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SOLAR STREET LIGHTING IN SENEGAL: LIFE-CYCLE COST, RELIABILITY, QUALITY ASSURANCE AND PERFORMANCE CONTRACTING AT SCALE

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ABSTRACT

The large-scale rollout of solar street lighting in Senegal poses a challenge that exceeds the mere deployment of equipment: how can continuity and reliability of service be assured over the long term? This article re-examines ANER's 2015 feasibility analysis for 50,000 luminaires, situating it within the subsequent expansion of national programmes and the regulatory provisions that govern photovoltaic equipment quality. The original 2015 cost benchmarks are used without re-indexation: FCFA 2.14 million per kilometre for solar lighting versus FCFA 4.67 million per kilometre for conventional lighting on a single carriageway, and FCFA 5.06 million and 11.88 million per kilometre, respectively, on a dual carriageway. Monitoring reports dated 2025 document 151,434 streetlights across 529 municipalities and preview a further tranche of 100,000 units. On this empirical basis, the study proposes to anchor life-cycle cost (LCC) to delivered service through metrics such as cost per useful lumen-hour, nighttime availability, mean time between failures and mean time to repair (MTBF and MTTR), battery replacement cycles, and photometric performance. A sensitivity analysis quantifies how battery replacements drive expenditures over a ten-year horizon. The proposed protocol integrates these indicators with conformity assessment and monitoring, allowing contractual obligations to rest on verifiable performance.[1, 7]

KEYWORDS: solar street lighting; life-cycle cost; reliability; maintenance; battery; LED; quality assurance; remote monitoring; Senegal.

Nomenclature and Abbreviations

The list of abbreviations and symbols that follows is consistent with the terminology and equations adopted in this article. Monetary values are expressed consistently within each calculation; the sensitivity analysis employs normalised cost units.

Abbreviation or symbol	Definition	Unit
ANER	Agence nationale pour les énergies renouvelables (National Agency for Renewable Energies, Senegal)	—
ARCOP	Autorité de régulation de la commande publique (Public Procurement Regulatory Authority, Senegal)	—
BMS	Battery management system	—
CAPEX	Capital expenditure	—
CIE	International Commission on Illumination	—
DoD	Depth of discharge	—
ESMAP	Energy Sector Management Assistance Program	—
FCFA	CFA franc, the monetary unit used for the Senegalese cost figures	—
IEA	International Energy Agency	—
IEC	International Electrotechnical Commission	—
IRENA	International Renewable Energy Agency	—

Abbreviation or symbol	Definition	Unit
ISO	International Organization for Standardization	—
KPI	Key performance indicator	—
LCC	Discounted total life-cycle cost over the study horizon	Monetary unit
LED	Light-emitting diode	—
MEPM	Ministère de l'Énergie, du Pétrole et des Mines (Ministry of Energy, Petroleum and Mines, Senegal)	—
MTBF	Mean time between failures	—
MTTR	Mean time to repair	—
PV	Photovoltaic	—
SOH	State of health	—
A	Availability, as defined in Equation (3)	Dimensionless or %
C_0	Initial investment cost	Monetary unit
$C_{maint,t}$	Preventive and corrective maintenance cost in year t	Monetary unit
$C_{rep,t}$	Component replacement cost in year t	Monetary unit
$C_{sup,t}$	Monitoring and communication cost in year t	Monetary unit
$C_{vand,t}$	Cost of vandalism or other damage borne under the contract in year t	Monetary unit
$C_{fin,t}$	End-of-life expenditure incurred in year t	Monetary unit
LCOSlight	Discounted cost per unit of lighting service, as defined in Equation (2)	Monetary unit/(lm·h) when flux is used
N	Study horizon used for the terminal residual value	Years
$N_{bat,rep}$	Number of battery replacements during the observation period	Count
N_{pannes}	Number of failures during the observation period	Count
N_{points}	Number of lighting points monitored	Count
r	Annual discount rate, expressed as a decimal	Dimensionless
RV□	Residual value at the end of the study horizon N	Monetary unit
T	Observation period used in Equation (4)	Years or another stated time unit
t	Annual time index in the discounted sums	Year index
$h_{available,t}$	Hours of lighting service actually available in year t	h
$\Phi_{useful,t}$	Useful luminous flux in year t, or the specified contractual photometric metric	lm when luminous flux is used

Units are defined as follows: h denotes hour, km kilometre, lm lumen, and lm·h lumen-hour. MTBF and MTTR must be expressed in the same time unit. Equation (4) yields a failure rate per lighting point per unit time; to report failures per 100 points, multiply the result by 100. Equation (5) represents the replacement proportion over the observation window; for annual reporting, the period must be one year. If Equation (2) uses a photometric quantity other than luminous flux, substitute its unit for lm in the denominator.

1 INTRODUCTION

Autonomous solar street lighting can be deployed in urban, peri-urban, and rural settings while limiting the need for grid extensions, trenching, and cabling. Its performance, however, must be evaluated over time. In programmes that encompass tens of thousands of luminaires, installation acceptance alone is not an adequate measure of success; prescribed illuminance and autonomy must be maintained, and faults must be corrected within response times commensurate with the expected service level.[1,2,24] The delivered performance of a streetlight depends on the full system, including the photovoltaic module, the battery, the charge controller, the LED luminaire, and the supporting structure, and it is further shaped by the resources devoted to monitoring and maintenance. This study connects these technical factors to operating costs and contractual obligations. Using available evidence on national fleet expansion, it develops a service-cost model, conducts sensitivity analysis, and proposes a framework for outcome monitoring.[8, 30]

1.1. Contributions

The contribution is sixfold. First, it situates the cost figures reported in the 2015 ANER study within their historical context rather than interpreting them as current price levels. Second, it assesses the operational consequences of the documented growth of the national fleet. Third, it links life-cycle cost and the cost per useful lumen-hour to availability, MTBF, and MTTR. Fourth, it evaluates the impact of battery replacement on ten-year expenditures. Fifth, it follows equipment quality from acceptance through routine operation. Sixth, it proposes an ex post evaluation protocol and a set of measurable indicators suitable for contracting.

2. Sources and Method

The analysis is based on a documentary corpus comprising the 2015 ANER/BESD report, monitoring records for solar street lighting, recent contracting decisions, Senegalese regulations governing photovoltaic equipment quality, and relevant international standardisation references. Historical costs are retained with the units and reference period used in the source report. In domains where national time series are unavailable, supplementary calculations are provided as model illustrations with explicit assumptions. This separation distinguishes evidence-based findings from results that will require validation in the field.[1, 30]

3. Technical Architecture and Failure Chain

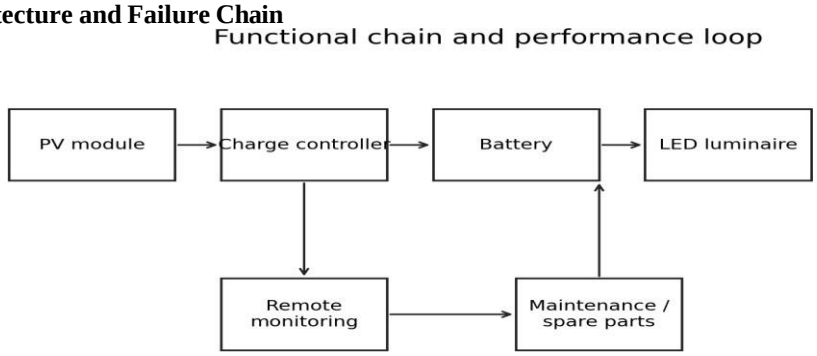


Figure 1: Simplified functional architecture of a stand-alone solar streetlight and its monitoring and maintenance loop.

Source: author's elaboration.

Subsystem	Function	Failure modes to monitor	Indicator
PV module	Daytime generation	Soiling, cracks, connections, shading	Energy / current / inspection
Controller	Charge and lighting management	Settings, electronics, sensors	Alarms / logs
Battery	Storage for nighttime operation	Capacity loss, temperature, high depth of discharge (DoD)	State of health (SOH), voltage, replacements
LED/driver	Lighting service	Lumen depreciation, driver failure, LED failure	Illuminance, power, failure
Pole/foundation	Mechanical stability	Corrosion, impact, vandalism	Inspection / conformity
Remote monitoring	Diagnostics	Communication loss, sensor failure	Data transmission rate

The 2015 analysis identifies the battery as the primary determinant of service life. Within the tested conditions, lead-acid chemistries generally exhibit shorter longevity than high-grade lithium-based systems. These findings are bounded by the report's specific technical framework. In practice, ageing trajectories are strongly conditioned by temperature, charge protocol, depth of discharge, and the performance of the battery management system (BMS) or controller. Selecting a given technology therefore does not remove the need to evaluate its real operating profile.[1,22,23]

4. Historical Economic Benchmark: The 2015 ANER Study

Configuration	Solar (FCFA/km)	Conventional (FCFA/km)	Solar/conventional ratio	Historical difference
Single carriageway	2,139,755	4,668,659	0.46	−54.2%
Dual carriageway	5,062,439	11,878,773	0.43	−57.4%

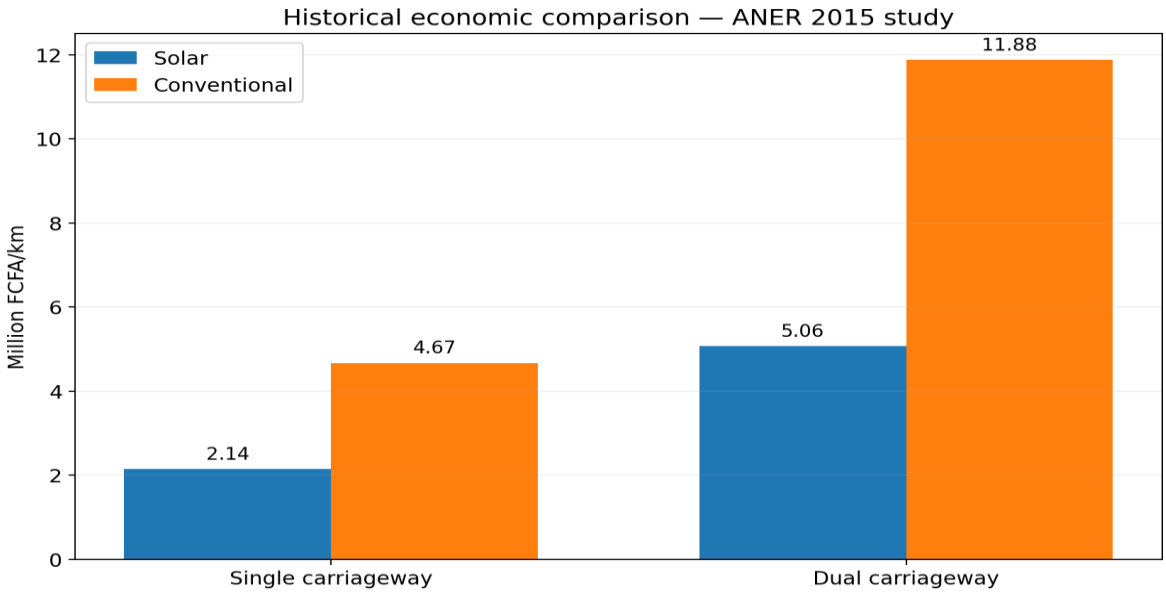


Figure 2: Comparative discounted costs reported in the 2015 ANER study. These historical values have not been re-indexed and do not represent current market prices.

The disparities shown in the table stem from the configurations and assumptions adopted in 2015. They offer a reference point for interpreting the economic advantage estimated at that time, but they do not define the current purchase cost of a new installation. Across the service life, any advantage is contingent on factors such as degradation of batteries and luminaires, maintenance outlays, damage or vandalism, monitoring, and recycling. Above all, costs must be appraised in relation to the level of photometric performance actually delivered.[1,17,18,24]

The 2025 sectoral monitoring report details a programme initiated in November 2022, structured in three phases, with an overall budget of FCFA 324.287 billion and an initial duration of 48 months. It indicates that the first phase, targeting 50,000 streetlights, has been completed. Documented deployments amount to 95,761 units in the second phase and 5,673 in the third, yielding a cumulative total of 151,434 streetlights across 529 of the 553 planned municipalities. The same report announces forthcoming works for a further 100,000 units. These figures capture the progress reported in 2025.[2, 4]

5. Expansion of the National Programme

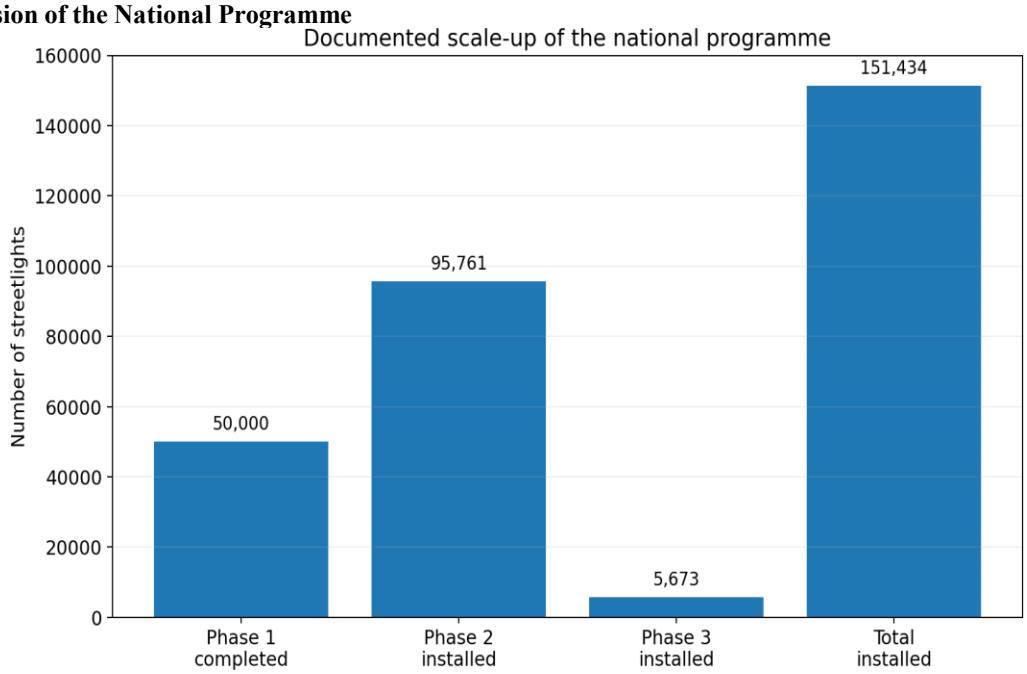


Figure 3: Documented scale-up of the solar street-lighting programme. Values reflect progress reported in 2025, rather than a real-time inventory for 2026.

At such a scale, even modest defect rates translate into a heavy volume of interventions. In a fleet of 151,434 luminaires, a 1% failure rate implies on the order of 1,514 lighting points requiring action, whereas a 5% rate corresponds to about 7,572. These figures are purely arithmetic illustrations and do not describe the situation of the Senegalese fleet. They underscore why spare-part inventories, team organisation, remote supervision, and response-time commitments need to be specified at the contract design stage.[2,24]

6. Life-Cycle Cost Model

$$LCC = C_0 + \Sigma_t (C_{maint,t} + C_{rep,t} + C_{sup,t} + C_{vand,t} + C_{fin,t})/(1+r)^t - RV_N/(1+r)^N \quad (1)$$

In Equation (1), C_0 is the upfront investment. The yearly cash flows include preventive and corrective maintenance (Cmaint), component replacements (Crep), monitoring and communications (Csup), and damage due to vandalism or similar events that are contractually borne (Cvand). Cfin denotes end-of-life expenditures, r is the discount rate, and RV is the residual value at the end of the analysis horizon. This formulation permits comparison of bids that combine different initial prices with distinct future expenditure profiles.[17,18]

$$LCOS_{light} = LCC / \Sigma_t [\Phi_{useful,t} \times h_{available,t} /(1+r)^t] \quad (2)$$

Equation (2) allocates the life-cycle cost to a discounted measure of delivered lighting service. Φuseful represents the useful luminous flux, or the photometric indicator specified in the contract, and havailable is the number of hours during which the service is effectively provided. The choice of metric is critical: for roadway applications, maintained illuminance and its spatial uniformity are more informative about the delivered service than the luminaire's nominal flux alone. The selected indicator must therefore remain aligned with site-specific requirements.[15,18,24]

6.1. Reliability and Maintainability

$$A = MTBF / (MTBF + MTTR) \quad (3)$$

$$\text{Failure rate} = N_{pannes} / (N_{points} \times T) \quad (4)$$

$$\text{Battery replacement rate} = N_{bat,rep} / N_{points} \quad (5)$$

Failure frequency and duration should be assessed jointly. High availability can be achieved despite recurrent faults when repair durations are short. Conversely, a small number of prolonged outages can compromise service for extended periods. MTBF and MTTR thus provide complementary evidence on intrinsic reliability and the effectiveness of maintenance practices.[18,24,25]

7. Illustrative Sensitivity to Battery Replacement

No open national dataset with observed maintenance costs and battery replacement records is available in the consulted sources. The analysis therefore employs normalised placeholders to illustrate their influence on the LCC: an initial CAPEX of 100 units, annual maintenance of 2 units, and 25 units per battery replacement over a ten-year horizon. These values are solely for illustration; they do not represent prices in Senegal or terms of any existing contract.

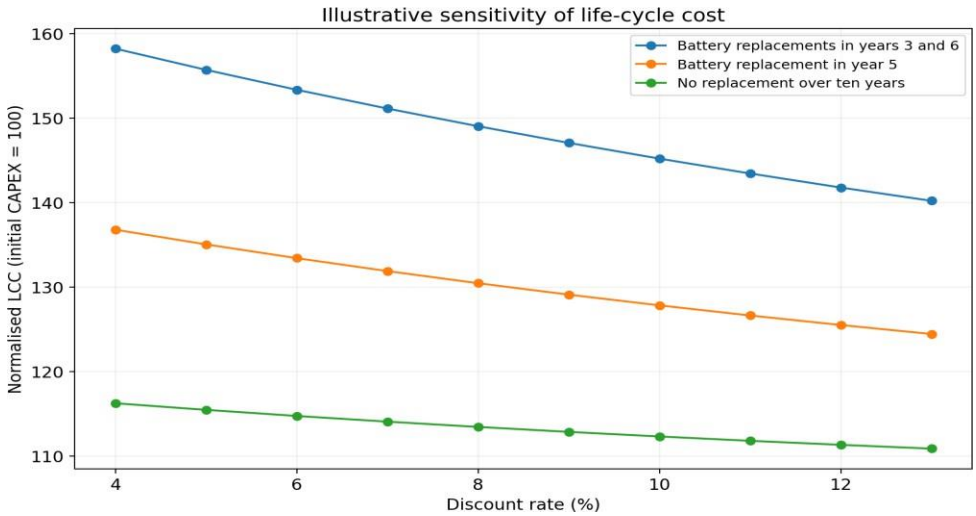


Figure 4: Illustrative sensitivity of normalised LCC to the discount rate and battery replacement frequency. Assumptions are for explanatory purposes and do not constitute market data.

Within the bounds of the illustrative assumptions, each additional battery replacement materially increases lifecycle expenditure, even when the upfront capital outlay is held constant. Bid evaluation should therefore appraise not only the nominal warranty duration but also the operational conditions required to sustain service. Parameters such as residual capacity, cumulative energy delivered, operating temperature, and cycle count delineate the substantive scope of the warranty.[17,18,22,23]

8. Quality Assurance and Standardisation

Decree No. 2025-1960, which governs quality control for equipment comprising a solar photovoltaic system, establishes the framework for enforcing demonstrable conformity. The draft implementing orders provide for inspections of both imported and domestically

manufactured equipment, along with certification by an authorised body designated by the Minister responsible for Energy. For a solar streetlight, the conformity process must address the requirements applicable to each constituent component, namely the luminaire, photovoltaic module, battery, controller, and mechanical structure. Acceptance should subsequently be linked to performance evidenced in operation and verified through measured data.[5, 16,19,20]

Stage	Recommended check	Evidence	Decision
Before supply	Certificates, data sheets, type tests	Technical documentation	Qualification
Lot acceptance	Sampling and inspection	Test reports / serial numbers	Acceptance/rejection
Commissioning	Photometry, autonomy, remote monitoring	Georeferenced baseline	Technical acceptance
Operation	Alarms, energy, faults	Monitoring history	Maintenance
Annual audit	Illuminance, battery, corrosion	Stratified sample	Corrective action / penalty

9. Performance Framework and Contracting

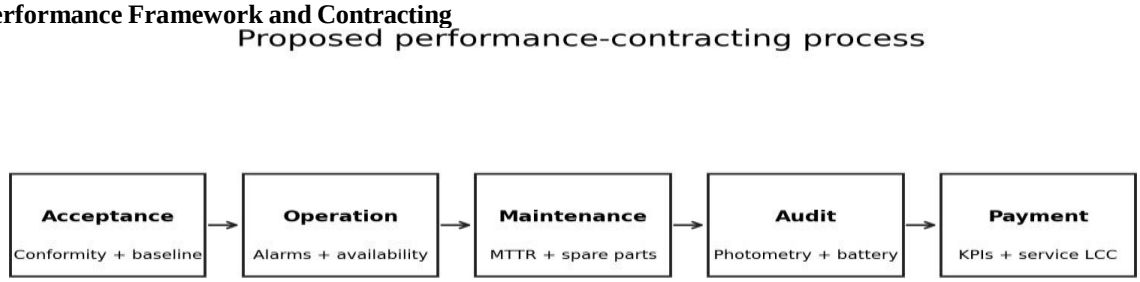


Figure 5: Proposed performance-contracting process, from acceptance to annual payment.

KPI	Unit	Target to be set in the contract	Use
Nighttime availability	%	According to service class	Availability payment
Failure rate	Failures/100 points/year	By technology/lot	Reliability
MTTR	Hours or days	By area	Maintainability
Illuminance conformity	% of points	According to photometric class	Lighting service
Uniformity conformity	% of road sections	According to specification	Road-lighting quality
Valid monitoring data	%	Contractual threshold	Monitoring
Battery replacement	%/year	Monitoring indicator, not a stand-alone target	Durability
Maintenance cost	FCFA/point/year	Measured	LCC
Component conformity	%	100% required for critical requirements	Quality/safety

The contracting model delineates distinct remuneration streams for equipment supply, service availability, and the management of non-conformities. A fixed tranche can be combined with a tranche indexed to verified performance outcomes. The choice of coefficients and the calibration of any penalty regime must be derived from contract-specific legal, financial, and risk assessments. The framework set out here identifies the indicators to be monitored; it does not prescribe penalty rates without evidentiary support.[24,28, 30]

10. National Protocol for Ex Post Evaluation

- Develop a georeferenced registry by assigning each lighting point a unique identifier linked to its lot, supplier, and commissioning date.
- Establish an acceptance baseline that records technical specifications, photographic documentation, serial numbers, photometric measurements, energy autonomy, and the status of remote monitoring.
- Collect monthly data on operating hours, alarms, downtime intervals, maintenance interventions, components replaced, and documented failure causes.
- Undertake an annual audit using a stratified sample by region, installation age, supplier, battery technology, and roadway classification.
- Compute annually the realized life-cycle cost, service availability, mean time to repair, failure incidence, battery replacement frequency, and compliance with photometric requirements.
- Publish aggregated indicators to enable year-over-year tracking while safeguarding commercially sensitive information.

11. Validation Scenarios

Scenario	Purpose	Measurements	Expected outcome
V1	Initial acceptance	Photometry, autonomy, conformity	Baseline
V2	Hot season	Battery temperature, autonomy	Thermal robustness

V3	Dust/soiling	PV current, cleaning	Generation loss
V4	Remote-monitoring failure	Detection and intervention	Continuity of operation and maintenance
V5	Battery ageing	SOH, autonomy, replacement	Actual cost
V6	Audit after several years	Corrosion, structure, LED, battery	Residual performance

12. DISCUSSION

In economic terms, the 2015 analysis indicates a comparative advantage for solar lighting within the configurations evaluated. This conclusion is strictly contingent on the historical assumptions used in that report. Any assessment of current tenders must weigh acquisition price alongside operating costs, replacement cycles, and the level of service actually delivered. A discounted life cycle cost for lighting that remains compliant and available offers the most robust basis for comparison.[1,17,18,24]

Scaling the fleet requires a maintenance system capable of managing large numbers of geographically dispersed assets. Aggregated national indicators can mask difficulties concentrated in specific lots or sites. Disaggregated monitoring by supplier, region, technology, and installation age would reveal recurrent failure patterns and support causal analysis. Remote monitoring adds value only if alarms lead to timely interventions, spare parts are accessible, and restoration of service is verified.[2, 4,24,29,30]

Quality must be controlled beyond initial acceptance. Certificates or factory tests confirm conformity at a single point in time; repeated measurements after one, three, five, and ten years indicate whether performance endures. Associating these observations with serial numbers and procurement lots helps differentiate isolated incidents from systematic design or manufacturing defects. Such traceability aligns standardization requirements with conditions observed in the field.[5–16,19,25, 27]

12.1. Recommendations

- create a national geospatial registry and preserve the complete intervention history for each streetlight;
- incorporate quantitative, verifiable commitments on nighttime availability and photometric performance in contracts;
- plan battery replacement cycles and end-of-life management;
- exploit remote monitoring data to track MTTR, periods of unavailability, and recurring failure modes;
- link conformity test results to individual lots and to performance measured in the field;
- size spare parts inventories using observed failure rates;
- conduct independent annual audits based on stratified sampling;
- provide access to an aggregated dashboard reporting the performance of the national fleet.

12.2. Limitations

This analysis is constrained by the lack, in the reviewed documentation, of an open, consolidated national database that covers failures, repair times, maintenance costs, battery temperatures, photometric measurements, and replacements. The sensitivity analyses illustrate economic mechanisms, not the realized performance of the Senegalese fleet. Deployment figures reflect the situation reported for 2025 and do not constitute an updated 2026 inventory. Finally, 2015 cost figures are used without reindexation because no homogeneous contractual dataset is available to justify a robust conversion.

13. CONCLUSION

Given the scale of Senegal's solar street-lighting fleet, continuous monitoring across the full service life of the installations is necessary. Counts of accepted units indicate deployment progress, while availability and photometric measurements reflect the service actually received by users. The 2015 economic benchmarks clarify the underlying cost structure, and the 2025 figures, with more than 150,000 units installed, underscore the need for structured maintenance, systematic monitoring, and lot-level traceability.[1, 7,17, 30]

The proposed framework relates life cycle costs to availability, reliability, maintainability, and lighting quality, while explicitly incorporating battery ageing and component conformity. Applying it across multiple lots and regions would enable comparisons of bids and technologies based on verifiable outcomes. Future work will prioritise field data collection to estimate failure distributions, actual expenditures, and ageing trajectories.[15, 20,24, 30]

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