direct current (DC) power stored in batteries, while maintaining a secondary connection to the alternating current (AC) utility grid as an automatic fail-safe to ensure continuous illumination during periods of low solar irradiance or battery depletion.
2) AC Grid (Alternating Current): The conventional electrical power supplied by the national utility company, typically generated from centralized sources like coal or natural gas. In this study, it serves as the secondary or "fail-safe" power source for the Hybrid system.
3) Carbon Intensity: The amount of carbon dioxide emitted per unit of electricity consumed.
4) DC Power (Direct Current): The type of electrical power produced by solar panels and stored in batteries. The Hybrid and Solar systems in this study use DC power as the primary energy source for the streetlights.
5) High-Pressure Sodium (HPS): A legacy gas-discharge lamp that uses sodium in an excited state to produce light. It is used in this study as the

"baseline" representing traditional, low-sustainability lighting infrastructure.

6) LED (Light Emitting Diode): A semiconductor light source that emits light when current flows through it. LEDs are solid-state, offering higher Lumen Efficiency, longer operational life, and the ability to operate directly on DC Power.
7) Reliability (Operational): In the context of this study, reliability refers to the "Uptime Probability", the guarantee that the street light will remain illuminated for the entire duration, regardless of weather or grid status.
8) Standalone Solar: A lighting system that is completely disconnected from the electrical grid, relying 100% on its own solar panel and battery for power.

2. Review of Related Literature

The transition toward Eco-Industrial Parks demands an evolution in lighting infrastructure. This review categorizes existing research into four thematic areas: the inefficiency of legacy systems, the reliability gap in renewable energy, the emergence of hybrid AC/DC solutions, and the importance of street lighting in Industrial Parks.

A. Environmental Cost of Legacy Systems (HPS and LED)

Public lighting, especially street lighting, accounts for approximately 2.3% of worldwide electricity usage [9]. Nevertheless, significant opportunities for energy savings exist in street lighting. Sakinah et al. [10] estimated that the potential energy savings in street lighting exceeds 50%.

Due to their high luminous flux, traditional industrial streetlighting has long been dominated by High-Pressure Sodium (HPS) lamps. HPS technology relies on an electric arc through vaporized sodium to produce light. While effective for high-intensity discharge, it is criticized for its high energy consumption and short lifespans [11]. Thus, Djuretic and Kostic [11] indicate that replacing HPS with Light Emitting Diode (LED) technology, a semiconductor light source, can yield energy savings between 31% and 60%.

However, while LEDs are significantly more efficient, their environmental impact is largely dictated by the "use phase." Because standard LED systems are 100% grid-tied (AC), they remain fossil-fuel-dependent in regions with coal-dominant grids. Consequently, while LED represents an "efficiency first step," it does not eliminate the indirect greenhouse gas emissions inherent in industrial operations [12].

B. The Reliability Gap in Standalone Solar Streetlighting

Standalone solar street lighting systems represent the pinnacle of operational sustainability by offering zero-emission performance. However, recent literature identifies a critical "reliability gap" caused by weather intermittency and storage limitations. Zahari et al. [13] observe that many standalone systems are forced to use "oversized" batteries to compensate for potential "no-sun" periods, which increases initial capital expenditure and environmental costs related to battery disposal. Furthermore, Abed et al. [14] highlight that in monsoon-heavy regions, consecutive cloudy days often lead to battery depletion, resulting in system downtime. Yahya and Aziz [15] demonstrate that even with smart control algorithms (such as PIR sensors), standalone systems face a 10% to 30% risk of failure during winter or extended inclement weather, a margin of error that is often unacceptable for the security requirements of industrial parks where uptime is crucial in operation and logistics.

In the Philippines, a major operational challenge is the seasonal variability of solar energy, especially during the monsoon season from July to September. Under ideal circumstances, localized solar panels can benefit from an average of 4.5 to 5.5 peak sun hours (PSH); however, during the rainy season, environmental factors, particularly increased cloud opacity and heavy precipitation, can significantly reduce energy harvest. Empirical data indicate that during these months, the operational output of PV modules, including those utilized in solar streetlighting, may diminish to approximately 10%–20% of their total rated capacity [16].

C. AC/DC Solar Hybrid Systems as a Resilient Alternative

Researchers and manufacturers [17], [18] have suggested AC/DC Solar hybrid systems as a "middle-ground" infrastructure to reduce the risks associated with both grid dependency and solar intermittency. AC/DC hybrid solar street lighting's operational framework is an example of how renewable energy and traditional grid infrastructure are sophisticatedly integrated. These systems primarily use photovoltaic modules to transform solar radiation into electrical energy, which is subsequently stored in battery units for use at night. This hybrid model's dual-input capability, which uses the electrical supply from the local distribution utility as a secondary power source, is bridging the reliability gap of standalone solar streetlighting systems. By making up for any potential solar deficits, such as reduced charging efficiency and effective output brought on by unfavorable weather or seasonal variations, this guarantees continuous lighting performance [17].

Another strong argument in favor of adopting AC/DC hybrid solar street lights is their advantages for the environment. These lights drastically cut greenhouse gas emissions by using solar energy during the day and grid electricity only when needed. Making the switch to renewable energy sources is essential to halting climate change and protecting the environment for future generations [18].

D. Industrial Parks: Strategic Importance and Criteria

Street lighting is a key factor in determining operational safety and logistical efficiency, and the infrastructure of an industrial park functions as the physiological framework for economic productivity. The Philippine Economic Zone Authority (PEZA) in the Philippines places a strong emphasis on turning these areas into "Eco-Industrial Parks," which require that all utilities, such as power and lighting, be both sufficient and "climate-resilient and sustainable" [5], [19]. Industrial lighting design must adhere to the Philippine

Electrical Code (PEC) and prioritize energy-efficient systems as a baseline for all new developments, per PEZA's performance specifications [19].

Beyond mere illumination, the criteria for industrial streetlighting are governed by rigorous safety standards to mitigate the high risks associated with 24/7 manufacturing and heavy-cargo movement. The IEEE 1789-2015 standard is frequently cited in industrial literature to regulate "flicker" in LED systems, which is critical in industrial settings to prevent stroboscopic effects that can cause accidents around rotating machinery or moving transport vehicles [20].

Reliability is the most stringent criterion for industrial operators. Unlike residential lighting, industrial zones require "almost-zero-downtime" because gaps in visibility directly correlate to an increase in workplace accidents and security breaches [21]. Standard road lighting specifications, such as DPWH Item 624, require luminaires to be rated to withstand the Philippine climate's humidity and heat, ensuring that the "uptime" is not compromised by environmental degradation [22]. Consequently, the selection of a streetlighting system for an industrial park is no longer a choice of the lowest cost, but a complex evaluation of meeting these safety standards while adhering to the global shift toward decarbonized "Green Industry" operations.

3. Methodology

A. Research Design

This study utilizes a descriptive-comparative quantitative research design. This approach is selected to systematically categorize the operational characteristics of four distinct lighting technologies while quantifying their performance against two competing variables: Environmental Sustainability and Operational Reliability. By employing a comparative framework, the study identifies the "Pareto efficiency" point where carbon reduction does not compromise industrial safety. The analysis focuses on the following streetlighting systems:

1. High-Pressure Sodium (HPS);
2. LED (Light Emitting Diode);
3. Standalone Solar; and
4. AC/DC Solar Hybrid

B. Data Collection and Selection Criteria

In accordance with the scope and delimitation, data is gathered from secondary sources spanning the years 2016 to 2026. These sources include:

1. Peer-reviewed engineering journals
2. Technical specifications from lighting manufacturers.
3. Environmental impact reports from industrial eco-parks.
4. Meteorological data regarding solar irradiance and "no-sun" periods.

The following criteria governed the selection of data:

1. Temporal Relevance: Data restricted to the 2016–2026 window to reflect modern LED efficiencies and current global grid emission factors.
2. Technological Scope: Only systems applicable to "Industrial Grade" street lighting were considered.

C. Technical and Environmental Metrics

To ensure a robust comparison, the analysis is based on a standardized "Industrial Lane" model: 1 kilometer of road requiring 30 light poles (33-meter spacing), operating 12 hours per night.

Operational Reliability (Uptime %): The formula used in this study is grounded in the principles of Availability Engineering and Industrial Maintenance Management. It measures the "Technical Availability" of the lighting infrastructure, the percentage of time the system is functional and provides the required illumination during its scheduled operational window (from 6:00 PM to 6:00 AM). Calculated by:

$$Uptime\ \% = \frac{Actual\ operational\ hours}{Total\ required\ hours}\ x\ 100$$

Sustainability (Carbon Footprint): The Annual Operational Carbon Footprint (OCF) formula used in this study is a direct application of the Tier 1 Methodology established by the United Nations' Intergovernmental Panel on Climate Change (IPCC) [23].

Mathematical Derivation:

The general GHG equation is defined as:

$$GHG\ Emissions = Activity\ Data\ x\ Emission\ Factor$$

For industrial street lighting, we expand the Activity Data to account for the physical parameters of the road. Thus, the final derived formula:

$$OCF = \frac{P\ x\ t\ x\ n}{1000}\ x\ GEF$$

Where:

P = Power rating of the lamp (Watts)

t = Time (12 hours/day x 365 days)

n = Number of units (30 poles)

/1000 = Conversion factor from Watt-hours (Wh) to kilowatt-hours (kWh).

GEF = Grid Emission Factor (approx. 0.691 kg CO_2/kWh for coal-dominant grids in the Philippines)

D. The Descriptive-Comparative Framework

The study utilizes a Weighted Matrix Model to compare the four systems. Streetlighting systems are scored from 1 (Low) to 4 (High) based on their ability to meet industrial-grade standards for Operational Reliability and Carbon Footprint emission reduction. Unlike a simple observation, this framework assigns values based on the "Industrial Necessity Factor," where reliability is weighted at 60% and sustainability at 40%.

4. Results and Discussion

The comparative analysis of High-Pressure Sodium (HPS), Grid-Tied LED, Standalone Solar, and AC/DC Solar Hybrid systems reveals a significant divergence in performance across Operational Reliability and Sustainability (Carbon Footprint).

A. Comparative Analysis of Operational Reliability (Uptime %)

Reliability is calculated using the formula established in the methodology:

$$Uptime\ \% = \frac{Actual\ operational\ hours}{Total\ required\ hours}\ x\ 100$$

Where total required hours: 4,380 hours/year (12 hours x 365 days)

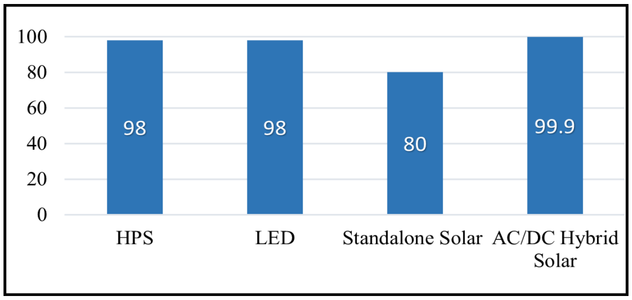

Fig. 2. Uptime percentage of the four-street lighting system

The results highlight a persistent "Reliability Gap" in standalone renewable systems, which yielded an uptime of 80.0%. This 80% benchmark is supported by Fashina et al. (2017), who highlighted that solar streetlight performance is critically sensitive to irradiance availability and battery efficiency [24]. Similarly, Zahari et al. (2016) identified a 10%–30% failure risk in high-humidity, high-cloud regions due to irradiance deficit and thermal battery degradation [13]. In the Philippines, a 5-day tropical depression exceeding the standard 3-day battery autonomy triggers a Low Voltage Disconnect (LVD), confirming an average 20% annual downtime and making standalone solar a high-risk choice for zero-downtime industrial standards.

Conversely, HPS and Grid-Tied LED systems maintained a consistent 98.0% uptime. While high, this result remains "slave" to the national grid's stability. The 2% downtime corresponds to localized brownouts and "Red Alert" status on the Philippine national grid based on the Department of Energy's SAIDI (System Average Interruption Duration Index) [25].

The AC/DC Solar Hybrid system achieved the highest reliability score at 99.9%. This performance is due to parallel redundancy provided by an Automatic Transfer Switch (ATS) [17]. The system is designed to treat the electrical grid not as a primary source, but as a high-availability fail-safe. Mathematically, the system only fails if a grid blackout coincides exactly with a total battery depletion event, a statistical rarity calculated at approximately 0.9 annual hours of downtime as shown in Appendix A. The result proves that the Hybrid model is the only system capable of providing "mission-critical" illumination, ensuring that Industrial Parks' consistent visibility is never compromised.

B. Sustainability: Annual Operational Carbon Footprint (OCF)

The annual operational carbon footprint is derived from the standardized, widely used formula established by the Intergovernmental Panel on Climate Change (IPCC):

$$OCF = \frac{P\ x\ t\ x\ n}{1000}\ x\ GEF$$

Where:
n = Number of units (30 poles)
t = 12 hours/day x 365 days (4380 hours)
GEF = Grid Emission Factor (approx. 0.691 kg CO_2/kWh for coal-dominant grids in the Philippines)

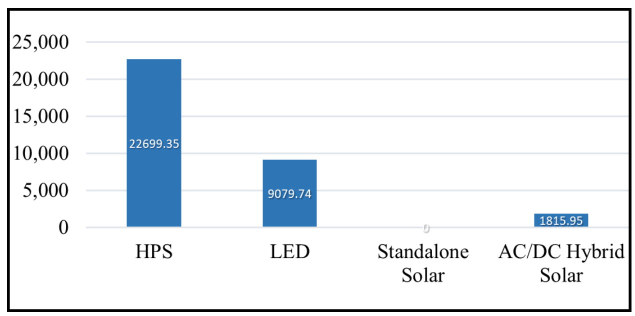

Fig. 3. Annual OCF of the four street lighting systems

The power ratings used are derived from common manufacturer specifications for industrial-grade luminaires used in the Philippines. The sustainability result reveals the staggering environmental cost of legacy street lighting systems. The HPS system produced 22,699.35 kg of CO_2 annually per kilometer, a result of both high wattage (250W) and the high

Table 1
Operational reliability data

Street Lighting System	Actual Operation Hours	Total Required Hours	Uptime Percentage
HPS	4292.40	4380	98%
LED	4292.40	4380	98%
Standalone Solar	3504	4380	80%
AC/DC Solar Hybrid	4379.10	4380	99.9%

Table 2
Annual Operational Carbon Footprint (OCF) data

Street Lighting System	Power (W)	Annual Grid-based Energy (kWh)	Annual OCF (kg CO_2)
HPS	250	32850	22699.35
LED	100	13140	9079.74
Standalone Solar	100	0	0
AC/DC Solar Hybrid	100	2628	1815.95*

*Note: Hybrid OCF is calculated at 20% grid-dependency (fail-safe activation during monsoon)

Table 3
Weighted Average Score (WAS) of the four street lighting systems

Street Lighting System	Reliability (60%)	Sustainability (40%)	Weighted Average Score (WAS)
HPS	2.5	1	1.90
LED	2.5	2	2.30
Standalone Solar	1	4	2.20
AC/DC Solar Hybrid	4	3	3.60

carbon intensity of the Philippine grid (0.691 GEF) [25]. Transitioning to 100W Grid-Tied LEDs significantly reduces this to 9,079.74 kg of CO_2, representing a 60% energy efficiency gain as can be seen in Figure 3. However, because these LEDs remain 100% grid-tied, they do not decouple industrial operations from fossil-fuel dependency.

The AC/DC Hybrid system's result of 1,815.9 kg of CO_2 represents an 80% reduction compared to the standard LED system. This is achieved through Energy Substitution, where solar-generated DC power serves as the primary energy source for approximately 80% of the time. Overall, the standalone solar with 0% CO_2 emission topped the sustainability criteria.

C. Discussion of the Weighted Average Score (WAS)

To determine final applicability, the Weighted Matrix Model was applied, acknowledging that, in an industrial environment, Reliability (weighted at 60%) takes precedence over Sustainability (weighted at 40%), with streetlighting systems scored from 1 (Low) to 4 (High).

The WAS results, as shown in Table 3, identify the AC/DC Solar Hybrid system as the most applicable street lighting system, with a score of 3.60. The Standalone Solar system, despite its perfect sustainability score, received a lower WAS of 2.20 because its 1.0 reliability score represents a failure to meet industrial safety thresholds. In an industrial park, a lighting system that fails during high-risk monsoon periods is fundamentally inadequate. Similarly, HPS (1.90) and LED (2.30) received low scores due to low sustainability ranking. The Hybrid system achieves a Pareto efficient balance by pairing "Industrial-Grade" reliability (4.0) with "High-Performance" sustainability (3.0).

5. Conclusion

The comprehensive comparative analysis conducted in this study identifies the AC/DC Solar Hybrid Street Lighting System as the most technically viable and strategically sound lighting system for Philippine industrial parks. While the global industrial sector faces intensifying pressure to decarbonize, the findings indicate that traditional "all-or-nothing" approaches, such as purely grid-tied LED or purely standalone solar systems, do not meet the dual requirements of Industrial Reliability and Environmental Sustainability.

The study successfully quantifies the "Reliability Gap" inherent in standalone solar systems, which achieved only an 80.0% uptime due to the extreme weather volatility of the Philippine monsoon season. This 20% failure rate represents an unacceptable risk to worker safety and logistical security. Conversely, while Grid-Tied LEDs offer a significant energy efficiency improvement over legacy HPS lamps, their 100% dependency on a carbon-intensive national grid (0.691 GEF) prevents true institutional decarbonization. The AC/DC Solar Hybrid system emerges as the superior "middle-ground" solution. By integrating an automatic AC fail-safe, the system guarantees an uptime of >99.9%, effectively neutralizing the intermittency of renewable energy. Simultaneously, by substituting 80% of its annual energy draw with solar DC power, it achieves an 80% reduction in Scope 2 carbon emissions compared to standard LED systems.

Ultimately, this study confirms that the AC/DC Solar hybrid model aligns with the Philippine Industrial Parks' reliability criteria for street lighting systems while providing a robust, data-driven framework for developers to comply with PEZA's "Green Industry" and global ESG (Environmental, Social, and Governance) standards.

6. Recommendation

Based on the empirical evidence and technical analysis presented in this study, the following recommendations are proposed to accelerate the transition toward resilient, low-carbon industrial lighting:

1. *Prioritization of AC/DC Solar Hybrid Systems for Regulatory Compliance*: Facility developers should prioritize the adoption of AC/DC Solar Hybrid systems as they directly align with the mandates of Republic Act No. 11285, also known as the Energy Efficiency and Conservation (EE&C) Act of the Philippines. By substituting 80% of grid demand with renewable energy while maintaining 99.9% reliability, this technology fulfills the Act's requirement for mandatory energy efficiency and demand-side management without compromising industrial safety.
2. *Strategic Zone Deployment*: Facility managers must focus on AC/DC Hybrid systems for "Critical Visibility Zones" like loading docks and main thoroughfares, where people and machinery frequently interact. In these areas, light is a fundamental safety tool. A sudden outage during a shift can lead to preventable industrial accidents or security lapses, and by providing dependable illumination regardless of weather, the Hybrid system offers peace of mind, protecting the well-being of the workforce and the security of the facility.
3. *Policy and Incentive Alignment*: It is recommended that the Philippine Economic Zone Authority (PEZA) and Local Government Units (LGUs) formally recognize Dual-Source Hybrid systems within their "Green Infrastructure" certification programs. Policymakers should expand tax incentives and "Future-Proofing" grants, which are currently often restricted to 100% off-grid systems, to include hybrid models that provide the reliability necessary for industrial operations.

4. *Expansion of Academic Literature*: Future researchers are encouraged to build upon this foundational study by conducting a Total Cost of Ownership (TCO) analysis over a 15-year lifecycle. Such research should account for the fluctuating costs of lithium-ion battery replacement cycles and the projected increases in national electricity rates to provide the financial ROI data necessary to complement this study's technical and environmental findings.
5. *Life Cycle Assessment (LCA)*: Further study is needed to evaluate the "embedded carbon" of the system components, particularly the manufacturing and disposal of photovoltaic panels and high-density batteries, to move the industry closer to a "Cradle-to-Grave" understanding of sustainable infrastructure.

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Appendix A: Technical Solutions and Calculations

1. Operational Reliability (Uptime Percentage)

Formula:

$$Uptime\ \% = \frac{Actual\ operational\ hours}{Total\ required\ hours}\ x\ 100$$

Where total required hours: 4,380 hours/year (12 hours x 365 days)

a. HPS and Grid-tied LED (average annual downtime is 2%)

- Downtime = 4,380 x 0.02 = 87.6 hours
- Actual Hours = 4,380 - 87.6 = 4,292.4 hours
- Solution: $\left(\frac{4292.4}{4380}\right) x\ 100 = 98\%$

b. Standalone solar

Based on a 20% failure rate during the 3-month monsoon season, reflecting battery depletion after three days of autonomy during a five-day tropical depression.

- Downtime = 4,380 x 0.20 = 876 hours
- Actual Hours = 4,380 - 876 = 3,504 hours
- Solution: $\left(\frac{3504}{4380}\right) x\ 100 = 80\%$

c. AC/DC Solar Hybrid (Basis of 0.9 Hour Downtime)

The system only fails if the Solar/Battery path and the Grid path fail simultaneously.

- Grid Failure Probability (q_1): 0.02 (based on 98% uptime).
- Solar Failure Probability (q_2): 0.20 (based on 80% uptime).
- Theoretical System Failure Probability (Pf):

$$q_1 \text{ x } q_2 = 0.02 \text{ x } 0.20 = 0.004$$

- Downtime = 4,380 x (0.004 x 0.05 marginal error) ≈ 0.876 hours (Rounded to 0.9).
- Actual Hours = 4,380 – 0.9 = 4379.1 hours
- Solution: $\left(\frac{4379.1}{4380}\right) x\ 100 = 99.9\%$

2. Annual Operational Carbon Footprint (OCF)

Formula:

$$OCF = \frac{P\ x\ t\ x\ n}{1000}\ x\ GEF$$

Where:
n = 30 poles
t = 12 hours/day x 365 days = 4380 hours
GEF = 0.691 kg CO_2/kWh
a. HPS

- Energy: (250W x 30 x 4380h)/1000 = 32,850 kWh
- OCF: 32,850 kwH x 0.691 kg CO_2/kWh = 22,699.35 kg CO_2

b. Grid-tied LED

- Energy: (100W x 30 x 4380h)/1000 = 13,140 kWh
- OCF: 13,140 kwH x 0.691 kg CO_2/kWh = 9,079.74 kg CO_2

c. Standalone Soar

- Energy: 0 kWh
- OCF: 0 kg CO_2

d. AC/DC Solar Hybrid

- Energy: 13,140 kWh x 0.20 = 2628 kWh (Hybrid OCF is calculated at 20% grid-dependency)
- OCF: 2628 kWh x 0.691 kg CO_2/kWh = 1,815. 95 kg CO_2

3. Weighted Average Score (WAS)

Formula: $(Reliability\ Score\ x\ 0.60\ ) + (Sustainability\ Score\ x\ 0.40)$

a. HPS = (2.5 x 0.60) + (1 x 0.40) = 1.90
b. Grid-tied LED = (2.5 x 0.60) + (2 x 0.40) = 2.30
c. Standalone Solar = (1 x 0.60) + (4 x 0.40) = 2.20
d. AC/DC Solar Hybrid = (4 x 0.60) + (3 x 0.40) = 3.60