From Principles to Performance: Advancing the IDA/IES Framework for Responsible Outdoor Lighting

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DOI: https://doi.org/10.51584/IJRIAS.2026.11070008

Received: 03 July 2026; Accepted: 14 July 2026; Published: 23 July 2026

ABSTRACT

Outdoor lighting (OL) is essential for safety, security, mobility, and nighttime economic activity; however, inappropriate use of artificial light at night contributes to light pollution, ecological disruption, energy waste, and adverse health effects. The widely adopted IDA/IES Five Principles for Responsible Outdoor Lighting provide valuable conceptual guidance but remain predominantly qualitative, offering limited operational specificity, measurable performance criteria, or structured implementation methods. This study identifies a critical gap between responsible-lighting principles and engineering practice, particularly the absence of explicit consideration of user requirements, performance verification, and a repeatable design methodology. To address this gap, a performance-based seven-question framework—Why, Who, Where, How Much (level), What (spectrum), When, and How—is developed and integrated with measurable photometric, spectral, spatial, angular, temporal, and validation parameters. The framework is demonstrated through a real-world parking-lot lighting case study that incorporates Eye Corneal Illuminance (ECI), Spectral Power Distribution (SPD), Equivalent Melanopic Lux (EML), photon exposure, adaptive dimming, and post-installation validation principles. Quantitative assessment showed substantial reductions in residential light exposure, including bedroom-window ECI of 0.9 lux, melanopic exposure of 0.35 melanopic lux, estimated melatonin suppression below 1.83%, and potential energy savings of 25–42% under adaptive-control scenarios while maintaining required lighting performance. The principal contribution of this research is the transformation of responsible outdoor lighting from a qualitative set of principles into a measurable, reproducible, and verifiable engineering workflow. The proposed framework provides lighting designers, municipalities, and standards bodies with a practical pathway for evaluating, comparing, optimizing, and validating environmental, visual, energy, and human-centric lighting outcomes, thereby advancing responsible outdoor lighting toward an evidence-based performance paradigm.

Keywords: Outdoor lighting; Light pollution; IDA/IES principles; Spectral power distribution (SPD); Human-centric lighting; Circadian metrics; SaCH; Sustainable lighting; Performance-based design

INTRODUCTION

Outdoor lighting is an essential component of modern infrastructure, enabling visibility, enhancing safety, and supporting mobility and social interaction at night (Tavares et al., 2021; Simmons et al., 2022; Zielińska-Dąbkowska et al., 2023; Peña-García, Martínez, and Ernst, 2024; Wåseth, Zaikina, and Pont, 2025). However, the excessive or poorly controlled use of artificial light has led to significant light pollution—manifesting as skyglow, glare, and light trespass—with well-documented consequences for ecosystems, human health, and energy consumption (Thurairajah et al., 2020a). To address these concerns, the International Dark-Sky Association (IDA) and the Illuminating Engineering Society (IES) introduced the Five Principles for Responsible Outdoor Lighting (IDA/IES, 2020). These principles encourage the appropriate use of light with respect to purpose, location, intensity, timing, and colour (Thomas, D.C. et al., 2025). Despite their widespread adoption, they remain largely conceptual and lack the precision required for engineering design and verification.

This study addresses the central issue of existing principles that articulate intent but do not provide a pathway for implementation. The objectives of this research are to assess the adequacy of the current principles, identify missing design dimensions, and develop a structured, performance-based lighting framework.

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume XI Issue VII July 2026

Background

Evolution of Outdoor Lighting and Light Pollution

Advances in lighting technology, particularly the widespread adoption of LEDs, have significantly increased the scale, efficiency, and adaptability of outdoor lighting systems (Falchi et al., 2011; Gaston and Miguel, 2022). While these developments offer substantial energy savings, they have also intensified light pollution when not properly managed (Kompan et al., 2025).

- **Skyglow**: Atmospheric scattering that brightens the night sky (KÜÇÜK and Ekren, 2021; Thurairajah, 2026c)
- **Glare**: Excessive brightness causing visual discomfort or impairment (Thurairajah et al., 2020a; Thakur, Ganjoo, and Kumar, 2022)
- **Light trespass**: Unwanted light spilling into unintended areas (Thurairajah, 2026a; Thurairajah et al., 2023)

These phenomena adversely affect ecosystems, astronomical observation, and human circadian rhythms (Thurairajah et al., 2026c; Thakur, Ganjoo, and Kumar, 2022).

DA/IES Five Principles

The IDA/IES framework is structured around five guiding principles (IDA/IES, 2020):

1. Useful (Why?)
2. Targeted (Where?)
3. Appropriate Levels (How much?)
4. Controlled (When?)
5. Color Consideration (What?)

Although effective as communication tools, these principles lack the defined metrics and procedural guidance required for practical implementation (Thurairajah et al., 2020a).

Table 1 maps each principle to its associated key metric and identifies the corresponding design gap.

Table 1: Principle-to-Metric Mapping

Principle	Associated Metrics	Identified Gap
Useful	Task analysis	No formal justification method
Targeted	BUG ratings, trespass	No defined thresholds
Appropriate Levels	Illuminance	No quantitative limits
Controlled	Timing schedules	No control logic specification
Color Consideration	Correlated Colour Temperature (CCT)	No consideration of SPD

Table 2 presents the outcome-based framework, delineating the intended impact across each domain.

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Table 2: Outcome-Based Framework

Domain	Intended Impact
Environmental	Reduction in light pollution
Visual	Improved visibility and safety
Human	Enhanced circadian health (CH)

Identified Limitations

The existing framework is constrained by the following key limitations:

- The absence of defined quantitative thresholds for practical implementation (Thurairajah et al., 2020b).
- An over-reliance on Correlated Color Temperature (CCT) rather than Spectral Power Distribution (SPD) (Thurairajah et al., 2020b).
- A lack of integration with objective performance metrics (Thurairajah et al., 2020b).
- Insufficient consideration of safety, security, and human-centric factors (Thurairajah, U. 2026b).
- The absence of a structured, repeatable design methodology (Thurairajah, U. 2026b).

Terminology and Metrics

ALAN	- Artificial Light at Night
OL	- Outdoor Lighting
OTL	- Outdoor Trespass Lighting
ECI	- Eye Corneal Illuminance
EML	- Equivalent Melanopic Lux
MSAN	- Melatonin Suppression at Night
SaCH	- Sleep and Circadian Health
SPD	- Spectral Power Distribution
CCT	- Correlated Color Temperature

METHODOLOGY

Research Approach

This study employed a mixed-methods research design combining qualitative framework development with quantitative case-study evaluation. The methodological process consisted of four sequential stages: (i) review of responsible outdoor-lighting literature and standards, (ii) identification of limitations within existing principle-based guidance, (iii) development of a performance-based framework linking design decisions to measurable indicators, and (iv) application of the framework to a real-world outdoor-lighting project.

The study was guided by the premise that responsible outdoor lighting should be evaluated as a multi-domain performance system rather than solely as a photometric compliance exercise. Accordingly, environmental, visual, human-centric, operational, and verification considerations were incorporated into a unified design methodology. Existing guidance documents, including the IDA/IES Five Principles, provided the conceptual foundation for the framework.

Framework Development Process

The proposed seven-question framework was developed using a structured analytical process intended to transform principle-based guidance into a measurable engineering workflow.

First, the IDA/IES Five Principles were systematically reviewed to identify the fundamental design dimensions already represented in responsible lighting practice, namely purpose, targeting, illumination level, operational control, and color considerations. Second, these principles were compared with practical outdoor lighting design requirements identified in engineering practice, environmental lighting guidance, and human-centric lighting literature. This comparison revealed several limitations, including the absence of explicit user identification, insufficient consideration of measurable exposure criteria, and the lack of a repeatable design and validation methodology.

To address these limitations, two additional dimensions were introduced:

- Who? — identification of users, affected populations, and environmental receptors;
- How? — establishment of a structured design, commissioning, measurement, and feedback process.

Performance indicators were selected according to four criteria:

1. Technical measurability;
2. Relevance to responsible-lighting outcomes;
3. Engineering applicability;
4. Compatibility with existing standards and guidance.

Based on these criteria, illuminance, luminance, uniformity, Eye Corneal Illuminance (ECI), Spectral Power Distribution (SPD), Equivalent Melanopic Lux (EML), photon exposure, adaptive-control parameters, light-trespass indicators, and post-installation validation procedures were incorporated into the framework. The resulting methodology was organized around seven fundamental design questions: Why, Who, Where, How Much, What Spectrum, When, and How. Table 3 presents the resulting Principle-to-Performance framework, detailing each dimension, its corresponding key question, and its specific role in the design process.

Table 3: Principle-to-Performance Framework

Dimension	Key Question	Role in Design
Purpose	Why?	Establishes the necessity of lighting
Users	Who?	Identifies stakeholders and affected populations
Spatial	Where?	Controls the distribution of light
Photometric	How much?	Defined required illumination levels
Spectral	What (SPD)?	Specifies spectral characteristics
Temporal	When?	Determines operational timing
Methodology	How?	Provides a design and validation process

Performance Indicators and Evaluation Criteria

The framework integrates measurable indicators across five technical domains:

- Photometric: illuminance, luminance, and uniformity;
- Spatial: light trespass, shielding effectiveness, BUG ratings, and ECI;
- Spectral: SPD characteristics and melanopic response metrics;
- Temporal: control schedules, adaptive dimming, and operational timing;
- Validation: commissioning, field measurement, and post-installation verification.

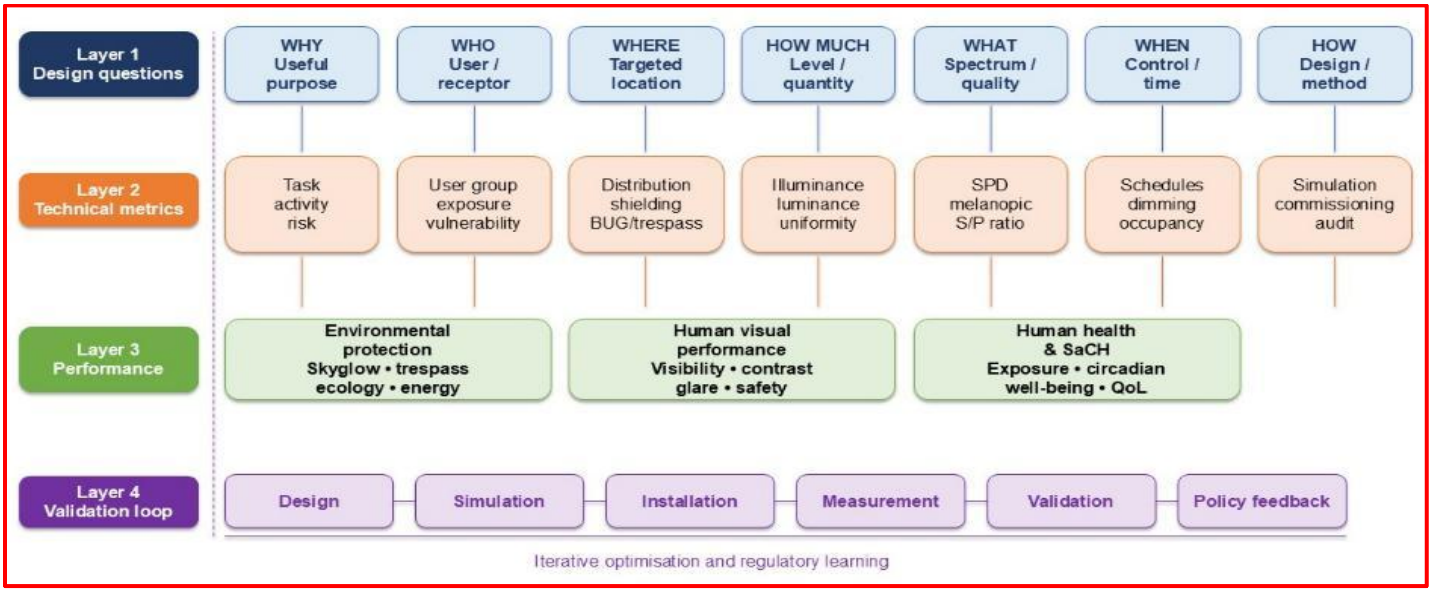
The purpose of these indicators is to translate qualitative responsible-lighting objectives into quantifiable and verifiable performance criteria that can be assessed during design, implementation, and operation.

Framework Development

Seven-Question Design Framework

Figure 1 illustrates the integrated framework that combines seven design questions with measurable technical parameters. These parameters—photometric, spectral, spatial, angular, and temporal—are evaluated across three domains: environmental performance, visual performance, and human health (SaCH). An iterative feedback loop supports validation and policy alignment.

Figure 1. Extended Performance-Based Outdoor Lighting Framework



An extended framework operationalising responsible outdoor lighting through seven design questions, measurable metrics, three performance domains, and an iterative validation–policy feedback loop.

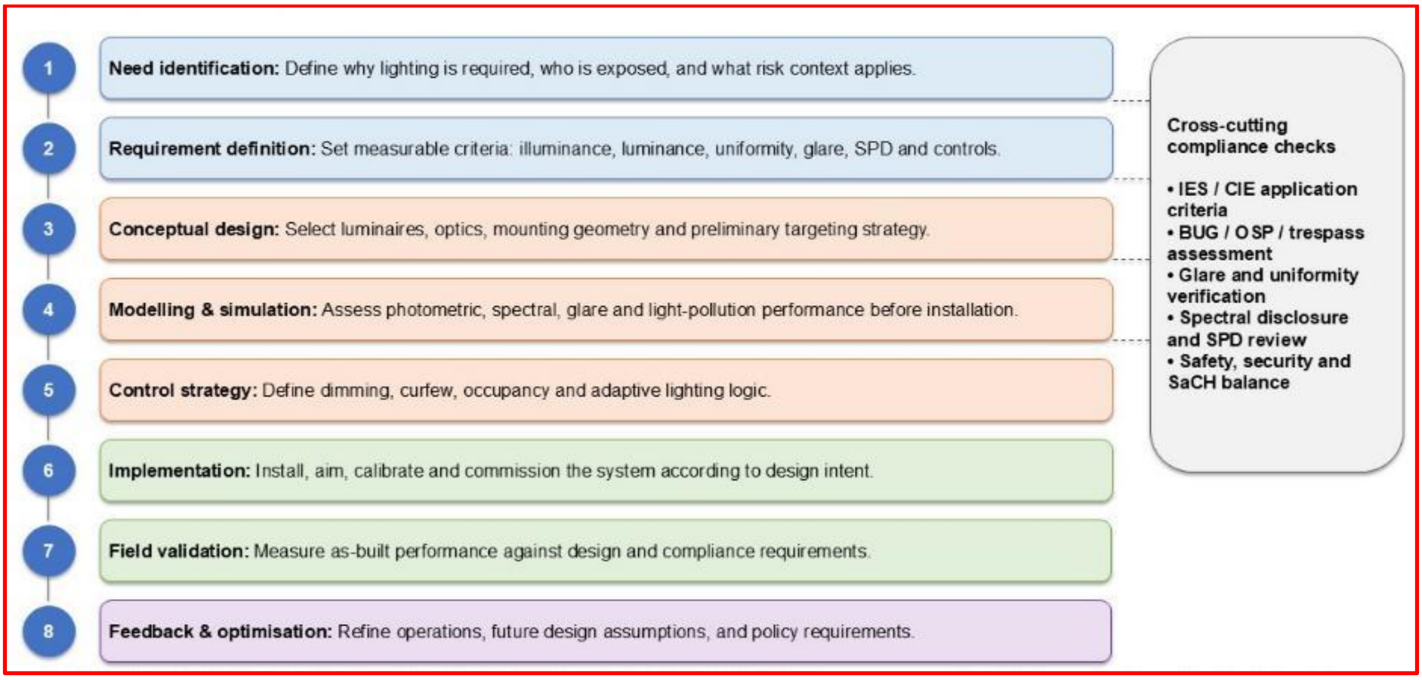
Performance-Based Workflow

Figure 2 presents a structured workflow moving from conceptual intent to implementation:

- Needs identification and user definition
- Requirement specification using measurable criteria
- Design and simulation

- Adaptive control integration
- Installation and commissioning
- Post-installation validation and optimization

Figure 2. Performance-Based Outdoor Lighting Design Workflow



Workflow linking needs, measurable requirements, design, simulation, controls, installation, field validation, and feedback for outdoor lighting systems.

Principles-to-Performance Mapping

Figure 3 demonstrates how qualitative principles can be translated into measurable outcomes across environmental, visual, human, and policy domains.

Figure 3. Principle-to-Performance Mapping Matrix

Performance domain	WHY Useful	WHO User	WHERE Targeted	HOW MUCH Level	WHAT Spectrum	WHEN Controlled	HOW Method
Environmental	Avoid unneeded ALAN	Protect receptors	Limit skyglow/trespass	Reduce reflected flux	Limit short-wavelength impact	Reduce duration	Audit and improve
Visual	Task-based visibility	User-specific adaptation	Control glare & spill	Maintain adequacy	Colour quality & contrast	Light when needed	Verify as-built
Human / SaCH	Avoid avoidable exposure	Sensitive users & dwellings	Limit unwanted ocular exposure	Minimize excess intensity	Assess SPD / melanopic content	Respect biological timing	Measure exposure
Policy / Design	Need justification	Receptor-based approval	Zoning / shielding criteria	Min/max thresholds	SPD disclosure criteria	Curfew / dimming rules	Commissioning requirements

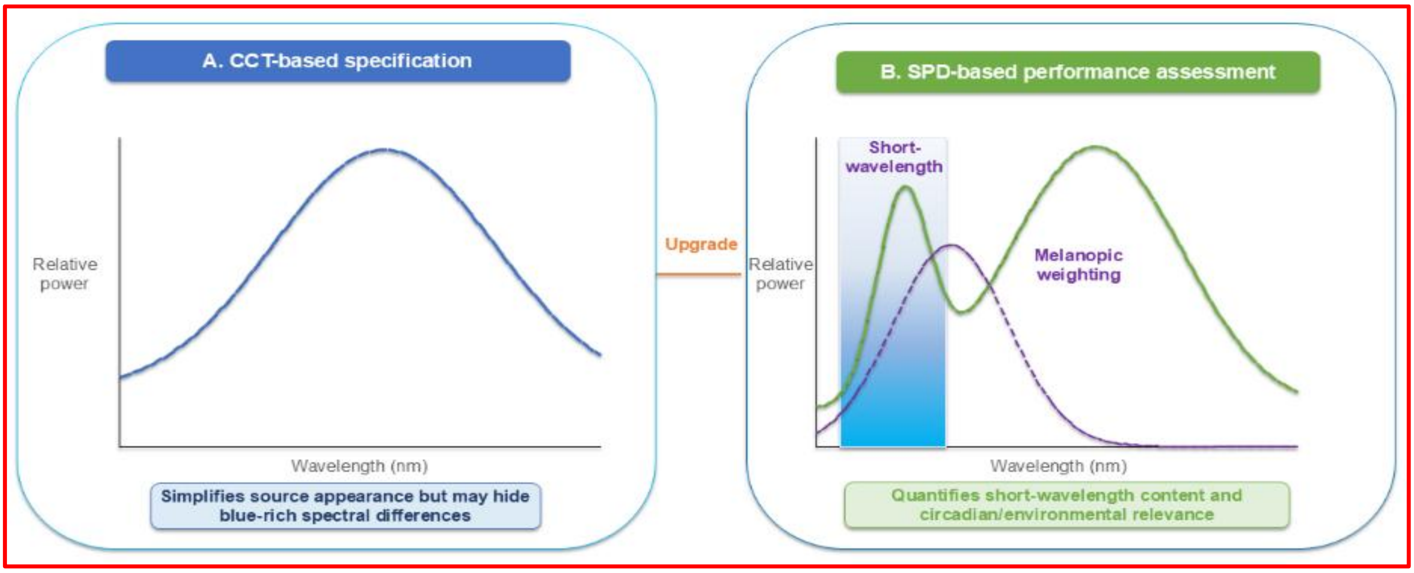
Matrix mapping the IDA/IES principles and extended dimensions to environmental, visual, human/SaCH, and policy/design outcomes.

INTERNATIONAL JOURNAL OF RESEARCH AND INNOVATION IN APPLIED SCIENCE (IJRIAS)
ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume XI Issue VII July 2026

Spectral Design: CCT versus SPD

Figure 4 contrasts CCT-based and SPD-based design methodologies. While CCT serves as a simplified visual descriptor, SPD enables a more rigorous evaluation of spectral composition, particularly with respect to the short-wavelength energy that drives circadian and ecological impacts (Thurairajah, U. 2026b).

Figure 4. Spectral Design Concept: Moving Beyond CCT



Conceptual comparison shows why SPD-based analysis is more suitable than CCT alone for evaluating spectral, circadian, and environmental lighting impacts.

Case Study

The framework is conceptual and analytical; this case study was used to empirically test and validate it. This is a real engineering project showing the required lighting calculation simulations in detail.

Study Location

The engineering project was conducted at Seneca College (Newnham Campus), Toronto, Ontario, Canada. The site included parking lot lighting adjacent to residential dwellings located north of the project area. Figure 5 below shows a map of the Seneca College site (Seneca College, 2021):

Figure 5. Seneca College Site Location (Google Maps, 2025).

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Lighting Design Configuration

The proposed parking lot lighting system used GE Evolve LED luminaires with asymmetric forward distribution. Table 4 provides the final components and reproducible measurement protocol used in this paper.

Table 4. Lighting System Configuration.

Item	Description
Luminaire	GE Evolve LED, full cutoff
Wattage	274 W
CCT	3000 K
CRI	70
Distribution	Asymmetric Wide
Mounting Height	11.4 m
Absolute Lumens	32,000
Protection Rating	IP65
Software (Autolux 2023)	The calculation for the horizontal level at the finished grade. ECI at 1.5m height at the property line and bedroom windows.

Data Collection, Instrumentation, Modeling Assumptions, and Validation

The case-study evaluation was based on project-specific lighting-design information, luminaire photometric files, lighting simulations, and exposure calculations. Input data included site geometry, luminaire locations, mounting heights, luminaire distributions, wattages, CCTs, CRIs, and calculation-plane definitions. Horizontal illuminance was evaluated at finished grade, while Eye Corneal Illuminance was calculated at a vertical observer height of 1.5 m at property-boundary and residential-receptor locations.

All primary calculations were performed using AutoLUX 2023 simulation software under full-output operating conditions to represent conservative nighttime exposure scenarios. Adaptive dimming conditions were analyzed separately using sensitivity-analysis procedures and should therefore be interpreted as modeling estimates rather than measured operating conditions.

Spectral and melanopic calculations were derived using the adopted SPD assumptions for the selected luminaires. EML, photon exposure, and estimated melatonin-suppression indicators are therefore exposure-related metrics and should not be interpreted as direct clinical or physiological outcomes. Rather, they provide comparative indicators of potential circadian-relevant exposure under the modeling assumptions adopted in this study.

Post-installation validation forms a core component of the proposed framework. Recommended validation activities include field verification of illuminance, vertical ECI measurements at receptor locations, confirmation of luminaire aiming and shielding, review of adaptive-control operation, and comparison of measured performance against design-stage simulation predictions. This validation process provides the feedback mechanism necessary for continuous optimization and performance assurance. The proposed lighting design satisfied the required parking lot illumination criteria while maintaining low ocular exposure levels at adjacent residential windows. Figure 6 below shows a lighting calculation for the parking lots 6 and 8 at the Seneca College site.

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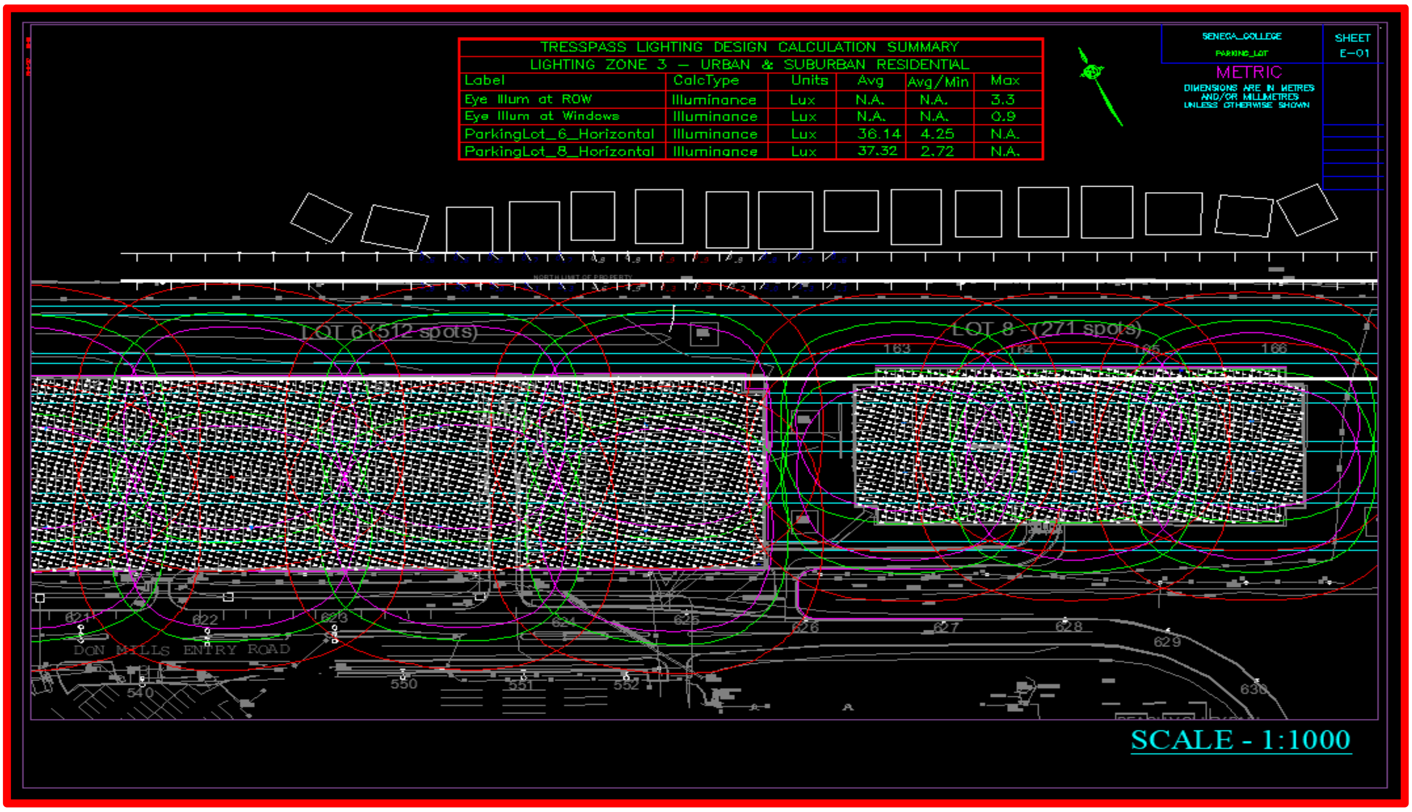
Figure 6. Lighting Calculations at Seneca College.



RESULTS

Outdoor Lighting Criteria and Results

Table 5 below shows the engineering project lighting design criteria and results for the parking lot at the Seneca College site and the corresponding results after the lighting calculations for parking lots 6 and 8.

Table 5. Engineering Project Lighting Design Criteria and Results.

Location	**Average Horizontal Illuminance**	**Uniformity Ratio**	**Maximum ECI at Property Line**	**Maximum ECI at Bedroom Window**
Design Criterion	30.0 lux	4.0:1	8 lux (RP-8, 2025)	8 lux (RP-8, 2025)
Lot 6	36.14 lux	4.25:1	3.3 lux	0.9 lux
Lot 8	37.32 lux	2.72:1	3.3 lux	0.9 lux

Method 1 - PL Results

Photon flux calculations demonstrated that ocular exposure levels remained substantially below proposed nighttime thresholds. Table 6 below provides the photon flux per square meter and the corresponding percentage of MSAN (Brainard et al., 1988).

Table 6. Photon Flux and MSAN Results.

Location	**OL Zone**	**Photons/s/m²**	**Estimated Melatonin Suppression (Brainard et al., 1988).**
Proposed Threshold	LZ3	3.2×10^{16}	Threshold
Lot 6	LZ3	3.6×10^{15}	<1.83%
Lot 8	LZ3	3.6×10^{15}	<1.83%

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Method 2 - EML Results

Table 7 shows that the calculated EML result values at residential bedroom windows remained below the proposed ≤1 melanopic lux threshold.

Table 7. EML Results.

Location	**Illuminance**	**EML (CIE, 2020).**
Full Luminaire Output	321.7 lux	123.45 lux
Bedroom Window	0.9 lux	0.35 lux

Figure 7 below shows the reference source (D65), the user-selected OLS, and the corresponding alpha-optic weighted spectra for both sources (CIE, 2020). Figure 7 illustrates the differences between the reference and user-selected spectral distributions.

Figure 7. Alpha-Optic Spectral Distribution.

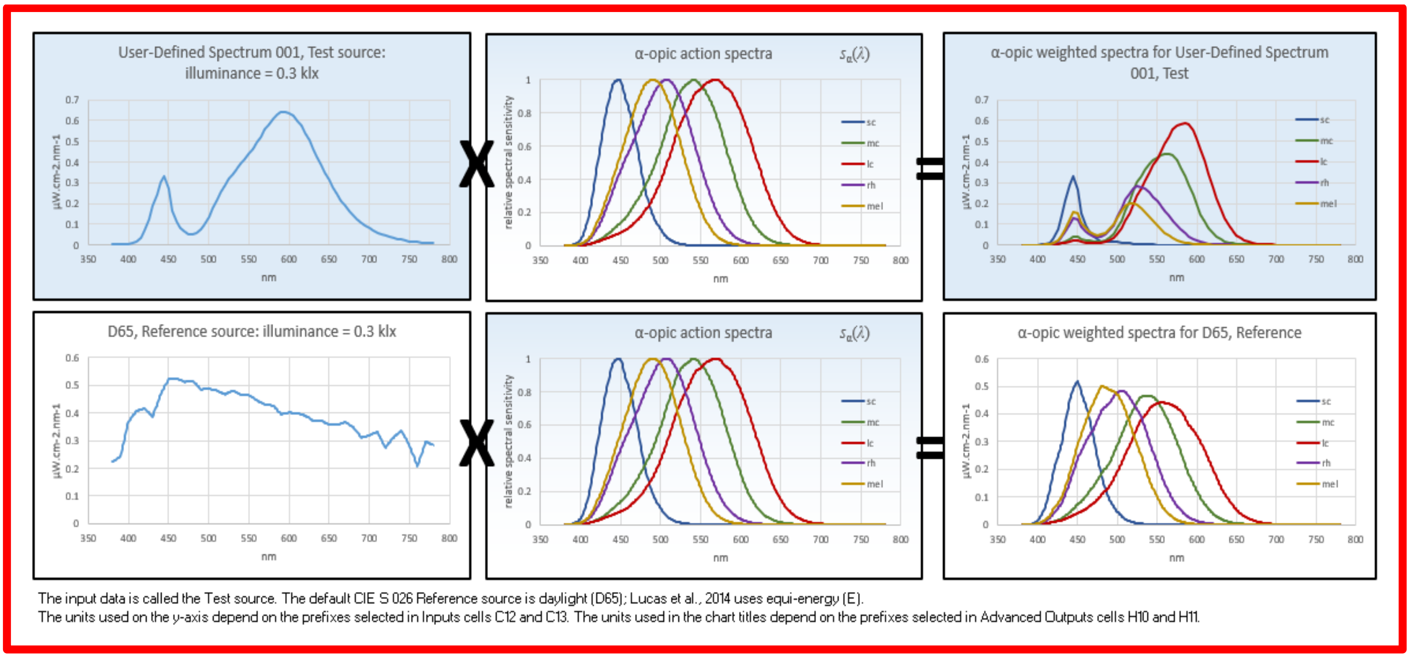

Table 8 provides a case study design example that provides an expanded seven-question framework to address these limitations.

Table 8. Seven-question framework

No.	**Seven-question framework**	**Remarks**
1	Purpose: Why is the lighting installation necessary?	Nighttime visibility & safety
2	Users: Who are the key stakeholders and affected populations?	Nighttime campus users, particularly female and vulnerable users.
3	Spatial: Where must light be distributed?	Parking, walkways, limit trespass
4	Photometric: How much illumination is required?	30 Lux due to CCTV

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5	Spectral: What spectral characteristics are necessary?	SPD with limited shortwave
6	Temporal: When should the lighting be operational?	100%, 50% no activity
7	Methodology: How will the design be structured and validated?	Validated after installation

Quantitative Evidence, Sensitivity Analysis, and Performance Benchmarking

To strengthen the empirical basis of the proposed seven-question framework, the case-study results were further analyzed through three quantitative approaches: (i) performance-margin analysis, (ii) dimming-based sensitivity analysis, and (iii) comparative design-scenario benchmarking. The purpose of this additional analysis is not to claim universal performance values, but to demonstrate how the proposed framework can convert responsible-lighting principles into measurable, testable, and repeatable engineering evidence.

Performance-Margin Analysis

The case study provides measurable evidence that the proposed framework can simultaneously satisfy functional lighting needs while reducing off-site and human-centric exposure. The design target for parking-lot average horizontal illuminance was 30 lux, while the calculated values were 36.14 lux for Lot 6 and 37.32 lux for Lot 8. This represents a design margin of approximately +20.5% for Lot 6 and +24.4% for Lot 8 relative to the minimum target. At the same time, bedroom-window eye corneal illuminance (ECI) was limited to 0.9 lux, compared with the adopted maximum criterion of 8 lux. This corresponds to an 88.75% reduction below the allowable threshold. The property-line ECI was 3.3 lux, which is 58.75% below the adopted 8 lux criterion. Table 17 presents performance-margin analysis based on case-study results.

Table 17. Performance-margin analysis using case-study results

Performance parameter	Criterion/threshold	Case-study result	Quantitative margin	Interpretation
Parking-lot average illuminance — Lot 6	30 lux	36.14 lux	+20.5% above target	Functional lighting requirement satisfied
Parking-lot average illuminance — Lot 8	30 lux	37.32 lux	+24.4% above target	Functional lighting requirement satisfied
Property-line ECI	8 lux maximum	3.3 lux	58.75% below limit	Off-site light exposure is substantially controlled
Bedroom-window ECI	8 lux maximum	0.9 lux	88.75% below limit	Residential exposure was substantially reduced
Photon exposure at the window	3.2×10^{16} photons/s/m² threshold	3.6×10^{15} photons/s/m²	88.75% below threshold	Photon-based exposure substantially constrained
Window melanopic exposure	≤1 melanopic lux	0.35 melanopic lux	65% below threshold	Circadian-relevant exposure minimized
Estimated melatonin suppression	Threshold condition	<1.83%	Below the proposed concern level	Human-centric exposure was explicitly evaluated

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These results demonstrate that the proposed framework does not merely recommend "lower light levels" in qualitative terms; rather, it provides a measurable method for balancing visibility, residential protection, and circadian exposure. In particular, the simultaneous achievement of acceptable task illuminance, low vertical ECI, low photon exposure, and low melanopic exposure supports the central claim that responsible outdoor lighting should be evaluated as a multi-domain performance system.

The current table reports a Lot 6 uniformity ratio of 4.25:1 against a criterion of 4:1. Lot 6 is slightly above the uniformity criterion but could be addressed through design optimization.

Dimming-Based Sensitivity Analysis

A further sensitivity analysis was undertaken to estimate the effect of adaptive dimming on energy use and human-centric exposure. Since the framework includes temporal control as one of its core dimensions, dimming can be treated as a measurable performance variable rather than a qualitative operational preference. For this analysis, the full-output case-study values were used as the reference condition: bedroom-window ECI = 0.9 lux, EML = 0.35 melanopic lux, and photon exposure = 3.6×10^{15} photons/s/m².

Assuming a first-order proportional relationship between dimming level and emitted luminous output, the following scenario-based values can be used to demonstrate sensitivity. These values should be presented as modeled sensitivity estimates, not as field-measured results. Table 18 presents the model sensitivity of exposure metrics to adaptive dimming.

Table 18. Model Sensitivity of exposure metrics to adaptive dimming

Operating condition	Relative output	Bedroom-window ECI	Estimated EML	Estimated photon exposure	Interpretation
Full output	100%	0.90 lux	0.350 melanopic lux	3.60×10^{15} photons/s/m²	Reference case-study condition
Moderate dimming	75%	0.675 lux	0.263 melanopic lux	2.70×10^{15} photons/s/m²	Reduced exposure while preserving partial visibility
Standard low-activity dimming	50%	0.450 lux	0.175 melanopic lux	1.80×10^{15} photons/s/m²	Strong reduction in residential and circadian exposure
Deep low-activity dimming	30%	0.270 lux	0.105 melanopic lux	1.08×10^{15} photons/s/m²	Suitable for low-activity or environmentally sensitive periods
Curfew/off-period condition	0%	0 lux	0 melanopic lux	0 photons/s/m²	Maximum reduction, subject to safety and security constraints

This analysis illustrates that temporal control is not merely an energy-saving strategy; it also provides a direct mechanism for reducing human-centric and ecological exposure. At 50% output, the estimated bedroom-window ECI decreases from 0.90 lux to 0.45 lux, while EML decreases from 0.35 to 0.175 melanopic lux. At 30% output, EML falls to approximately 0.105 melanopic lux. These reductions are particularly relevant for residential and ecologically sensitive contexts where low nighttime exposure is a primary design objective.

Energy Benchmarking Under Alternative Control Scenarios

Energy performance was benchmarked on a per-luminaire basis using the reported 274 W luminaire wattage. For a 12-hour nightly operation period, a fixed-output design consumes approximately 3.288 kWh per luminaire

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per night. The proposed temporal framework allows this baseline to be compared against adaptive dimming scenarios. Table 19 presents energy benchmarking under alternative operating scenarios.

Table 19. Energy benchmarking under alternative operating scenarios

Scenario	Control logic	Nightly energy per luminaire	Energy reduction vs fixed 100% output	Annual saving per luminaire
Fixed-output baseline	100% output for 12 h	3.288 kWh/night	0%	0 kWh/year
Mild adaptive control	100% for 6 h + 75% for 6 h	2.877 kWh/night	12.5%	≈150 kWh/year
Standard adaptive control	100% for 6 h + 50% for 6 h	2.466 kWh/night	25.0%	≈300 kWh/year
Deep adaptive control	100% for 6 h + 30% for 6 h	2.137 kWh/night	35.0%	≈420 kWh/year
Extended low-activity control	100% for 4 h + 50% for 8 h	2.192 kWh/night	33.3%	≈400 kWh/year
Late-night priority control	100% for 2 h + 50% for 10 h	1.918 kWh/night	41.7%	≈500 kWh/year

These scenario results demonstrate that the proposed framework can be used not only to reduce light pollution and human exposure but also to benchmark operational energy savings. The 50% low-activity dimming strategy discussed in the paper is estimated to reduce energy by 25%, while extended low-activity operation can theoretically increase savings to approximately 33–42% per luminaire, depending on site use and safety requirements. These values are broadly consistent with evidence from adaptive exterior lighting, indicating that occupancy-based controls and dimmable sources can yield significant energy savings compared with traditional fixed-output systems. Adaptive Solutions for Outdoor Lighting reports that adaptive exterior lighting products combining occupancy-based controls with efficacious dimmable sources can offer 30–75% energy savings over traditional systems (CLTC, 2013).

Comparative Design-Scenario Benchmarking

To further demonstrate the practical value of the proposed framework, four design scenarios were benchmarked against the same performance categories: visual adequacy, light trespass, spectral/circadian evaluation, energy performance, and validation. Table 20 presents comparative design-scenario benchmarking.

Table 20. Comparative design-scenario benchmarking

Design scenario	Description	Visual performance	Trespass / ECI control	Spectral/circadian control	Energy performance	Validation strength
Scenario A: Conventional fixed-output design	100% output throughout the night; compliance focused mainly on illuminance	Can satisfy average illuminance	May not explicitly verify bedroom-window ECI	Usually based on CCT only	Baseline energy use	Limited post-install verification
Scenario B: IDA/IES-aligned	Uses useful, targeted, low-level, controlled,	Encourages appropriate lighting	Encourages shielding and reduced spill	Encourages warmer color but does not	May reduce energy if	Primarily principle-based

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qualitative design	and warmer-colored principles			require SPD/EML evaluation	controls are adopted	
Scenario C: Photometric compliance design	Meets project illuminance/uniformity criteria and checks property-line/window ECI	Quantitatively assessed	Quantitatively assessed using ECI	Limited unless SPD/EML is added	May remain fixed output	Moderate verification
Scenario D: Proposed seven-question performance framework	Integrates user, spatial, photometric, spectral, temporal, and validation dimensions	Quantitatively assessed	Bedroom-window ECI = 0.9 lux; property-line ECI = 3.3 lux	Photon exposure = 3.6×10^{15} photons/s/m²; EML = 0.35 melanopic lux; MSAN <1.83%	25–42% scenario-dependent savings	Strongest: simulation, commissioning, measurement, and feedback

This benchmarking demonstrates that the novelty of the proposed framework lies in its ability to integrate multiple performance dimensions into one repeatable design method. Unlike a conventional compliance approach, the proposed framework evaluates not only whether the site is sufficiently illuminated, but also who is exposed, where the light travels, how much light is required, what spectral content is emitted, when the system operates, and how performance is validated.

DISCUSSION

Transition from Principles to Performance

While the five principles serve as an effective advocacy tool, their qualitative nature limits their utility for practical implementation, which demands precise, measurable criteria. A performance-based approach is therefore essential to ensure consistency and facilitate rigorous design verification.

Importance of "Who" in Design

Effective lighting design necessitates an integrated approach that addresses the distinct requirements of diverse stakeholders, including:

- Drivers and pedestrians
- Residents
- Vulnerable populations
- Ecological receptors

Defining Performance Requirements

Effective performance specifications require the establishment of clear, quantifiable targets, such as:

- Minimum and maximum illuminance levels
- Glare limits
- Spectral constraints

Balancing Safety, Security, and Circadian Health

Effective lighting design requires a careful balance between competing priorities to mitigate the risks of:

- Over-lighting: glare, energy waste, ecological harm
- Underlighting: reduced visibility and perceived safety

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Role of Spectral Design

Reliance on classical photometrics is inadequate. SPD-based design, by contrast, allows for a more accurate evaluation of (Thurairajah, U. 2026b):

- Circadian health effects
- Ecological sensitivity

Comparative Evaluation: IDA/IES vs Performance-Based Framework

Table 9 provides a conventional IDA/IES-based design approach and the proposed framework.

Table 9. Comparison Framework

Aspect	**IDA/IES-only design**	**Author's 7-question framework**
Approach	Qualitative guidance	Measurable + validated
User consideration	Implicit	Explicit (Who")
Metrics	Limited (lux, CCT)	Multi-domain (lux, SPD, EML, temporal)
Validation	Rare / not required	Required ("How")
Spectral method	CCT-based	SPD + melanopic metrics

Quantitative Comparison (Using the Case Study)

A. Light Trespass / Glare Control

Representative implementation of the IDA/IES principles: Meets illuminance (≈30–40 lux), Limited verification at property boundaries, and Typical spill at windows: ~2–5 lux (industry typical, not enforced)

Author's framework (measured): Bedroom window: 0.9 lux, and Property line: 3.3 lux

Table 10 provides trespass lighting improvement for this study location.

Table 10. Trespass Lighting Improvement

Metric	**IDA/IES-only**	**Author's framework**	**Improvement**
Window exposure	~2–5 lux	0.9 lux	↓ ~55–80%
Trespass control	Qualitative	Measured ECI	Verified within the case-study context

Impact: Reduced glare, reduced sleep disruption risk, and Better residential acceptance

B. Energy Use (Operational Efficiency)

IDA/IES-only: Often fixed output (100% all night), and no adaptive control requirement

Author's framework: Temporal control: 100% when active, and 50% when no activity

Estimated Improvement

Assuming: 12-hour operation and 6 hours of low activity

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume XI Issue VII July 2026

Table 11 provides energy use (operational efficiency) improvement for this study location.

Table 11. Energy Improvement

Scenario	Energy Use
IDA/IES	100% × 12h = 12 units
Author's framework	(100% × 6h) + (50% × 6h) = 9 units

Energy reduction ≈ 25%, and additional benefits include a lower carbon footprint and less skyglow.

C. Circadian / Human Health Impact

IDA/IES-only: Uses CCT (e.g., 3000K) as a proxy, and no evaluation of melanopic lux, photon exposure, and melatonin suppression.

Author's framework (measured):

- Photon exposure: 3.6×10^{15} photons/s/m² at windows
- Melatonin suppression: <1.83%
- EML at window: 0.35 melanopic lux

Table 12 provides Circadian / Human Health Impact improvement for this study location.

Table 12. Circadian Improvement

Metric	IDA/IES-only	Author's framework
Circadian evaluation	None	Explicit
Melatonin suppression	Unknown	<1.83%
Melanopic exposure	Unknown	0.35 lux

Impact: Near-threshold-safe nighttime exposure and explicitly evaluated human-centric exposure indicators.

D. Spectral Optimization

IDA/IES-only: Uses CCT (e.g., 3000K) and cannot distinguish blue spike variations and ecological sensitivity.

Author's framework: Uses SPD (Spectral Power Distribution), evaluates short-wavelength content, and circadian weighting.

Table 13 provides spectral optimization improvement for this study location.

Table 13. Spectral Optimization Improvement

Metric	IDA/IES-only	Author's framework
Spectral precision	Low (CCT only)	High (SPD-based)
Biological relevance	Weak	Strong

Ecological sensitivity	Not addressed	Explicitly addressed

Impact: Reduced blue-light hazard and Better ecological protection

E. Design Verification / Reliability

IDA/IES-only: No required validation loop, and Design → install → rarely rechecked

Author's framework: Full lifecycle, including simulation, commissioning, and post-install validation.

Table 14 provides Design Verification / Reliability improvement for this study location.

Table 14. Design Verification / Reliability Improvement

Feature	IDA/IES-only	Author's framework
Post-install validation	No	Yes
Iterative optimization	No	Yes
Measurable compliance	Partial	Full

Combined Performance Improvement Summary

Table 15 provides Combined Performance Improvement Summary for this study location.

Table 15. Combined Performance Improvement Summary

Category	Improvement
Light trespass	↓ 55–80%
Energy consumption	↓ ~25%
Melatonin suppression	Controlled (<1.83%)
Circadian exposure	Measured + minimized
Spectral control	High precision (SPD vs CCT)
Design reliability	Validated within the case-study context

The proposed framework reframes responsible outdoor lighting as a measurable human-environment performance system rather than a primarily qualitative design philosophy.

IDA/IES-only: Use less light, and aim it better

This framework: Light as a measurable, human-environment system. This represents a transition toward from guidance → engineering discipline.

To evaluate the effectiveness of the proposed framework, a comparison was conducted against a conventional IDA/IES-based design approach.

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Comparison table

Table 16 provides a comparison table for this study location.

Table 16. Comparison Table

Metric	IDA/IES-only	Proposed Framework	Improvement
Energy use	Fixed output	Adaptive control	~25% reduction
Light trespass	Limited control	Verified ECI ≤0.9 lux	↓ significant
Circadian impact	Not evaluated	<1.83% MSAN	Controlled
Spectral design	CCT-based	SPD-based	Higher precision

The improvements across the Environmental performance (reduced spill, skyglow), Human-centric performance (controlled melanopic exposure), and Engineering reliability (validated design process). This comparison demonstrates that the performance-based framework provides measurable, multi-domain improvements that cannot be achieved through qualitative IDA/IES principles alone.

Policy Integration and Standardization Pathways

The transition from a principle-based to a performance-based outdoor lighting framework introduces important implications for policy development and standardization. While the IDA/IES Five Principles provide high-level guidance, their qualitative nature limits their enforceability within regulatory environments. The proposed seven-question framework offers a structured pathway toward measurable, verifiable, and enforceable lighting standards.

Integration with Existing Standards

The proposed framework can be aligned with existing standards, such as:

- IES RP-8 (Roadway Lighting) – photometric criteria (illuminance, uniformity)
- CIE guidelines – glare, environmental zones, and spectral considerations
- DarkSky/IDA guidelines – light trespass, skyglow reduction

However, the framework extends these standards by:

- Incorporating explicit user-centric design ("Who")
- Integrating spectral and circadian metrics (SPD, EML)
- Introducing mandatory validation ("How")

This enables a transition from compliance-based design to performance-based certification.

Regulatory Implementation Pathways

To implement the framework within policy, the following staged approach is recommended:

Stage 1: Guideline Enhancement

Embed the seven design questions into planning and design guidelines, and require consideration of user groups (residents, vulnerable populations), and Environmental receptors.

Stage 2: Metric-Based Requirements

Introduce quantitative thresholds, including maximum illuminance and uniformity limits, Light trespass limits (e.g., ECI at property lines/windows), spectral constraints (short-wavelength limits via SPD), and temporal controls (adaptive dimming schedules).

Stage 3: Performance Verification

Require design-stage simulation, post-installation measurement, and compliance reporting.

Stage 4: Certification and Enforcement

Develop a performance certification scheme, like energy codes, that includes verified compliance with multi-domain metrics and periodic revalidation.

Standardization Challenges

Despite its advantages, several challenges exist:

- **Measurement Complexity:** SPD, melanopic metrics, and photon-based calculations require advanced instrumentation
- **Industry Readiness:** Designers and municipalities may lack expertise or resources
- **Regulatory Alignment:** Current standards are fragmented across jurisdictions
- **Cost Implications:** Increased upfront analysis and validation costs

Opportunities for Adoption

The framework supports future standardization by enabling:

- Unified multi-domain performance metrics (visual, environmental, human)
- Integration with smart lighting systems and adaptive controls
- Alignment with sustainability goals (SDGs, carbon reduction targets)

Ultimately, this framework provides a foundation for evolving outdoor lighting standards from prescriptive compliance toward evidence-based regulatory systems.\

Novelty Positioning Against Existing Standards and Frameworks

The novelty of this study is not that it replaces existing standards, but that it provides an operational bridge between principle-based guidance, photometric standards, human-centric metrics, adaptive controls, and post-installation validation. Existing guidance documents and standards each address important parts of the outdoor-lighting problem, but they tend to focus on either qualitative principles, photometric compliance, circadian exposure, energy performance, or adaptive controls. The proposed framework integrates these previously fragmented dimensions into a unified performance-based methodology. Table 21 presents novelty positioning of the proposed seven-question framework.

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Table 21. Novelty positioning of the proposed seven-question framework

Existing framework/standard	**Primary focus**	**Limitations in relation to responsible outdoor lighting**	**What is new in this paper**
IDA/IES Five Principles for Responsible Outdoor Lighting	Establishes five high-level principles: useful, targeted, low-level, controlled, and warm-coloured lighting (IDA/IES, 2020).	Provides strong conceptual guidance but remains largely qualitative; it does not prescribe a full engineering workflow, quantitative thresholds, user-exposure evaluation, SPD-based assessment, or post-installation validation.	Converts the five principles into a seven-question performance framework by adding explicit "Who?" and "How?" dimensions and linking each principle to measurable photometric, spectral, spatial, temporal, and validation metrics.
CIE 150:2017 Guide on the Limitation of the Effects of Obtrusive Light from Outdoor Lighting Installations	Provides guidance and recommended limits for lighting parameters intended to contain obtrusive effects of outdoor lighting (CIE, 2017).	Focuses primarily on obtrusive-light control and environmental impact limits; it does not, by itself, provide a complete user-centered, circadian, adaptive-control, and validation framework for all responsible-lighting decisions.	Extends obtrusive-light control into a broader multi-domain performance model that includes ECI, EML, photon exposure, adaptive dimming, and post-installation feedback.
CIE Position Statement on Obtrusive Light and Light Pollution	Identifies benefits and drawbacks of light at night and highlights good design, local knowledge, and adaptability as mitigation approaches (CIE, 2025)	Provides strategic direction but does not translate adaptability and exposure reduction into a structured seven-step design and verification process.	Operationalises adaptability through a design workflow that moves from need identification to requirement setting, simulation, controls, commissioning, field validation, and optimisation.
DarkSky / IDA principles	Advocates for responsible outdoor lighting by limiting unnecessary, misdirected, excessive, uncontrolled, and blue-rich light (IDA/IES, 2020).	Strong advocacy and policy value, but limited engineering specificity for lux, ECI, EML, photon flux, SPD weighting, dimming scenarios, and compliance verification.	Provides an engineering translation of DarkSky intent by showing how responsible-lighting principles can be evaluated using measurable environmental, visual, and human-centric indicators.
WELL Standard — Circadian Lighting Design	Uses equivalent melanopic lux / melanopic light intensity to support circadian health, measured on the vertical plane at eye level (IWBI, n.d.).	Primarily building-occupant- and indoor/workplace-health-oriented, it does not function as a complete outdoor-lighting design framework for roadways, parking areas, ecological receptors, glare, trespass, and adaptive controls.	Transfers melanopic thinking to outdoor lighting assessment by combining EML with ECI, photon exposure, spectral power distribution, and spatial trespass analysis.

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EN 13201 Road lighting	Multi-part road-lighting standard covering performance requirements, calculation of performance, measurement methods, and energy performance indicators (BSI, 2026).	Strong for road-lighting photometric compliance and measurement, but not primarily structured around user-specific exposure, residential ECI, melanopic exposure, SPD-based circadian/ecological risk, or full responsible-lighting policy feedback.	Adds a user-centered and human-environment performance layer to conventional road-lighting compliance by integrating "Who?", "What spectrum?", "When?" and "How validated?" into the design method.
ANSI/IES RP-8 Recommended Practice: Lighting Roadway and Parking Facilities	Provides roadway and parking-facility lighting design techniques and criteria; the current IES listing identifies chapters including obtrusive light, controls, roadway lighting, street lighting, intersections, and parking facilities (IES, 2025)	Comprehensive for roadway and parking lighting practice, but current design application may still be interpreted mainly through photometric compliance unless supplemented by explicit circadian, SPD, ECI, adaptive-control, and validation requirements.	Uses the parking-lot case study to demonstrate how RP-8-type photometric practice can be extended into a measurable responsible-lighting framework incorporating residential exposure, EML, photon flux, adaptive dimming, and post-installation validation.
Existing adaptive-lighting frameworks	Focus on dimming, occupancy sensing, daylight response, tunable sources, and energy reduction; adaptive exterior lighting has been reported to offer substantial energy savings when controls are coupled with dimmable sources (CLTC, 2013).	Often, technology- or energy-centered approaches may not fully integrate human exposure, spectral/circadian metrics, ecological sensitivity, light trespass, and policy validation into one design framework.	Repositions adaptive lighting as a multi-objective responsible-lighting tool: dimming is evaluated not only for energy savings but also for reduced ECI, EML, photon exposure, skyglow potential, and human/ environmental impact.

This comparison shows that the proposed framework occupies a distinct methodological position. It does not duplicate IDA/IES, DarkSky, CIE, WELL, EN 13201, RP-8, or adaptive-lighting guidance; instead, it synthesizes their partial strengths into a single performance-based design structure. Its principal novelty is the transformation of responsible outdoor lighting from a set of qualitative principles into a measurable engineering workflow. The framework contributes four new elements: (i) explicit identification of exposed users and receptors through the "Who?" dimension; (ii) integration of photometric, spatial, spectral, melanopic, and photon-based metrics; (iii) quantitative evaluation of adaptive temporal controls; and (iv) mandatory validation through simulation, commissioning, field measurement, and feedback. In this sense, the framework advances responsible outdoor lighting from advocacy and compliance toward evidence-based, human-environment performance design. This paper does not replace IDA/IES, CIE, WELL, EN 13201, or RP-8. Instead, it operationalizes their partial strengths into a unified performance-based workflow for responsible outdoor lighting.

Limitations

Despite its contributions, several limitations should be acknowledged. First, the framework was demonstrated using a single parking-lot lighting case study. While the case study provides evidence of practical applicability, it is insufficient to establish universal validity across all outdoor lighting applications. Consequently, the reported performance outcomes should be interpreted as project-specific evidence rather than generalized performance benchmarks. Second, several quantitative thresholds and assumptions adopted within the case study reflect specific project requirements, lighting classifications, and regulatory conditions. These values may differ among jurisdictions, environmental zones, roadway classes, and application types. The framework itself is intended to remain adaptable by allowing local standards and project-specific performance requirements to be incorporated into the evaluation process. Third, although the framework was developed through systematic analysis of responsible-lighting principles and engineering requirements, it has not yet undergone extensive independent validation by external practitioners or standards-development organizations. At its current stage, the framework should therefore be considered an analytically derived and case-study-demonstrated methodology rather than a formally validated industry standard. Future studies should incorporate structured expert review by lighting designers, municipal engineers, environmental scientists, public health researchers, and standards body representatives to evaluate the framework's usability, indicator relevance, repeatability, and implementation feasibility. Finally, broader empirical testing is required to assess the framework's scalability and adaptability across diverse outdoor lighting contexts. Future research should evaluate its application in residential neighborhoods, roadway corridors, commercial districts, institutional campuses, public plazas, parks, recreational facilities, and environmentally sensitive areas. Multi-site investigations would help establish whether the proposed indicator set remains robust across different user groups, ecological conditions, operational requirements, and policy environments. Such studies would provide the evidence base necessary for benchmarking, standardization, and eventual integration into professional guidance and regulatory processes.

CONCLUSIONS

While the IDA/IES Five Principles mark a significant advancement in sustainable outdoor lighting, their primarily qualitative nature limits their utility as a comprehensive, standalone design framework.

The analysis reveals three critical gaps in existing design methodologies:

- The absence of a user-centric design approach to address the "Who" component.
- The lack of standardised, measurable performance requirements.
- The absence of a structured, repeatable design and validation methodology.

To address these limitations, as indicated and tested above, the author introduced an expanded seven-question framework. By integrating photometric, spectral, spatial, and temporal metrics into a structured workflow, the framework facilitates a quantifiable approach to design, verification, and optimisation.

Responsible outdoor lighting represents a context-sensitive engineering discipline that expands the foundational five principles into a seven-question framework:

1. **Purpose** (Why?): Determining the necessity and objectives of the lighting installation.
2. **User Focus** (Who?): Identifying stakeholder requirements and affected populations.
3. **Spatial Control** (Where?): Managing the placement and direction of light distribution.
4. **Photometric Intensity** (How much?): Setting appropriate illuminance levels and uniformity.
5. **Spectral Quality** (What?): Specifying spectral characteristics tailored to the application.
6. **Temporal Scheduling** (When?): Establishing operational timing and control strategies.
7. **Methodology** (How?): Implementing a structured, repeatable design and validation process.

Responsible outdoor lighting goes beyond simply reducing light levels; it requires the strategic application of appropriate illumination, validated by measurable performance metrics. This research represents a transition from qualitative principle-based guidance toward measurable engineering evaluation. This is an important step toward establishing outdoor lighting as a performance-based engineering discipline, rather than a purely principle-driven practice. While further validation and standardization are necessary, the proposed framework provides:

- a practical foundation
- a measurable methodology
- and a scalable pathway toward responsible outdoor lighting design.

This paper bridges the gap between responsible lighting principles and practical engineering implementation by translating broad environmental and human-centric objectives into a structured, measurable, and verifiable design framework. The proposed seven-question framework is intuitive, practical, and readily adoptable by lighting designers, municipalities, and standards bodies. Its integration of ECI, SPD, EML, photon exposure, adaptive dimming, and field validation strengthens the methodological novelty of the study by enabling lighting impacts to be measured, compared, optimized, and verified. The paper transforms the IDA/IES Five Principles from a qualitative responsible-lighting philosophy into a measurable seven-question engineering framework that integrates user requirements, photometric performance, spectral evaluation, adaptive controls, human-centric metrics, and validation.

Competing Interests

The author has declared that no competing interests exist.

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