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Lifecycle Cost (LCC) and Carbon (LCA) Integrated KPI Framework for Metro Assets

AMMAR ISMAIL DALVI
Ph.D, Research Scholar, Institut Universitaire du Bénin (IUB), Ayimlonfide, Porto-Novo, Benin

Abstract- ***Metro systems must move large numbers of people, meet net-zero goals, and remain affordable throughout their lifespans. Yet, financial and carbon checks are often done separately, making it harder to make sound choices about buying equipment, upgrading signals, improving power systems, or renovating stations. Without considering both costs and carbon impacts together, organizations save money in the short term but face higher energy or upkeep costs later, or run into surprising operational problems. This review brings together research and trade publications from 2020 to 2025 that use life-cycle assessment (LCA), life-cycle cost (LCC), or combined procedures for rail and metro systems. It follows the PRISMA 2020 and PRISMA-S guidelines to examine key choices, such as which metrics are used, how system perimeters are set (including maintenance, upgrades, and end-of-life), how electricity conceptions and peak demand are handled, and how future costs are estimated. The review also examines how studies address uncertainty and convert LCA and LCC results into key performance indicators (KPIs). A structured coding method is used to systematically compare studies. The review indicates the avoidance of various important impact areas. For subterranean and building-heavy projects, construction materials, including concrete and steel, are major contributors. Operational emissions depend primarily on electricity sources, peak demand, additional station equipment, and energy recovered from braking. The main cost drivers are how often parts need to be replaced and the price of energy, while service operational disruptions are capable of markedly raising costs. Analogizing results across studies remains difficult due to distinctions in limitations and data origins. The Metro Eco-Value KPI Framework (MEVKF) has four main parts: a set of KPIs for different metro system areas, a basic data inventory for each asset group, clear rules for updating KPIs, and a visualization tool to show cost and carbon trade-offs, including uncertainty and scenarios. The framework is meant to be rolled out in stages. Agencies can start with a core set of KPIs (like NPV and GWP with context) and add more metrics over time—such as energy use, peak direction, reliability, and renewals—using digital tools like BIM and asset registers to make data collection easier.***

Keywords: Life Cycle Costing; Life Cycle Assessment; Metro Rail; Embodied Carbon; Operational Emissions; Asset Management; Eco-Efficiency; KPI Framework; Traction Power; Stations; Signalling; Rolling Stock.

I. INTRODUCTION

Urban rail and metro systems play a key role in reducing carbon emissions by promoting mass transit ridership and supporting urban densification. However, metro construction is associated with substantial embodied carbon, particularly for underground lines, stations, and power infrastructure. Operational emissions are also variable, contingent on electricity sources, peak demand, and operational practices. For instance, metros powered by fossil-fuel-based electricity or distinguished by high station energy consumption may exhibit higher-than-anticipated emissions. Consequently, decision-making has to include both construction and operational carbon across all asset categories. Besides, metro organizations face whole-life affordability strains. Energy price volatility, maintenance escalation, climate-related degradation, and technology refresh cycles (signalling, communications, cybersecurity) can materially shift costs over the asset life. Therefore, decision-making that focuses only on CAPEX or is only concerned with operational energy is insufficient. What is required is a decision-ready sustainability logic that combines whole-life costs and whole-life carbon in a way that is comparable...

Life-cycle assessment (LCA) and life-cycle cost (LCC) are primary tools for evaluating metro assets across their full lifespan. In practice, these assessments are often conducted by separate teams using differing boundaries, time frames, and comparison methods. Although approaches such as eco-efficiency seek to merge these perspectives, research demonstrates that integration methods (e.g., ratios or weighted sums) can alter rankings and introduce sensitivity to methodological choices. The Metro Eco-Value KPI Framework (MEVKF) is designed for metro assets, including trains, signalling, power, and stations. Its objective is not to produce a single universal score, but to show a repeatable KPI process that helps set consistent boundaries, clarifies assumptions, and enables reliable comparisons and decision support over time. By conforming KPI definitions with asset types and specifying data sources and cost years, MEVKF keeps both engineers and stakeholders in guiding sound decisions and assuring explicit reporting.

1.1 Aim of the study

The aim of this review is to develop a decision-ready, integrated KPI framework that combines LCC (economic performance) and LCA-derived carbon metrics (environmental performance) for metro assets, enabling consistent benchmarking and transparent trade-off analysis across rolling stock, signalling, traction power, and stations.

1.2 Objectives

· Identify and classify how studies (2020–2025) define functional units and system scopes for LCC and LCA in rail/metro contexts.

· Synthesize reported hotspots and dominant cost/carbon drivers across the four metro asset domains.

· Review integration mechanisms (eco-efficiency, monetization, MCDA, visualization) that connect LCC and LCA outputs to decisions.

· Propose a KPI taxonomy, minimum inventory fields, and governance rules to improve comparability and auditability.

· Provide an illustrative KPI accounting template that agencies can adjust in procurement and asset-management workflows.

1.3 Research questions

· RQ1: What functional units and boundary conventions best support cross-asset comparability in metro systems?

· RQ2: Which life-cycle stages and inventory variables dominate cost and carbon results for each asset domain?

· RQ3: Which integration methods provide robust, interpretable decision support considering uncertainty and changing electricity mixes?

·RQ4: What governance courses are necessary for auditable, repeatable LCC+LCA KPI reporting over time?

II. METHODOLOGY

This review adheres to frequent review declarations, employing PRISMA 2020 as the primary reporting framework and PRISMA-S for search transparency (Page et al., 2021; Rethlefsen et al., 2021). The chief purpose is framework synthesis rather than effect-size pooling; therefore, a narrative synthesis with structured coding is utilized.

2.1 Eligibility criteria. Studies were included if they (i) applied LCA, LCC, or an integrated approach to rail/metro or closely related transport infrastructure and energy systems; (ii) reported modelling choices relevant to metro asset decisions (functional unit, border, renewal cycles, electricity scenarios, discounting); and (iii) were published between 2020 and 2025 or were traditional sector reports released in that period. Studies were excluded if they only reported rapid operational emissions without a life-cycle skeleton or if they did not describe assumptions adequately for comparative interpretation.

2.2 Search strategy and screening. Search strings merged rail/metro terms (“metro”, “urban rail”, “railway infrastructure”, “rolling stock”, “traction power”, “substation”, “station building”, “signalling”, “CBTC”) with life-cycle terms (“life cycle assessment”, “embodied carbon”, “life cycle costing”, “net present value”, “eco-efficiency”, “integrated LCA LCC”) and governance terms (“carbon data standards”, “data quality”, “audit trail”). Screening took place in two stages: (a) title/abstract and (b) full-text eligibility.

2.3 Data extraction and coding. Each included source was coded on: functional unit; boundary conventions (A1–C4 and treatment of Module D credits where relevant); temporal horizon; discounting and price base year for LCC; inventory scope (materials, energy, labour, replacements, downtime); impact metrics (GWP as minimum); integration method (ratio/portfolio, weighted sum, monetization, MCDA, visualization); and governance practices (data provenance, uncertainty reporting, versioning).

2.4 Synthesis approach. Findings were synthesized in two ways: by asset domain (rolling stock, signalling, traction power, stations) and by cross-cutting method themes (functional unit selection, boundary completeness, uncertainty/scenario design, and integration form). The output is a set of framework design rules and minimum KPI requirements rather than pooled numerical averages.

2.1 Conceptual foundations for integration

Integration of economic and environmental life-cycle effects is commonly operationalized through eco-efficiency and analysis portfolios. Methodological work clarifies that eco-efficiency can be expressed as a ratio, a (weighted) sum, or a portfolio system, and that the choice affects ranking stability, sensitivity to weights, and understandability (Heijungs, 2022). In parallel, integration investigation outlines graphical conclusion aids that display LCA and LCC simultaneously, improving contact to stakeholders who are not specialists (Wu et al., 2023). In metro asset portfolios, such integration aids are valuable because decisions must often be justified transparently across engineering, finance, and sustainability governance.

III. CROSS-CUTTING SYNTHESIS: FUNCTIONAL UNITS, BOUNDARIES, UNCERTAINTY, AND GOVERNANCE

3.1 Functional units and normalization

A functional unit anchors comparability. In metro contexts, three families recur: (i) engineering units (per trainset-year, per route-km-year, per station-year, per substation), (ii) service units (per passenger-km or per passenger trip), and (iii) area-based units for stations (per m^2-year). Many analyses select a single unit without providing a transparent translation for others, making comparisons across studies difficult.

MEVKF therefore instructs dual reporting: an engineering unit for asset management and a service unit for policy narratives. Dual reporting reduces the risk of "hiding" infrastructure burdens inside ridership assumptions while still promoting mode comparisons when needed (e.g., rail vs BRT) under a compatible service unit (Yeboah & Kaewunruen, 2025).

3.2 Boundary completeness and life-cycle stages

Limit rituals are a key driver of comparability. The proof base shows frequent boundary truncation: some studies focus on construction but omit maintenance and end-of-life; others focus on operation but omit embedded impacts. Keeping and renewal are particularly important for metro procedures because many components have lifespans shorter than those of the civil structure. For example, signalling equipment and control centre ICT may refresh multiple times, while stations undergo refurbishment cycles driven by passenger knowledge standards and MEP segment lifetimes.

Rail and infrastructure carbon governance is evolving rapidly, but spread infrastructure still faces inconsistent boundary rules across standards and reporting schemes. A thematic analysis of carbon data requirements draws attention to the need for unified data schemes, clear data ontology, and translucent emission-factor provenance; without these, the same help can yield materially different results depending on boundary conventions and databases (Xu & MacAskill, 2024). Rail-specific work on consistent data collection similarly argues that repeatability requires standardized data capture and clear mapping from physical assets to carbon reckoning structures (Najafpour Navaei et al., 2024).

3.3 Uncertainty, scenario design, and update cycles

Decision-ready KPIs must carry suspense and scenario format. In metro backdrops, three strategy groups are critical: electricity mix scenarios (current grid vs forecast vs deep decarbonization), renewal/refresh scenarios (especially for digital systems), and climate/hazard scenarios that can alter supervision cost profiles. LCC research on climate transformation impacts shows that supervision and reanimation costs can shift materially under future stressors, implying that static LCC can misrank chances (Soleimani-Chamkhorami et al., 2024).

Update cycles should be defined in the KPI governance register. A practical rule is: update emission factors annually; reconcile functional energy and tariffs quarterly using billing and SCADA; update inventories from as-built data at commissioning; and re-estimate renewal schedules when trustworthiness trends drift. Sector reporting initiatives provide supporting infrastructure for benchmarking and reporting cadence (UIC, 2022), while national studies illustrate carbon footprint component structures suitable for adaptation (RISSB, 2022).

IV. SYNTHESIS BY METRO ASSET DOMAIN

4.1 Rolling stock

Rolling stock decisions include procurement, mid-life overhaul, and operational approach. Operational carbon is primarily electricity-driven and is sensitive to grid intensity and operational timing. Current research establish that "carbon-efficient" operation can differ from "energy-efficient" function when the grid's marginal generation varies with time and renewable availability. A case study in Applied Energy shows how timetable optimization can reduce emissions by coordinating traction demand with the availability of renewable generation, disclosing a demand-response aspect in rail–power integrated systems (Wu et al., 2025).

From the cost standpoint, rolling store LCC is driven by procurement CAPEX, organized maintenance and overhaul cycles, energy costs, and reliability-driven service tempests. KPI reporting should diverge physical performance (kWh/train-km) from market conditions (tariffs) by also reporting significant cost intensity (currency/train-km) and peak need contributions where applicable. For integrated KPIs, options can be compared on the eco-efficiency plane using NPV per trainset-year versus GWP per trainset-year, with scenario bands for electricity and service patterns. Such screening supports procurement shortlisting before applying qualitative criteria (comfort, accessibility, supply-chain stability).

4.2 Signaling

Signalling and train control assets are often considered low-carbon because of their modest direct energy use. However, embodied impacts of electronics, server infrastructure, cabling, and redundancy can turn substantial when refresh cycles are short. Signalling also influences system performance indirectly: headway reduction and functional steadiness can reduce stop-start driving, dwell variability, and knock-on delays; these developments may reduce traction energy and improve service reliability, yielding sidestepped carbon and avoided cost.

The literature provides fewer metro-specific integrated LCA–LCC studies for signalling than for civil infrastructure. Nevertheless, integration mechanics are supported by model-based and BIM-enabled workflows that enable traceable variant comparison, even when the system is largely electromechanical and ICT-driven (Viscuso et al., 2022). Automated, continuous model-based carbon assessment also supports keeping inventories current as designs evolve, which is particularly relevant for systems with frequent configuration changes (Hussain et al., 2023).

MEVKF recommends a three-layer KPI set for signalling: (i) direct KPIs (embodied carbon per route-km controlled; LCC per route-km), (ii) reliability/availability KPIs (MTBF, MTTR, delay minutes attributable), and (iii) conservative system-effect KPIs (estimated avoided traction energy owing to augmented refined operations). The third layer should be scenario-based and clearly labelled as an estimate rather than an audited accounting figure.

4.3 Traction power

Traction power systems connect metro operations to the wider energy transition. Life-cycle performance depends on equipment inventories, losses, peak demand, replacement schedules, and the carbon intensity of electricity. Comparative studies of traditional substations versus battery-based substations and wayside energy storage show that both costs and environmental impacts depend strongly on utilization, battery life, replacement frequency, and end-of-life handling, accentuating the need to explicitly consider keeping and regenerations (Pam et al., 2023).

Traction power also interacts with operational KPIs: regenerative braking benefits depend on receptivity and network voltage constraints, and energy storage can facilitate peak demand and enhance receptivity. Therefore, KPI reporting should include peak-to-average ratios, demand charges, and regeneration utilization indicators, not just annual kWh. Carbon accounting can be enhanced by accounting for changing over time electricity factors or marginal emissions, especially when operations are optimized to be consistent with renewables (Wu et al., 2025). Recent work proposes index systems for traction substations that integrate economic, efficiency, safety, environmental, and low-carbon considerations, indicating the growing adoption of life-cycle evaluation scorecards in traction asset management (Liu et al., 2025).

4.4 Stations

Stations are hybrid assets—both buildings and transport nodes. Their life-cycle impacts include embodied carbon from structure, finishes and MEP systems, and functioning impacts from HVAC, lighting, escalators/lifts, and passenger services. Underground metro evidence indicates that civil works and materials can dominate construction impacts, implying that early design decisions have long-lived consequences (Shinde et al., 2024). Material substitution and design optimization, therefore, afford considerable scope for embodied carbon reduction; for railway station systems, recent sustainability assessments point out opportunities to reduce the embedded carbon environmental limitation via material preferences and system-level design alternatives (Thomas et al., 2024).

Operational station energy is often a major contributor to whole-system electricity consumption because stations operate continuously and experience high passenger flows. (Energy benchmarking analysis of subway station with platform screen door system in China, 2022) KPIs should capture energy intensity (kWh/m²-year), energy per entry (kWh/entry), and peak directive (kW), with climate normalization where feasible. For LCC, station renewals and refurbishments occur at intervals driven by MEP lifetimes and traveler experience standards. MEVKF recommends reporting both the core station LCC (structure + base MEP) and the commercial fit-out LCC separately when retail drives different refresh cycles.

V. PROPOSED FRAMEWORK: MEVKF (METRO ECO-VALUE KPI FRAMEWORK)

MEVKF is a practical pipeline that converts heterogeneous engineering and operational data into comparable KPIs for decision-making spanning metro asset domains. It is structured as five layers:

Layer A — Scope and normalization: define asset domain, functional unit, assessment horizon, and boundary (cradle-to-grave; explicit stage breakdown). MEVKF recommends dual functional units: (1) an engineering unit (per route-km-year, per trainset-year, per station-year) and (2) a service unit (per passenger-km) to support both asset management and policy narratives.

Layer B — Inventory minimums: define the minimum data fields required to consistently compute carbon and cost for each asset domain. For stations, include major material quantities, MEP inventories, and annual energy by end-use; for traction power, include equipment BOM, losses, peak demand profile, and replacement schedule; for signalling, include equipment lists, cable lengths, server/ICT assets, and refresh intervals; for rolling stock, include mass and material constituents, traction/aux energy per duty cycle, and overhaul schedules.

Layer C — LCA computation: compute GWP (minimum) plus optional indicators if the decision requires more comprehensive environmental coverage. Data sources must be versioned; emission factors should be scenario-based and in accordance with guidance on infrastructure carbon data requirements (Xu & MacAskill, 2024).

Layer D — LCC computation: compute NPV using evident bargain rates and price base year, including CAPEX, OPEX, renewals, and end-of-life. For climate-sensitive assets, scenario-test maintenance escalation (Soleimani-Chamkhorami et al., 2024).

Layer E — Integration and decision view: combine results using (i) base KPIs (NPV, GWP) considering uncertainty bands, (ii) an eco-efficiency portfolio plane to screen overwhelmed options, and (iii) optional composite indices only when weights and perceptiveness commentary are transparent (Heijungs, 2022). Graphical integration aids approval touch and government (Wu et al., 2023).

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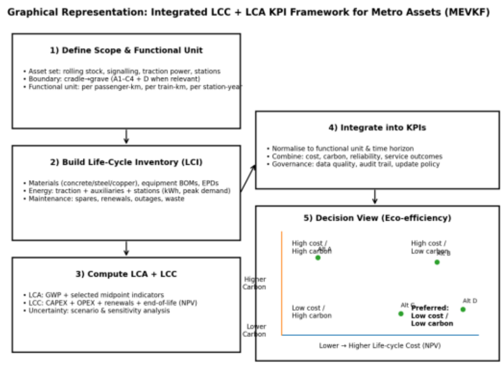
5.1 Graphical representation of MEVKF



5.2 Integrated KPI table (minimum set)

Table 1 suggests a minimum set of KPIs that can be added consistently across projects. Metrics can be extended, but the minimum set should remain stable for benchmarking.

Asset domain	KPI group	Example KPI (minimum)	Data minimum (inputs)	Unit / notes
Rolling stock	Carbon	Operational carbon intensity (scope-2) scenario set	kWh/train-km; grid EF scenarios; aux share	$kgCO_2e$/train-km; report by scenario
Rolling stock	Carbon	Embodied GWP amortized per trainset-year	vehicle mass; material mix; component list; overhaul & EoL	tCO_2e/trainset-yr; include mid-life overhaul
Rolling stock	Cost	LCC (NPV) per trainset-year	CAPEX; maintenance schedule; energy price; residual value	Currency/trainset-yr; disclose discount rate
Rolling stock	Service	Energy per passenger-km (distribution)	kWh/train-km; passengers; timetable; load factors	kWh/pax-km; report percentile bands
Signalling	Carbon	Embodied GWP per route-km controlled (incl. refresh)	equipment BOM; cabling; servers; refresh interval; EoL	tCO_2e/route-km; stage breakdown
Signalling	Cost	LCC (NPV) per route-km	CAPEX; licensing; spares; refresh; cyber/IT OPEX	Currency/route-km; include obsolescence
Signalling	Reliability	Availability / MTBF / MTTR trend	incident logs; redundancy model; maintenance records	% and hours; link to delay minutes
Traction power	Carbon	Lifecycle GWP per substation (incl. replacements)	BOM; transformer losses; maintenance; replacements; recycling	tCO_2e/substation; stage breakdown
Traction power	Cost	NPV including energy and demand charges	tariff; peak kW; kWh; CAPEX; maintenance; battery replacements	Currency/yr; separate energy vs demand
Traction power	Efficiency	Peak-to-average traction demand ratio	SCADA load profile; timetable; train density	Dimensionless; guides storage sizing
Traction power	Carbon	Regeneration utilisation rate (proxy)	regen energy; receptivity; storage/cross-line demand	%; link to avoided kWh

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Stations	Carbon	Embodied carbon per m^2 (A1–A5) + amortized	material quantities; EPDs; construction processes	$kgCO_2e/m^2$; also per station-yr
Stations	Carbon	Operational carbon per entry	kWh end-use; passenger entries; grid EF; peak kW	$kgCO_2e$/entry; scenario-based
Stations	Cost	LCC (NPV) per station-year	CAPEX; energy; maintenance; refurb cycles; security/cleaning	Currency/station-yr
Stations	Energy	HVAC intensity & peak demand	HVAC kWh; floor area; setpoints; occupancy schedule	kWh/m^2-yr and kW; climate-normalize

VI. WORKED KPI CALCULATION TEMPLATE (ILLUSTRATIVE)

This section presents a calculation template to implement MEVKF without the need for custom modelling for each decision. It demonstrates how inventory fields correspond to KPIs and how scenario sets maintain decision relevance.

6.1 Carbon KPI template. For an asset option j, amortized embodied carbon can be represented as:

GWP_emb(j) = [Σ(A1–A5 impacts) + Σ(renewal impacts over horizon) + end-of-life impacts] / horizon_years.

Operational carbon is computed using annual electricity and scenario-informed emission factors:

GWP_op(j, s) = kWh_annual(j) × EF_grid(s),

where s ∈ {current, forecast, deep-decarbonisation}. When time-of-use data is known, EF_grid can be replaced by a time series EF_t and energy series kWh_t. This supports carbon-aware optimization, in which decisions coordinate demand with low-carbon supply requirements rather than exclusively decreasing energy demand (Wu et al., 2025).

6.2 Cost KPI template. NPV over horizon H with discount rate r:

NPV(j) = CAPEX0(j) + Σ_{t=1..H} [OPEX_t(j) + Renewal_t(j) + Failure_consequence_t(j)] / (1+r)^t − Residual_value_H(j)/(1+r)^H.

6.3 Integration and dominance screening. Options are plotted in the cost–carbon plane. If a choice is higher-cost and higher-carbon than another across all procedures (or within uncertainty bands), it is vanquished and can be dismissed from the shortlist. Only then should preference-driven weighting be applied, and weights should be sensitivity-tested (Heijungs, 2022).

6.4 Governance metadata. To defend auditability, each KPI update should record: the frontier definition, functional unit(s), data sources and database versions, emission factors used (including year), buy rate and cost base year, renewal assumptions, and indecision settings. This provides direct evidence that irresponsible data origin and boundary limitations are the principal sources of non-comparability in infrastructure carbon reporting (Xu & MacAskill, 2024; Najafpour Navaei et al., 2024).

VII. DISCUSSION AND IMPLEMENTATION GUIDANCE

MEVKF is intentionally conservative: it prioritizes repeatability and auditability over maximum theoretical completeness. (Popov et al., 2020) The synthesis indicates that inconsistent boundaries are the primary reason LCC and LCA outputs cannot be compared across projects. Without a stable minimum inventory and a boundary register, “integrated” KPIs risk becoming a collection of one-off studies.

Integration robustness is a second challenge. Eco-efficiency provides an accessible decision view, but ratio versus weighted-sum formulations can alter rankings and are sensitive to normalization and weighting. MEVKF therefore recommends a tiered integration approach: publish base KPIs with scenario sets; use the eco-efficiency plane for screening; and apply MCDA or combined indices only for decisions calling for explicit choosing trade-offs, with documented consequences and perceptiveness analysis.

Digitization is a decisive enabler. BIM-enabled integration workflows can make wares traceable, support variant comparison, and lessen manual effort. In building contexts, BIM-integrated LCA–LCC workflows show how to keep economic and environmental models aligned as the design changes (Viscuso et al., 2022). Automated, continuous model-based carbon assessment further demonstrates how passionate calculation and visualization can be embedded into project workflows (Hussain et al., 2023). In metro settings, a realistic route is to connect BIM/as-built quantities, SCADA energy profiles, and asset registers (maintenance and renewal plans) to a KPI motor that recalculates audited KPIs on a scheduled cadence.

Finally, the organizational proportions matter. KPI ownership is often split: engineering owns abundances and performance, finance owns cost models and discounting, and sustainability teams own emission factors and reporting. MEVKF encourages a governance model with named data owners, validation checks, and an update cadence. Sector endeavours provide comparators and saying structures that metro mechanisms can adapt (UIC, 2022; RISSB, 2022).

VIII. EFFECTS ON PROCUREMENT AND ASSET MANAGEMENT

For procurement, MEVKF enables tender evaluation beyond “lowest CAPEX” or “lowest operational energy.” Tenderers can provide a life-cycle data pack: mass and material breakdown, expected traction/aux energy based on duty cycle, maintenance intervals, and end-of-life routes. For stations, EPD-backed material quantities and MEP component lists populate embodied carbon KPIs, while energy models and measured data populate operational KPIs. For traction power, options such as adding conventional substations versus installing wayside storage can be compared using techno-economic and environmental lifecycle metrics, with replacement schedules and end-of-life assumptions explicitly specified (Pam et al., 2023).

For asset management, MEVKF supports reanimation prioritization by identifying cost and carbon hotspots across the portfolio. Infrastructure LCA studies show that personified impacts can be significant and that decarbonization scenarios can shift hotspots over time (Ramos da Silva et al., 2023; Damián & Zamorano, 2023). Underground metro evidence indicates that construction-stage impacts can dominate for certain alignments, stressing the value of early design optimization (Shinde et al., 2024). Station-level reexaminations show that material choices and system-level design can reduce embodied impacts in station projects (Thomas et al., 2024).

At the system level, MEVKF can support mode comparisons when required. Comparative lifecycle cost and sustainability assessment between very-light rail and BRT illustrates how uniform functional units and boundaries enable more defensible modal decisions (Yeboah & Kaewunruen, 2025). Such results reinforce the need for boundary discipline and scenario-oriented sensitivity checks.

IX. LIMITATIONS AND FUTURE RESEARCH

This review is limited by the uneven dispersal of metro-specific integrated LCA–LCC studies across asset domains. Civil works and system-level carbon studies are more prevalent than signalling and digital-control systems. Differences in emission factor databases, regional electricity mixes, and cost base years also limit direct quantitative comparison; therefore, this paper focuses on methodological synthesis and framework design rather than pooled numerical estimates. Future deterioration priorities include: (i) metro-specific datasets for signalling equipment embodied impacts and refresh cycles; (ii) standardised inventories for traction power support (transformers, rectifiers, cabling, switchgear) with reported end-of-life routes; (iii) empirical studies linking signalling modernisation to avoided traction energy and avoided delays; and (iv) governance research on implementing auditable KPI engines integrated with asset management systems.

X. CONCLUSION

This review synthesized evidence from 2020 to 2025 on LCC, LCA, and integration approaches relevant to metro assets and proposed MEVKF, an integrated KPI framework constructed for repeatable decision-making in rolling stock, signalling, traction power, and stations. The synthesis indicates that boundary and data governance choices drive comparability more than the selection of software tools. MEVKF therefore emphasizes dual functional units, minimum inventory fields, scenario-based grid factors, transparent discounting, and a tiered integration approach that screens vanquished options before applying preference-driven weighting. MEVKF can be implemented incrementally: begin with GWP and NPV plus a governance register; expand to domain KPIs (energy, peak demand, reliability, renewals); and then integrate digital integration with BIM and asset registers. By matching carbon and cost KPIs to procurement and asset-management processes, MEVKF sustains tender evaluation, renewal planning, and explicit reporting aligned to decarbonization pathways.

MEVKF can be implemented incrementally: begin with GWP and NPV, plus a governance register; expand to domain KPIs (energy, reliability, renewals); and then incorporate digital integration with BIM and asset registers. Through aligning carbon and cost KPIs with asset-management processes, MEVKF supports procurement decisions, renewal planning, and accountable reporting aligned with decarbonization pathways.

Appendix A. KPI Governance Checklist (MEVKF)

This checklist is intended to operationalize MEVKF in organizations where data ownership is distributed across engineering, finance, operations, and sustainability reporting teams. The goal is to make KPI results repeatable, auditable, and comparable across projects and over time.

A1. Boundary and functional-unit register

1. Declare the functional unit(s) used (engineering unit and service unit) and provide a conversion method between them (e.g., train-km to passenger-km using measured load factors).
2. Declare the lifecycle stages included (A1–A5, B1–B7 where relevant, C1–C4, and Module D credits if used). Provide a simple stage coverage matrix for each KPI.
3. For station KPIs, declare whether MEP equipment, finishes, retail fit-out, and tenant energy are included.

A2. Data provenance and version control

4. For each inventory variable (materials, energy, maintenance), record the data source type: measured, as-built, as-designed, supplier declaration, or database default.
5. Record database versions and emission-factor sources used for GWP computations. If region-specific factors are used, record the region and year.

6. For costs, record price base year, currency, inflation treatment, and discount rate(s). If multiple discount rates are used (e.g., public-sector guidance vs. private cost of capital), treat them as scenarios rather than mixing them.

A3. Minimum quality checks

7. Mass/quantity sanity checks: compare material quantities to typical ranges (e.g., station structural concrete per m²; cable per route-km) and flag outliers.
8. Energy reconciliation: reconcile operational energy with metered/billing totals; if sub-metering is used (traction vs stations), verify that the sum is close to the system total.
9. Renewal plausibility: compare renewal intervals to manufacturer recommendations and previous reliability data; avoid arbitrary smoothing of renewals across years.

A4. Uncertainty and scenario reporting

10. Provide at least three electricity scenarios (current, forecast, deep decarbonization). For each scenario, record the factor source and year.

11. Provide at least one sensitivity analysis for: discount rate, energy price, and a key renewal interval (e.g., signalling refresh cycle or battery replacement).

12. Where results are used for procurement ranking, publish uncertainty bands or scenario ranges to reduce false precision.

A5. Integration and decision rules

13. Use dominance screening in the cost–carbon plane before applying weights or monetization.
14. If MCDA or composite indices are used, publish weights, the rationale, and sensitivity results. Avoid single “magic numbers” without traceability.

15. Record decision context (procurement, renewal planning, retrofit) and the baseline assumed for “avoided” impacts. Avoid double-counting avoided energy and avoided emissions.

A6. Update cadence and roles

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16. Assign data owners for each KPI input class (materials/BIM, energy/SCADA, maintenance/EAM, finance/LCC, sustainability/LCA).

17. Define an update cadence and event triggers (e.g., annual emission-factor refresh; quarterly energy reconciliation; update after major renewal or retrofit).
18. Define sign-off roles: technical owner, finance owner, sustainability owner, and final accountable sponsor for published KPI dashboards.

Appendix B. Example Data Schema for LCC+LCA KPI Engine

An internal KPI engine benefits from a simple schema that links assets, activities, and measurements. A minimal schema can be implemented in a spreadsheet, a database, or an asset-management system.

B1. Core entities

• Asset: unique ID, asset domain (rolling stock/signalling/traction power/stations), location, commissioning date, expected life, functional unit link (route-km, trainset, station).
• Lifecycle activity: construction, renewal, maintenance, operation, energy, end-of-life. Each activity stores quantities and references.

• Quantity record: material type, quantity, unit, source (as-built, supplier), date, uncertainty class.
• Emission factor: factor ID, region, year, unit, source, version, applicable lifecycle stage.
• Cost record: CAPEX/OPEX, amount, currency, price base year, date, escalation rules, uncertainty class.

B2. Computation outputs

• GWP stage results: A1–A5, B-stage maintenance/renewals, C-stage end-of-life, and optional Module D.

• LCC cashflow table: year-by-year CAPEX/OPEX/renewal/failure consequence, discounting, NPV.
• KPI register: KPI name, definition, functional unit, boundary coverage, update timestamp, scenario set, data owners.

B3. Field application notes

• Keep "scenario" as a first-class field: electricity factor scenario, tariff scenario, discount rate method, renewal interval scenario.

• Record metering coverage: which meters feed traction energy, station energy, depot energy,

and losses. Avoid mixing non-comparable scopes.

• Link KPI outputs to dashboards but keep raw audit tables accessible so reviewers can trace any published KPI back to inputs.

This appendix purposefully excludes stipulating a specific software stack. The key point is traceability: each reported KPI must be reproducible from stored inputs and documented assumptions.

Updated approximate word count (includes references and appendices): 5881

Appendix C. KPI Dictionary and Procurement

C1. KPI dictionary (minimum definitions)

1) NPV_total: Net present value over the assessment horizon (CAPEX + OPEX + renewals + end-of-life − residual), expressed per engineering functional unit (e.g., trainset-year, station-year). Must disclose discount rate and price base year.

2) GWP_total: Total life-cycle global warming potential (A1–C4, plus renewals), expressed per engineering unit and per service unit when applicable. Must disclose emission-factor sources and grid scenarios.

3) Energy_intensity: Annual energy per train-km (rolling stock) and per m^2-year / per entry (stations), separated into traction and auxiliaries where possible.
4) Peak_demand: Peak kW (stations and traction substations) and peak-to-average ratio, used to manage demand charges and to size storage or infrastructure expansions.
5) Availability: Asset availability (%) and associated delay minutes attributable, especially for signalling and power assets; used to estimate reliability consequences in LCC.

C2. Procurement scoring use case

A practical tender evaluation can combine MEVKF outputs without collapsing them into a single opaque index. First, screen bids that fail the minimum technical requirements. Second, compute a short list of audited base KPIs: NPV_total (scenario set), GWP_total (scenario set), and one service KPI (e.g., kWh/train-km or kWh/entry). Third, apply dominance screening in the cost–carbon plane: remove options that are higher-cost and higher-carbon than another option across the agreed scenarios. Only after the dominated options are removed, apply a transparent weighting to incorporate non-life-cycle criteria (delivery risk, interoperability, passenger comfort). This sequencing avoids the common mistake of using weights to “hide” dominated options and improves stakeholder belief in the final selection.

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