Lifecycle Cost Optimization of Energy-Efficient Electrical Building Services in Saudi Arabia: A Sustainable Engineering Framework.

Abstract

Electrical building services are frequently procured using initial capital cost even though energy consumption, maintenance, component replacement and operational disruption continue throughout a building's service life. This review examines how life-cycle cost optimisation can improve decisions about lighting, power distribution, electrical controls, metering, renewable-energy interfaces and associated building-service systems in Saudi Arabia. A structured integrative review was undertaken using relevant peer-reviewed Saudi and international studies, building-energy guidance and life-cycle costing standards. The evidence suggests that energy-saving options must be evaluated against local tariffs, duty cycles, desert-climate conditions, equipment reliability and realistic maintenance obligations rather than simple payback alone. Saudi case studies demonstrate that technical energy savings do not always yield a positive investment net present value, while integrated envelope-and-services interventions can materially alter the economics of electrical infrastructure. This paper proposes a five-stage engineering framework combining baseline definition, functional equivalence, discounted cash-flow modelling, sensitivity testing and post-occupancy verification. An explicitly hypothetical decision example illustrates why the preferred option may change with discount rate and replacement assumptions. The proposed approach supports more transparent electrical tender evaluations, operational resilience and evidence-based sustainability decisions aligned with Saudi Vision 2030. The framework requires project-specific validation before deployment.

Keywords: Life-cycle costing; Electrical building services; Energy efficiency; Saudi Arabia; Value engineering; Discounted cash flow; Building energy management; Vision 2030.

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1. Introduction

Saudi Arabia's expansion of airports, healthcare facilities, hospitality developments, industrial campuses and public infrastructure creates a sustained requirement for dependable electrical building services. These services extend beyond cables and switchboards: lighting, power quality, control networks, monitoring equipment, drives, renewable-energy interfaces and the electrical demands of mechanical systems are all part of a building's operational performance. Choices made during concept estimation and tendering can determine decades of subsequent electricity expenditure and maintenance demand. A lowest-price procurement strategy may therefore transfer costs from construction budgets into facility-management budgets rather than eliminate them.

The economic importance of building efficiency is well established. The International Energy Agency (IEA, 2025) estimates that buildings account for approximately 30% of global energy demand. In hot climates, cooling-related electrical demand often coincides with high solar exposure and challenging equipment operating conditions. The economic value of efficient equipment nevertheless depends on how it is used, not merely on its nominal laboratory efficiency. Electrical systems installed in intermittently occupied facilities, constantly operating hospitals and critical industrial buildings follow markedly different load profiles.

Saudi regulatory requirements provide a necessary baseline. The Saudi Code for Energy Conservation for nonresidential buildings, SBC 601, addresses lighting and other building-energy provisions alongside the envelope and mechanical services (Saudi Building Code National Committee, 2024). Compliance is necessary but does not, by itself, identify the least expensive compliant solution over a chosen analysis period. ISO 15686-5:2017 provides a general basis for comparing costs across the building life cycle. Combining regulatory compliance with disciplined financial modelling offers a more useful basis for early project decisions.

Recent Saudi research demonstrates both the opportunity and the methodological challenge. Alfalaha, Al Qahtani and Al-Sakkaf (2024) combined life-cycle costing and environmental assessment for a Saudi office-building case, showing that construction-material and envelope selections can change long-run costs. A separate Saudi residential retrofit study reported attractive compound payback in some scenarios but negative net present values for many examined cases (Journal of Building Engineering, 2025). Such differences matter because an undiscounted or simplified recovery metric can conceal replacements, the time value of money and divergent operating assumptions.

The central argument of this review is that life-cycle optimisation should be embedded in electrical estimating, technical evaluation and facility handover, rather than applied as a retrospective sustainability calculation. The proposed framework considers capital expenditure and operating expense together, while treating safety, code compliance, functional adequacy and reliability as mandatory constraints.

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2. Literature Review

2.1 Life-cycle costing and whole-life value

Life-cycle costing (LCC) evaluates expenditure over a defined study period, commonly including initial acquisition, installation, energy, inspection, preventive and corrective maintenance, replacement, and end-of-life costs, with any residual value treated explicitly. ISO 15686-5:2017 emphasises defined boundaries and consistent comparison of alternatives. Whole-life value extends the conversation to outcomes such as indoor environmental quality, operational continuity, future flexibility and emissions. These wider factors may be assessed separately where defensible financial values are unavailable; forcing every benefit into a monetary figure can create false precision.

The choice of analysis period is consequential. A thirty-year building assessment may include several replacements of controls, lamps, drivers, battery systems or electronic communication components, while cables and suitable switchgear can outlast the same period. Replacement timing depends on duty, thermal conditions, manufacturer support, operating practice and maintenance regimes. An engineering comparison should apply common building-level assumptions while preserving different component lives. Identical assumed lifetimes across all components will usually obscure important trade-offs. (International Organization for Standardization, 2017; United States Department of Energy, 2025).

2.2 Lighting systems and responsive controls

LED lighting and advanced controls present a clear illustration of the difference between equipment efficiency and delivered performance. High luminous efficacy is beneficial, but useful savings also depend on room occupancy, operating hours, daylight availability, dimming strategies, commissioning and user behaviour. In airports and hospitals, safety and illumination requirements constrain acceptable control sequences. In offices and shared spaces, occupancy-based reduction can be appropriate if sensors and controls operate reliably. Maintenance savings must account for drivers, controls, access equipment and cleaning, not only theoretical lamp replacement intervals. (Almushaikah & Almasri, 2021; International Energy Agency, 2024).

For tender evaluation, designers should compare lighting solutions with equivalent illuminance, uniformity, colour rendering, glare conditions and emergency-lighting provisions. A system that reduces energy by underlighting work areas is not a legitimate efficiency improvement. Similarly, a low-priced control package can generate extra lifetime costs when commissioning effort, software licences, unavailable spare parts and repeated sensor failure are omitted. A life-cycle comparison therefore requires a clear service definition before costs are estimated.

2.3 Power distribution, transformers and power quality

Electrical distribution introduces a different cost profile. Transformers, cables and protective assemblies have high upfront material and installation costs, whereas load losses, no-load losses and maintenance recur over their operating lives. The most economical cable cross-section can be larger than the minimum code-compliant conductor because lower resistance can reduce I^2R losses. However, oversizing without load analysis can increase materials, installation space and embodied impacts without proportionate operating savings. Engineers must evaluate realistic load diversity and future utilisation rather than assume continuous full-load operation. (Saudi Building Code National Committee, 2018c).

Distribution decisions should consider voltage drop, fault levels, protection coordination, harmonic currents, thermal derating and continuity of service. A highly efficient transformer may

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justify a higher purchase price in a continuously loaded facility but offer weak savings where utilisation is low. Power-factor correction and harmonic mitigation can reduce technical losses and improve service quality in suitable applications, yet benefit estimates should reflect actual power-quality measurements and local utility charging rules. Reliability outcomes, particularly in critical infrastructure, require separate risk analysis because outage consequences can dominate modest energy savings.

2.4 Smart metering, automation and operational intelligence

Building management systems, submetering and diagnostic dashboards enable operators to observe consumption that would otherwise remain concealed in aggregated utility bills. Their economic case is strongest when measurements lead to interventions: correcting schedules, identifying abnormal loads, improving set points and detecting deteriorating equipment. Merely installing sensors does not guarantee cost reduction. Data governance, calibration, commissioning, integration with existing protocols, cybersecurity and operator training are recurring resource requirements.

The physical infrastructure and software stack should be evaluated together. A low-cost controller may impose proprietary integration fees later; an advanced monitoring platform may provide extensive analytic features that remain unused. Tendering teams should document point lists, alarm responsibility, data retention, interoperability and licensing. Where predicted reductions depend on behavioural or operational changes, the investment case should identify the team responsible for maintaining those changes after handover.

2.5 Solar integration and climate-sensitive design

Distributed photovoltaic systems create opportunities for offsetting daytime building electricity demand. Al-Hanoot et al. (2024) reviewed distributed PV in Saudi Arabia and reported substantial regional variation in utilisation, performance and economic conditions. The appeal of PV depends on usable roof area, orientation, dust accumulation, cleaning, inverter replacement, export rules, tariffs and the degree of coincidence between generation and load. A uniform energy-yield assumption is inappropriate across differing locations and building types.

Integrated building design modifies these equations. Envelope insulation, glazing and shading can lower cooling loads, permitting changes in electrical and mechanical plant sizing. Alfalaha et al. (2024) found that an optimised combination of envelope and structural measures improved lifecycle performance in a Saudi office-building scenario. From an electrical perspective, load reduction changes cable sizing, transformer utilisation, standby-generation requirements and the business case for on-site generation. These interactions show why LCC should be performed at system level rather than as a catalogue comparison of isolated products.

2.6 Constraints in Saudi construction procurement

Electrical estimators frequently work from tender drawings, quantities, supplier quotations and technical specifications prepared under strict deadlines. Decisions may be fragmented between design consultants, main contractors, specialist subcontractors and operators. Consequently, procurement documents sometimes specify particular equipment without a consistent definition of utilisation, energy baseline or maintenance responsibility. Value engineering may be restricted to immediate cost reduction because the eventual operating organisation is not involved in selecting alternatives.

A further issue is uncertainty in local assumptions. Electricity tariff categories, equipment supply chains, imported replacement parts, maintenance labour arrangements and future functional

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changes affect the results. An apparently precise lifecycle figure can therefore be misleading if key assumptions are undocumented. The appropriate response is not to abandon modelling, but to use ranges, sensitivity analysis and transparent scenario definitions.

Recent international evidence reinforces the importance of discounting and environmental boundaries. The United States Department of Energy (2025) maintains building life-cycle costing tools, while ISO 14040 and ISO 14044 distinguish environmental life-cycle assessment from financial LCC (International Organization for Standardization, 2006a, 2006b). These complementary methods should not be merged into a single unqualified savings claim.

Renewable-energy pricing provides context rather than direct evidence for building-specific economics. The International Renewable Energy Agency (2024, 2025, 2026) documents changing generation and storage costs, but local tariff structures, space, load profiles and maintenance requirements govern project decisions. Global assessments also emphasise the construction sector's operational and embodied impacts (United Nations Environment Programme, 2025, 2026; National Institute of Standards and Technology, 2024).

For Saudi applications, commercial and low-rise energy conservation requirements must be distinguished from electrical safety provisions (Saudi Building Code National Committee, 2018a, 2018b, 2018c, 2021). Relevant evidence from Saudi residential efficiency, photovoltaic economics and office-building lifecycle studies should be interpreted by building type and study scope (Almushaikah & Almasri, 2021; Alfalaha et al., 2024; Ahmed & Asif, 2025; Al-Hanoot et al., 2024; Almohammadi & Allouhi, 2025). A broader systematic review confirms that life-cycle energy estimates remain sensitive to data quality and tool selection (Life cycle energy analysis of buildings, 2024).

3. Research Methodology

3.1 Research design

This study adopts a structured integrative review, reflecting the intersection of engineering design, financial appraisal, energy policy and Saudi construction practice. It synthesises published findings into a conceptual decision framework; it does not report new field measurements, original survey responses or a completed systematic-review census. This distinction is maintained throughout the findings and figures.

3.2 Data sources and evidence selection

Evidence was assembled from identifiable peer-reviewed research on Saudi building energy performance, life-cycle economics and distributed renewables, supported by authoritative technical and policy publications. Sources include the journal articles by Alfalaha et al. (2024) and Al-Hanoot et al. (2024), the Saudi residential retrofit analysis published in 2025, the Saudi Building Code resources, the IEA buildings assessment and ISO 15686-5:2017. The search was directed towards publications available up to October 2026, with particular emphasis on the 2020–2025 evidence period and foundational standards retained where essential.

Search concepts combined "Saudi Arabia", "building", "life-cycle cost", "energy retrofit", "electrical services", "lighting", "power distribution", "solar photovoltaic", "net present value" and "energy efficiency". Relevant materials were selected for direct bearing on building-service investment choices, credible methods and an identifiable publication source. Documents addressing solely unrelated energy technologies or lacking interpretable methods were not used as primary evidence. Because no comprehensive database export or reproducible screening log was produced, this paper does not claim exhaustive coverage or invent counts of identified and excluded records.

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3.3 Analytical synthesis

Evidence was organised into five analytic themes: functional performance, cost categories, operational energy, uncertainty and governance. Claims about measured savings were distinguished from proposed engineering procedures. The proposed LCC model adopts a consistent real- or nominal-currency basis, cash-flow timing, component replacement schedule and residual-value convention. Alternative solutions are screened for technical compliance before financial ranking. An illustrative scenario is included solely to demonstrate the calculations, not to represent an actual Saudi project.

3.4 Economic evaluation

For a study period N and real discount rate r, the present-value lifecycle cost can be expressed as LCC = C0 + Σ[(Et + Mt + Rt + Ot)/(1+r)^t] − SN/(1+r)^N, where C0 is initial capital cost; Et energy expenditure; Mt maintenance; Rt replacement expenditure; Ot other recurring operating cost in year t; and SN the residual value in the final year. When nominal annual cash flows are used, a consistent nominal discount rate is required. Net present value of an efficiency upgrade equals the discounted avoided baseline costs and any residual benefit less the incremental investment and extra operating or replacement costs.

Energy-cost predictions are sensitive to load factor, operating hours and tariff assumptions. Sensitivity tests should therefore vary discount rate, annual electricity consumption, real tariff growth where applicable, equipment lifetime, maintenance cost and observed versus expected savings. For critical systems, a compliant and sufficiently reliable design is a condition of eligibility for comparison, not a discretionary economic benefit that can be traded away.

4. Results and Discussion

4.1 Synthesis of Saudi evidence

The reviewed evidence supports the practical importance of integrated evaluation but does not support a universal percentage saving for every electrical installation. Alfalaha et al. (2024) found a cost advantage for selected Saudi office building configurations when comparing structural and envelope alternatives, and reported differences between initial-cost rankings and operational energy results. That study addresses building-level interactions rather than proving that a specific lighting fixture or transformer choice is universally superior.

The 2025 residential retrofit LCC study provides a useful caution: reported energy savings and relatively short compound payback periods did not automatically yield positive net present value for many examined options. This may arise because discounted cash-flow methods recognise the timing of expenditure and benefits more rigorously than simplified payback measures. Project teams should therefore report both a readily understandable recovery indicator and a complete discounted metric, with the latter governing economic ranking when assumptions are sound.

The distributed-PV review by Al-Hanoot et al. (2024) shows the significance of local solar and tariff conditions. Its findings cannot be directly transferred to all electrical subsystems; rather, they illustrate the need for region-specific performance assumptions, degradation assessment and replacement provisions. Collectively the selected studies suggest that a combined engineering–financial model is more defensible than a first-cost procurement comparison.

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4.2 Comparative decision criteria

Before ranking bids, evaluators should establish equivalent duty, safety, interoperability, warranty, equipment availability and maintenance access. Incomplete comparison boundaries can reward a supplier that omits required commissioning or software renewals. Table 1 distinguishes the categories that an electrical estimator should document for each technical option. The table is a proposed checklist rather than an empirical distribution of costs.

Table 1. Whole-life evaluation checklist for electrical building services

Cost or performance element	Evidence required	Decision risk if omitted
Capital and installation	Priced bill of quantities, installation and commissioning scope	Misleading lowest-bid ranking
Energy and demand	Load profile, operating hours, efficiency data, tariff basis	Unrealistic energy savings
Maintenance and spares	Service schedule, parts, labour and access requirements	Underestimated operating cost
Replacement and obsolescence	Expected service life, software support, inverter/driver replacements	Hidden mid-life expenditure
Reliability and compliance	Protection, continuity, standards and criticality	Unsafe or non-equivalent comparison
Residual value and disposal	Demolition, recycling, salvage assumptions	Biased end-of-period costs

4.3 Illustrative discounted-cost comparison

To explain the method, consider two functionally equivalent lighting and control solutions in a hypothetical nonresidential facility. Option A has initial cost of SAR 400,000 and annual combined energy and maintenance expenditure of SAR 85,000. Option B requires SAR 520,000 initially but annual combined expenditure of SAR 66,000. Assuming a twenty-year analysis period, a constant real discount rate of 5%, and no replacement or residual-value difference, the present-value annuity factor is approximately 12.462. Total discounted costs are therefore approximately SAR 1.459 million for A and SAR 1.342 million for B. The incremental initial cost of B is SAR 120,000; its annual saving is SAR 19,000; and its discounted net benefit relative to A is about SAR 117,000.

These figures are invented solely for pedagogical illustration and should not be presented as Saudi market quotations or observed research outcomes. The simple undiscounted payback of B is roughly 6.3 years, but payback alone cannot confirm the outcome when replacement profiles differ. If B required a substantial control-system replacement after ten years, the advantage might narrow or disappear. Equally, an increase in annual usage or energy expenditure could strengthen its value. This is why the bid recommendation should include a break-even analysis and documentation of uncertainty.

Table 2. Hypothetical twenty-year alternative comparison (not field data)

Measure	Option A	Option B
Initial capital cost	SAR 400,000	SAR 520,000
Annual energy plus maintenance	SAR 85,000	SAR 66,000
Discount rate / horizon	5% / 20 years	5% / 20 years
Present-value lifecycle cost	≈ SAR 1,459,000	≈ SAR 1,342,000
Difference relative to A	Reference	≈ SAR 117,000 lower
Key qualification	No replacements modelled	No replacements modelled

4.4 Interdependence of technical options

Treating lighting, distribution, controls and renewable generation as independent procurement packages can miss important interactions. Reducing lighting heat gains may influence cooling demand; lowering cooling demand may change electrical plant sizing; better power monitoring

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may reveal avoidable equipment use; rooftop PV benefits depend on daytime load. Integrated assessment should capture these relationships without double counting savings. For example, an efficiency reduction that already appears in an updated energy model should not be added again as a separate percentage saving from another specification.

Value engineering should also consider the cost of construction disruption, spare-parts logistics, access constraints and operational continuity. A low-cost component may create unusually high maintenance expense if reaching it requires closure of an occupied terminal or specialised lifting equipment. In the same way, a premium solution may fail to justify its price in a lightly used building. A decision framework is therefore valuable precisely because it resists automatic assumptions that either cheapest or most efficient equipment is always optimal.

4.5 Risk and uncertainty

A deterministic cost estimate is an incomplete account of the future. Sensitivity testing should begin with factors that plausibly determine the outcome: annual energy use, electricity price, operating schedule, discount rate and replacement intervals. Scenario analysis can distinguish a base case from high- and low-use conditions and from conservative maintenance assumptions. Where uncertainty is material, project teams may calculate the switching value at which the preferred option changes. This produces a practical procurement question: how much energy-saving underperformance can the proposed upgrade tolerate before its higher capital cost becomes uneconomic?

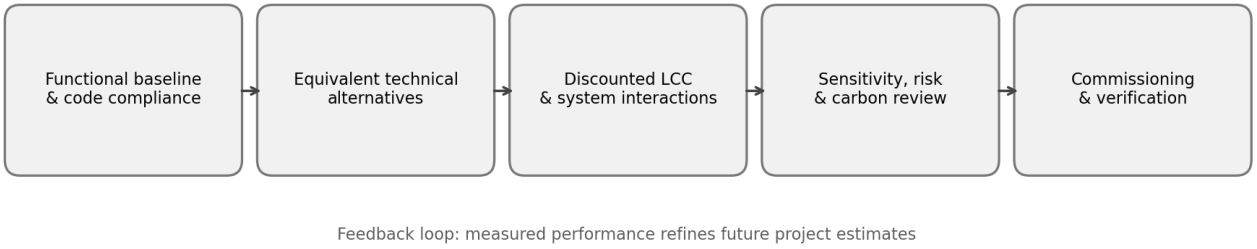
For projects with long construction lead times, procurement risk should be considered explicitly. Supplier substitution, commissioning delays, warranty limitations and equipment obsolescence can alter lifecycle expectations. Risk allocation in contracts matters as much as spreadsheet calculations. Performance requirements can be expressed through measurable efficiencies, acceptance testing, minimum supported service lives and metering arrangements. Without credible verification, promised efficiency savings remain marketing assumptions rather than accountable project outcomes.

5. Proposed Sustainable Engineering Framework

The proposed framework begins with a verified operational requirement and ends with measured performance. It deliberately links estimating activities, technical submittals and facility-management obligations so that energy and replacement assumptions are preserved across handover. Five gates are recommended: (1) functional and compliance baseline; (2) evidence-based alternatives; (3) whole-life economic evaluation; (4) uncertainty, reliability and sustainability review; and (5) commissioning, measurement and feedback. An alternative is not allowed to progress solely because it performs well at a single financial gate.

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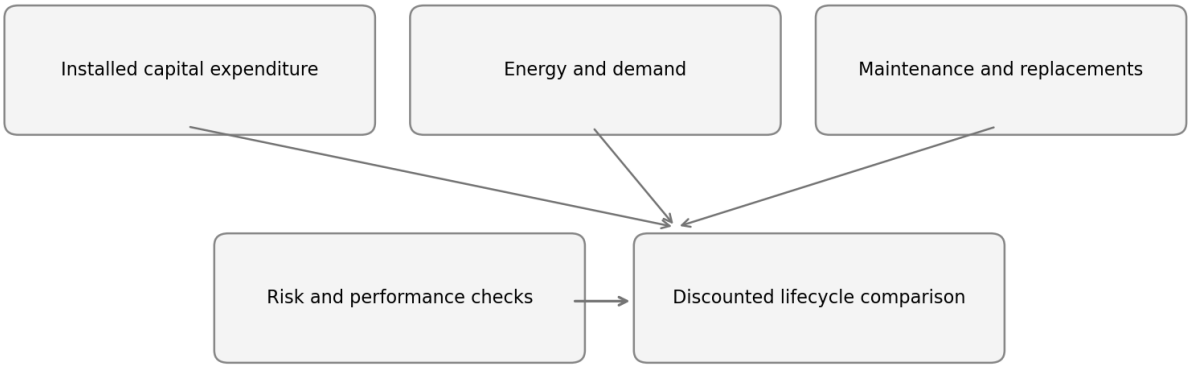
Figure 1. Proposed five-gate lifecycle-cost decision framework.



At the first gate, the estimator and designer define loads, occupancy, energy baselines, room functions, environmental conditions and applicable codes. At the second, suppliers submit technically equivalent systems, complete with energy data and required accessories. At the third, capital and recurrent cash flows are compared on a common basis. At the fourth, analysts test uncertainty, failure consequences and environmental considerations. At the fifth, commissioning records and measured energy data determine whether the predicted performance is credible.

The framework also specifies responsibilities. Designers maintain the technical baseline; estimators consolidate whole-life costs; procurement teams verify commercial completeness; contractors document installation and commissioning; and operators validate actual usage and maintenance. A shared assumptions register should move between these teams, preventing the original business case from being lost when the project changes hands.

Figure 2. Conceptual information inputs for a discounted electrical-services assessment.



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6. Recommendations

6.1 Require lifecycle comparisons at concept and tender stages

Saudi project owners should request a short, auditable lifecycle comparison for major electrical alternatives with material operating-cost differences. The comparison should include functional requirements, analysis period, discount assumptions, load profiles, tariff basis and replacement schedule. A procurement team can then distinguish legitimate savings from proposals that merely remove scope.

6.2 Improve energy and operating data

Project teams should collect metered demand, operating-hour and maintenance information from comparable assets where permission allows. Design-stage forecasts should be recorded separately from measured post-occupancy performance. Region-specific weather, dust exposure and occupancy patterns should inform annual simulations. Better datasets would improve cost estimating as well as facilities management.

6.3 Integrate electrical and mechanical design decisions

Design reviews should assess electrical distribution together with major building energy loads. Lighting controls, cooling efficiency, energy monitoring and PV integration should be coordinated so that capacity decisions and savings are not calculated in isolation. Alternatives should remain compliant with Saudi electrical, energy and fire-safety requirements.

6.4 Make operating responsibilities explicit

Owners should include operator training, metering handover, maintenance access and software support in procurement specifications. Where savings require ongoing controls adjustments or periodic calibration, these activities must have assigned budgets and responsible personnel. A measured verification plan is more persuasive than an unqualified promise of savings.

6.5 Link finance with sustainable infrastructure goals

Decision-makers can add a parallel environmental assessment when emissions or resource outcomes are material. Life-cycle carbon and lifecycle cost are complementary indicators, not interchangeable quantities. Public programmes aligned with Vision 2030 may prioritise measurable system efficiency, technical resilience and long-term affordability while retaining transparent reporting of additional capital needs.

7. Future Directions

Research is needed on representative Saudi nonresidential buildings, including airports, hospitals, educational campuses, logistics facilities and major mixed-use developments. Prospective studies should follow installed electrical systems beyond commissioning, reporting real energy, maintenance, replacement, reliability and user-service data. Comparisons would be stronger if authors documented tariff category, exact building use, discount convention and system boundary alongside their financial outputs.

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A particularly valuable research direction is integration of cost estimating with Building Information Modelling and digital asset registers. Quantity take-offs could be linked to equipment efficiency, service life, maintenance instructions and measured submeter data. Such integration would require standardised asset identifiers and robust data governance. Prediction models should be assessed on independent projects to determine whether they reduce estimating error rather than merely fit historical data.

Further analysis should evaluate the robustness of lifecycle rankings under alternative market and climate conditions. Researchers could study whether supplier support periods, dust-related maintenance, seasonal occupancy and different levels of building automation materially change the preferred technology. Multi-objective approaches may consider cost, energy, carbon and resilience simultaneously, provided the trade-offs remain explicit and safety is never relaxed to improve an optimisation score.

8. Conclusion

Lifecycle cost optimisation offers a rigorous basis for selecting energy-efficient electrical building services in Saudi Arabia. The literature indicates that initial capital cost, annual electricity consumption, maintenance, replacement and technical reliability must be examined together over a defined period. Saudi building studies also demonstrate that measured or modelled energy savings are not identical to financial viability: tariff assumptions, project context and discounted cash flow can materially change the outcome.

This paper proposes a five-gate framework that links compliance and functional equivalence with comparative lifecycle cost, uncertainty testing and post-occupancy verification. It is particularly relevant to electrical estimating, tender evaluation, design validation and commissioning because decisions in these activities can affect the future operating burden of buildings for decades. Its central contribution is a transparent engineering decision process, not a claim of newly measured savings or a universal optimal technology.

The next priority is empirical validation using Saudi facility data and realistic maintenance histories. With suitable implementation, lifecycle analysis can help project teams choose solutions that are technically reliable, economically defensible and supportive of Vision 2030 objectives for efficient, sustainable infrastructure.

Published Saudi case-study evidence (secondary analysis)

Ahmed and Asif (2025) examined Saudi residential retrofit scenarios using life-cycle costing, net present value and payback. They reported an approximately five-year average payback but negative net present value for many configurations. The apparent contradiction is relevant to this paper: a measure may recover nominal cost quickly while remaining unattractive after discounting and other assumptions. The findings are published case-study results, not measurements collected by the present author, and cannot automatically be transferred to an electrical-only building-services package. Source: https://doi.org/10.1016/j.jobe.2025.113316.

A subsequent Saudi villa investigation used electricity bills to calibrate an energy model and evaluated staged retrofit alternatives (Aloshan and Aldali, 2026; https://doi.org/10.1038/s41598-026-45057-4). These studies show how authenticated meter records, equipment specifications and option-specific investment costs can support stronger engineering evaluations. An independent

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building-services dataset remains necessary to quantify the specific economic contribution of lighting, controls and electrical distribution.

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