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The Lithium Iron Phosphate Alchemy Problem: Circularity Deficit, Extended Producer Responsibility Absence, and Unrecovered Lithium Value in Rwanda's Commercial E-Mobility Fleet (2026 to 2030)

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Abstract

Background

Rwanda's rapid electric mobility transition is generating a growing stream of end-of-life lithium iron phosphate batteries against a backdrop of zero domestic processing capacity for any chemical recovery pathway. The sovereign policy frameworks governing this transition reveal a dangerous linear policy lag, with Extended Producer Responsibility mandates only now entering the drafting phase.

Methods

This study employs a deterministic stock and flow model built using primary field data from active Battery-as-a-Service operators in Kigali, combined with deductive thematic coding of national policy documents.

Results

The model projects an annual Circularity Deficit of 319.59 tonnes, representing a complete recycling shortfall. As localized recycling remains unprofitable, linear disposal strips between USD 42,920 and USD 245,680 of unrecovered lithium value from the domestic economy annually, compounding to USD 1.23 million by 2030. Systematic coding confirms a profound structural regulatory misalignment across eight sovereign frameworks, with primary elicitation revealing the state has committed no capital toward physical recycling infrastructure, allocating USD 1.7 million to policy drafting alone. This study translates that gap into a costed Extended Producer Responsibility escrow, indexed at USD 1.45 to USD 4.00 per kilowatt hour of imported battery capacity, raising USD 214,600 to USD 592,000 in capital by 2030 to fund the collection infrastructure this transition currently lacks.

Conclusions

As the first empirical quantification of the Circularity Deficit, resource value loss, and a costed Extended Producer Responsibility instrument for a Lithium Iron Phosphate commercial fleet in an East African context, the findings provide a scalable analytical framework for peripheral e-mobility adopters across the Global South.

Background

The global transition to electric mobility represents a fundamental shift in energy security. The world is moving rapidly from a fuel-intensive energy system to a material-intensive system that relies heavily on a narrow group of critical minerals. This structural shift has bound the global transport sector to highly volatile commodity markets and geopolitical supply risks [1, 2, 3]. Within this transition, fleet operators in

emerging markets are increasingly adopting Lithium Iron Phosphate (LFP) battery chemistries to avoid the high costs of volatile metals like cobalt [4]. However, this strategic shift creates a significant cleaner production paradox. While stripping cobalt from the battery lowers the upfront procurement cost, it simultaneously undermines the economics of back-end recycling [5]. Because these packs contain no high-value metals to recover, the cost of extracting raw lithium significantly exceeds the secondary market value of the material [5]. This dynamic transforms batteries into potential economic liabilities upon mechanical failure owing to reduced financial incentives for recycling [6]. While emerging literature identifies direct regeneration as a lower capital recovery pathway highly beneficial for Lithium Iron Phosphate chemistry [7], its economic viability remains contingent on the existence of formal battery collection infrastructure, a prerequisite equally absent in the peripheral adopter markets examined in this study.

Within Sub-Saharan Africa, this cleaner production paradox is magnified by the prevailing linear model of importing, using, and discarding high-voltage hardware [8, 9, 10]. This is a systemic failure across the Global South rather than an isolated geographical anomaly: comparable regulatory and infrastructural gaps have been documented in Sub-Saharan African deployments generally [10], in India's three-wheeler electrification [11, 12], and in Vietnam's informal battery dismantling sector [13, 14], a pattern this study returns to under Generalizability of the Analytical Framework.

The Republic of Rwanda exemplifies this structural tension through its Second National Strategy for Transformation (NST2), which mandates aggressive transit electrification targets [15]. Notably, Rwanda is recognized in comparative African e-mobility literature as a continental policy leader in the adoption phase, rendering the regulatory gap identified in this study analytically significant: even the most progressive deployment frameworks on the continent remain structurally unprepared for circular closure. However, this rapid adoption relies on absolute import dependency for high-voltage hardware [16]. Furthermore, the state currently lacks an established domestic hydrometallurgical processing capacity to manage these assets at the end of their operational lifecycles. Consequently, a significant regulatory mismatch emerges, one this study terms a linear policy lag: the condition in which a sovereign government accelerates the importation and adoption of green technology hardware without concurrently enacting the statutory and fiscal mechanisms required to manage that hardware's end-of-life liability [17]. The sovereign government actively subsidizes the importation of commercial electric motorcycles to reduce carbon emissions; however, it lacks the enforceable legal framework required to manage the resulting end-of-life consequences. This lack of regulation functionally guarantees the localized stockpiling of hazardous materials [18, 19]. This structural vulnerability directly undermines Sustainable Development Goal (SDG) 7 targets for affordable clean energy transition and SDG 13 commitments to climate action, as unmanaged battery waste negates the emissions savings that motivated the transition.

Current literature on electric mobility transition risks in the Global South overwhelmingly focuses on the adoption phase, with end-of-life risks receiving substantially less analytical attention [20]. Instead, researchers frequently analyze the tax breaks and subsidies required to import vehicles and finance

public charging infrastructure [20, 21]. However, no published study has quantified the Circularity Deficit or modelled the resource value loss resulting from Lithium Iron Phosphate waste accumulation in an East African context. This creates a severe theoretical void because existing research fails to calculate what happens when an import-dependent transit network initiates deployment before enacting Extended Producer Responsibility laws and constructing the physical infrastructure to manage fleet obsolescence. This study addresses this void by collecting localized primary telemetry and subjecting it to a deterministic stock and flow model to quantify the exact fiscal and environmental consequences of this regulatory lag.

To achieve this, this study pursues three specific objectives. First, it calculates the Circularity Deficit generated by the commercial fleet. Second, it models the annual resource value loss from unrecovered lithium using verified energy capacity constant. Third, it evaluates the integration of Extended Producer Responsibility mandates within sovereign transition frameworks using deductive policy coding and, building directly from that evaluation, derives a costed Extended Producer Responsibility escrow model indexed to the resource value loss quantified under the second objective, translating the identified policy gap into an actionable fiscal instrument. The remainder of this Background section reviews the theoretical and empirical foundations underpinning this study, followed by the Methods, Results, Discussion, and Conclusions sections

Circular Economy Theory and the Infrastructure Assumption

The Circular Economy model proposes an industrial system that is restorative and regenerative by design, aiming to keep products and materials at their highest utility and value at all times [22], directly contrasting with the traditional linear economy of take-make-dispose. Integrating this paradigm into electric mobility transitions is increasingly championed as a key solution to the environmental footprint and supply chain vulnerabilities of lithium-ion batteries [23, 24].

However, the dominant application of Circular Economy theory in transition planning suffers from a severe conceptual flaw: scholars critique the mainstream framework as insufficiently attentive to rigid thermodynamic and capital boundaries [25], since the assumption that materials circulate perpetually ignores realities like the €34.3 million capital expenditure required to build and operate mid-scale hydrometallurgical recycling plants [26]. This paper tests the infrastructure assumption as an empirically verifiable hypothesis using the Circularity Deficit equation, mathematically comparing domestic processing capacity against incoming battery waste to force the theoretical model to account for the financial barriers of the Global South. In doing so, this study operationalizes what the Material Circularity Indicator framework would score as a fully linear outcome [27] and applies Circularity Break-Even Point logic [28] to characterize the resulting deficit as cumulative resource leakage persisting until domestic secondary supply capacity is established.

This research also utilizes the Multi-Level Perspective as a secondary theoretical lens, framing socio-technical transitions as an interaction between radical Niche innovations and established Regime

infrastructures. When advanced high-voltage technology is deployed in a municipal waste regime entirely unequipped to manage it, the system experiences a severe structural mis-match [29]. This study uses the Multi-Level Perspective to frame the asynchronous lifespan of commercial electric motorcycles as a structural lock-in rather than a mere administrative oversight.

Lithium Iron Phosphate (LFP) Recycling Economics and The Alchemy Problem

The automotive industry is increasingly transitioning to Lithium Iron Phosphate battery chemistries to eliminate reliance on volatile cobalt and reduce upfront manufacturing costs, but this substitution fundamentally undermines backend recycling economics. Lander et al. demonstrate that the profitability of urban mining depends on recovering high value metals like cobalt and nickel [30]; because Lithium Iron Phosphate packs contain none, the cost of extracting raw lithium exceeds the secondary market value of the recovered material [6, 30]. Processing further requires highly capitalized hydrometallurgical or pyrometallurgical infrastructure [31, 32], so when battery chemistry strips away recoverable value, recycling becomes economically unviable without state subsidy [5], diverting hardware to informal dismantling sectors or municipal landfills [33].

Recent literature qualifies this diagnosis with lower capital recovery pathways specific to Lithium Iron Phosphate chemistry: Ji et al. identify direct regeneration, the solid state thermal relithiation of degraded cathodes, as a profitable route [7], and Geiß et al. demonstrate acid free mechanochemical processing as a parallel alternative [34]. Both avoid the corrosive wastewater and re-precipitation steps that drive hydrometallurgical cost, yet both still depend on formal collection infrastructure delivering batteries to a licensed facility at volume, a prerequisite equally absent in Rwanda's confirmed zero capacity context. The Circularity Deficit is therefore applicable regardless of processing technology, since the absence of collection infrastructure renders any recovery pathway inoperative until that architecture exists (developed further in the Discussion, under Extended Producer Responsibility as the Structural Solution).

This dynamic transforms batteries from tradable commodities into permanent economic liabilities upon failure. No published study has calculated the annual resource value loss from Lithium Iron Phosphate waste accumulation in a landlocked Sub-Saharan African fleet context, the precise empirical gap this study addresses.

Extended Producer Responsibility in Developing Economy Contexts

Extended Producer Responsibility serves as the regulatory mechanism required to execute a circular economy by shifting the financial and logistical burden of post-consumer waste management back to producers. While widely implemented in the EU, its efficiency is frequently hampered by compliance and economic constraints [35], and applying these Western mechanisms in developing economies lacking formal recycling infrastructure faces severe transition friction [36].

Contemporary scholarship documents these structural barriers across Sub-Saharan Africa, including implementation challenges when states prioritize rapid technological adoption over backend compliance [37] and the operational factors limiting EPR adoption in West Africa [38]. This literature reveals a dangerous linear policy lag in developing countries that is not confined to policy laggard states, as established above with respect to Rwanda's own standing as a continental adoption leader: governments actively subsidize green technology importation but frequently fail to simultaneously enact the statutory mandates required to manage the resulting physical liability, allowing importing corporations to privatize the profits of adoption while socializing the environmental costs of disposal. No published study has systematically coded the state of Extended Producer Responsibility mandates across the specific sovereign frameworks governing Rwanda's NST2 transition using absence coding methodology, which is the methodological gap this study fills.

Taken together, no published study has quantified the Circularity Deficit or resource value loss of a Lithium Iron Phosphate commercial fleet in Sub-Saharan Africa, nor systematically coded the integration of Extended Producer Responsibility within Rwanda's NST2 frameworks the three theoretical voids this study addresses.

Methods

Research Design

This study utilizes a descriptive evaluative design anchored by deterministic scenario modelling. Attempting to forecast critical mineral procurement costs using smoothed statistical variance is fundamentally flawed in emerging markets. Continuous daily spot price datasets for lithium carbonate are not publicly accessible and remain held behind proprietary intelligence paywalls [39]. Because national procurement budgets cannot rely on inaccessible statistical averages, they must plan for absolute market amplitude. Therefore, a deterministic scenario approach is appropriate and methodologically necessary. This design aligns with recent macroeconomic guidance [40] demonstrating that delays in climate transition actions significantly increase future tail risks and financial shocks in emerging markets. The methodology deliberately utilizes historically verified maximum price peaks and troughs to establish rigid boundaries for the stress tests. This ensures that the model measures raw macroeconomic exposure rather than temporary market turbulence.

Data Sources

This study relied on a dual data extraction strategy. Primary operational telemetry is harvested through targeted key informant elicitation with technical personnel at Ampersand, Spiro, EnviroServe, and the Rwanda Environment Management Authority (REMA). This elicitation specifically extracted physical battery mass, topographical decay rates, domestic hydrometallurgical capacity, and the current status of environmental legislation. All human subject interactions were strictly anonymized to protect corporate

and institutional integrity. Secondary data builds the macroeconomic model. The quantitative extraction matrix deliberately excludes continuous spot price series due to proprietary restrictions. The model instead utilizes the United States Geological Survey Mineral Commodity Summaries 2025 [41] and the London Metal Exchange [42] to establish verified historical pricing extremes. Downstream statutory targets were extracted from the Ministry of Trade and Industry (MINICOM) Annual Report [43] alongside eight binding national frameworks, including the Second National Strategy for Transformation [15], Vision 2050 [44], and the SDG Accelerator Plan.

Circularity Deficit Model

To quantify the physical infrastructure gap, this study adapts standard industrial mass balance principles [45] to construct the Circularity Deficit equation. This formulation specifically operationalizes the thermodynamic and infrastructural limits of the Circular Economy [25] within a developing economy context. The Circularity Deficit (Δ) is computed using the following equation:

Eq. 1 $\Delta = Et(w) - I(c)$

In this equation, Et(w) represents the annual end-of-life battery waste inflow, and I(c) represents the verified domestic hydrometallurgical processing capacity. The waste inflow is derived by multiplying the total fleet volume by the primary validated battery mass and the localized annual failure rate across two geographic cohorts to account for topographical decay variances.

Et(w) is formulated as a gross physical outflow measurement, representing the total volume of batteries mechanically failing within the fleet during the projection period, rather than a net formal sector intake. This distinction means the model does not assume 100 percent formal collection; it measures the total waste generated regardless of which disposal pathway those batteries subsequently enter.

A portion of the gross annual failure cohort undergoes informal second-life cascading before final disposal. Primary elicitation with fleet operators confirmed that technically depleted batteries are subjected to cell-level reconditioning to harvest surviving capacity for secondary use, including off-grid solar applications. Following Kebir et al. [46], such cascading diversion represents a temporary deferral rather than a formal circular recovery pathway, as cells re-enter the waste stream at a lower state of health without hydrometallurgical processing. Accordingly, the Circularity Deficit (Δ) is calculated against total fleet failure volume rather than a discounted collection rate. This conservative approach is methodologically justified by the confirmed I(c) = 0 finding: regardless of what proportion of failed batteries reaches the formal collection system, the domestic processing capacity available to absorb them is zero tonnes per year. Therefore, the deficit is structural rather than logistical.

While empirical in construction, Δ is conceptually grounded in the Material Circularity Indicator framework [27], which provides a normalized restorativeness score from zero to one reflecting the degree to which a product's lifecycle returns material to the secondary supply chain. The Circularity

Deficit operationalizes the absolute mass and economic value of the linear fraction that fails to make that return. This study further applies Circularity Break-Even Point logic established by Wesselkämper et al. [28], defined as the point at which an economy's recycled material supply becomes sufficient to meet ongoing demand without further reliance on primary extraction, to characterize the deficit not merely as a static physical measurement but as cumulative resource leakage occurring prior to the establishment of domestic primary-resource independence. For Rwanda, the absence of Extended Producer Responsibility mechanisms means the Break-Even Point is not merely delayed but structurally unscheduled, rendering the Circularity Deficit an accelerating rather than diminishing liability across the 2026 to 2030 projection window.

Resource Value Loss and Energy Capacity Method

To calculate the economic loss from unrecovered materials, this methodology utilizes a validated energy capacity approach to isolate precise lithium content. The total stranded energy capacity of failed packs is calculated using a confirmed 3.24 kilowatt-hour baseline derived from the Ampersand Alpha MK1 specification. The annual lithium loss is then isolated using the validated electrochemical constant of 0.1 kilograms of lithium per kilowatt-hour [31, 47]. This constant is established by published whole-pack mineral composition data demonstrating that Lithium Iron Phosphate chemistry contains 6 kilograms of lithium per 60 kilowatt-hour pack, yielding a scaling ratio of 0.1 kilograms per kilowatt-hour applicable to any LFP pack regardless of capacity [31, 47]. Applied to the confirmed 3.24 kilowatt-hour Ampersand pack, this constant yields 0.324 kilograms of lithium per failed unit. This methodology establishes the rigid mathematical baselines required to test the Circular Economy infrastructure assumption in the Results section.

Deductive Document Analysis

To evaluate policy integration, this study employed deductive thematic coding using NVivo 14. Utilizing systematic absence coding [48], eight national strategies including NST2 [15] and the National E-Waste Management Policy [18] were queried against two predefined nodes: End-of-Life Liability Internationalization and Fiscal Buffer Mechanisms. This binary coding empirically verifies whether intervening legal mechanisms exist to buffer the physical waste accumulations identified in the modelling. It should be noted that the predefined coding nodes are operationalized using formal statutory vocabulary specific to Extended Producer Responsibility and fiscal mechanisms. Where a policy document expresses substantively equivalent intent through alternative terminology, the binary absence approach may not capture that intent, and results should be interpreted accordingly as a measure of statutory vocabulary presence rather than an exhaustive audit of policy intent.

Use of AI Tools

During the preparation of this work the author used Anthropic's Claude for structural review and formatting checks, and Gemini Notebook to assist with literature synthesis and source organization.

After using these tools, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

Results

Fleet Parameters and Baseline Data

The operational targets governing Rwanda's commercial electric mobility fleet were extracted through targeted primary elicitation and secondary document review. Table 1 presents the consolidated baseline data utilized to build the deterministic physical and economic models.

The current deployment scale within the study area consists of approximately 34,000 commercial electric motorcycles as of April 2026. This fleet is heavily concentrated within Kigali city limits. The primary hardware utilized by the dominant Battery-as-a-Service operators is the Lithium Iron Phosphate battery pack. Primary field data confirmed the standard physical mass of these commercial packs is 35 kilograms.

Operating on Kigali's steep topography under high-cycle commercial utilization significantly impacts hardware durability. Operational telemetry established a localized mechanical lifespan of exactly 3.5 years for battery packs operating within the primary urban cohort.

Downstream infrastructure reports establish the physical boundaries of the end-of-life phase. Sovereign registry data and primary waste operator elicitation confirmed that Rwanda's current domestic hydrometallurgical processing capacity for Class 9 lithium-ion batteries is zero tonnes per year. This absolute lack of chemical refining capability is defined as $I(c) = 0$ for the subsequent physical modelling. As established in Background, under Lithium Iron Phosphate (LFP) Recycling Economics and The Alchemy Problem, this confirmed zero capacity encompasses all processing modalities, including direct regenerative pathways, as no licensed facility of any chemical processing type currently operates within the national territory.

Finally, financial telemetry established the baseline cost of capital. Private fleet operators currently rely on commercial venture debt carrying an average lending rate of 17 percent (Development Bank Rwanda, as of April 2026). This rate establishes the high-cost financial environment in which localized hardware replacement cycles occur.

Table 1
Kigali commercial fleet and infrastructural baseline parameters (2026).

Parameter Category	Extracted Metric	Source and Verification
Fleet Deployment Scale (As of April 2026)	34000 commercial units	Corporate telemetry
Primary Battery Chemistry	Lithium Iron Phosphate	Technical specification sheets
Physical Pack Mass	35 kg per unit	Primary key informant elicitation
Accelerated Urban Lifespan	3.5 years (Kigali topography)	Primary key informant elicitation
Hydrometallurgical Capacity	0 tonnes per year	EnviroServe facility confirmation; REMA registry (April 2026)
Commercial Lending Rate	17% baseline APR	Development Bank of Rwanda (As of April 2026)

Circularity Deficit

The physical infrastructure gap is quantified by calculating the exact inflow of degraded hardware relative to domestic processing capacity. Utilizing the dual decay rate established under Circularity Deficit Model, the annualized waste inflow is calculated incrementally.

The primary urban cohort comprises 27200 units operating on a 3.5-year replacement cycle. This yields a 28.57% annual failure rate. Multiplying this volume by the 35-kilogram pack mass generates 271.99 tonnes of battery waste annually. The secondary provincial cohort comprises 6,800 units operating on a standard 5-year replacement cycle. This yields a 20.00% annual failure rate, generating 47.60 tonnes per year. The combined national inflow equals 319.59 tonnes per year.

The Circularity Deficit Equation subtracts the verified domestic processing capacity from this total annual inflow. Because the hydrometallurgical capacity remains at zero tonnes per year, the resulting Circularity Deficit is 319.59 tonnes annually. Figure 1 illustrates this annual Circularity Deficit, showing the 319.59-tonne end-of-life battery inflow against zero domestic hydrometallurgical processing capacity.

Kigali and provincial fleet combined end-of-life LFP battery waste inflow (319.59 tonnes) plotted against verified domestic hydrometallurgical processing capacity (0 tonnes per year).

Projecting this annual deficit across the 2026 to 2030 policy window generates a severe physical accumulation. The localized model confirms that Rwanda’s current commercial fleet will produce a cumulative stockpile of 1597.95 tonnes of lithium iron phosphate battery waste over this five-year period. Figure 2 plots the projected cumulative volume of high-voltage LFP battery waste across the 2026 to 2030 NST2 policy window. This cumulative mass of 1597.95 tonnes exceeds a critical regional benchmark. Specifically, this volume represents a physical mass surpassing the total general electronic

waste processing capacity of most sub-Saharan African nations. This finding confirms that the commercial motorcycle fleet alone generates a specialized waste burden that overwhelms baseline regional infrastructure limits for such waste.

Commercial e-moto fleet, Rwanda, showing cumulative high-voltage LFP battery waste accumulation from 2026 to 2030 (cumulative total: 1597.95 tonnes).

Resource Value Loss Across Three Scenarios

Beyond the physical toxicity of accumulating nearly 1600 cumulative tonnes of battery waste, linear disposal results in a severe resource value loss. By applying the energy capacity method established under Resource Value Loss and Energy Capacity Method, the physical mass is converted into its pure elemental equivalent.

Kigali's high cycle fleet generates 7771 failed packs annually, and the provincial fleet generates 1360 failed packs. This yields 9131 failed packs per year. Multiplying the 9131 failed packs by 3.24 kWh results in a total stranded energy capacity of 29,584 kWh annually. Applying an electrochemical constant of 0.1 kilograms of lithium per kilowatt hour yields 2.96 tonnes of unrecovered lithium per year. Figure 3 presents the resulting annual resource value loss across three deterministic price scenarios.

Baseline post-crash (USD 14500 per tonne, Jan 2024–2025), moderate recovery (USD 40000 per tonne, constructed midpoint), and historical peak stress (USD 83000 per tonne, November 2022), based on 2.96 tonnes of unrecovered lithium annually. Cumulative five-year projections are presented in Fig. 4 and Table 2.

Table 2
Annual and cumulative resource value loss matrix.

Market Scenario	Price Reference Period	Spot Price (USD/tonne)	Annual Unrecovered Lithium	Annual Value Loss	5-Year Cumulative Value Loss (2026–2030)
Baseline Post-Crash	Jan 2024–2025	14500	2.96 tonnes	USD 42920	USD 214600
Moderate Recovery	Constructed midpoint (no calendar reference)	40000	2.96 tonnes	USD 118400	USD 592000
Historical Peak	November 2022	83000	2.96 tonnes	USD 245680	USD 1228400

Note: Price Reference Period distinguishes verified historical price anchors (Baseline, Peak) from the constructed Moderate Recovery scenario, which represents the mathematical midpoint between the Baseline and historical Peak anchors rather than an observed market condition. Cumulative figures are undiscounted nominal sums assuming constant annual lithium loss (2.96 tonnes/year) and constant spot price across the 2026–2030 NST2 projection window, consistent with the treatment of the Circularity Deficit reported under Circularity Deficit in the Results section.

Across all three scenarios, annual resource value loss persists regardless of market conditions, reflecting the absence of a domestic recovery pathway. Even under highly favorable baseline market conditions, the linear disposal of this lithium constitutes a capital outflow of USD 42,920 annually. Under the moderate recovery scenario, this constitutes USD 118,400 annually. Under the peak historical stress scenario, this value escalates to USD 245,680 annually. Projected across the 2026 to 2030 NST2 window at constant annual throughput, this exposure compounds to a cumulative resource value loss of USD 214,600 under baseline conditions, USD 592,000 under moderate recovery, and USD 1,228,400 under peak historical stress. Figure 4 plots this cumulative escalation across the three scenarios.

Three deterministic spot price scenarios: baseline post-crash (USD 214600), moderate recovery (USD 592000), and historical peak stress (USD 1228400), assuming constant annual lithium loss (2.96 tonnes per year) and constant spot price across the projection window.

NVivo Policy Extraction

To evaluate the integration of transition safeguards within national frameworks, deductive thematic coding was performed using NVivo 14. The software queried the official document set using targeted Boolean strings to identify specific statutory vocabulary related to risk mitigation. The official document set comprised eight sovereign frameworks: the Second National Strategy for Transformation, Vision 2050, the Green Growth and Climate Resilience Strategy, Rwanda's Nationally Determined Contributions, the SDG Accelerator Plan, the MINICOM Annual Report, the Climate Change Portal Green Urban Transition document, and the National E-Waste Management Policy of 2018. Table 3 presents the extraction matrix evaluating these governing documents against three critical regulatory nodes. The

analysis focused exclusively on End-of-Life Liability Internationalization, Fiscal Buffer Mechanisms, and Recycling Infrastructure Targets.

Table 3
NVivo deductive thematic extraction matrix.

Sovereign Document	Node 1: End-of-Life Liability Internationalization	Node 2: Fiscal Buffer Mechanisms	Node 3: Recycling Infrastructure Targets
Second National Strategy for Transformation	STRUCTURAL SILENCE	STRUCTURAL SILENCE	STRUCTURAL SILENCE
Vision 2050	STRUCTURAL SILENCE	STRUCTURAL SILENCE	STRUCTURAL SILENCE
Green Growth and Climate Resilience Strategy (Nov 2023)	Existing economic development and activities should also be modernised to ensure effective uptake of the Precautionary Principle, the Polluter Pays Principle and Extended Producer Responsibility (EPR)	STRUCTURAL SILENCE	Sustainable e-waste recycling 17 0.1*
Rwanda Nationally Determined Contributions (3.0)	STRUCTURAL SILENCE	Promotes government subsidies	STRUCTURAL SILENCE
SDG Accelerator Plan (2025–2034)	STRUCTURAL SILENCE	Proposes buffers for commodity price volatility	STRUCTURAL SILENCE
MINICOM Annual Report	STRUCTURAL SILENCE	Promotes subsidized tariffs	STRUCTURAL SILENCE
Climate Change Portal: Green Urban Transition	STRUCTURAL SILENCE	Emphasizes import tax breaks	STRUCTURAL SILENCE
National E-Waste Management Policy (2018)	Calls for the development of guidelines	STRUCTURAL SILENCE	Plan for 30 collection centers

* Note: This verbatim extraction from the Green Growth and Climate Resilience Strategy (2023) reflects USD 17 million allocated for generic e-waste recycling with USD 0.1 million for operations and maintenance. However, the document lacks any specific infrastructure capacity targets (e.g., tonnes per year) dedicated to electric vehicle batteries.

The deductive coding revealed a pervasive structural regulatory misalignment across the highest national strategies. The Second National Strategy for Transformation does not explicitly mention Extended Producer Responsibility, fiscal stabilization funds, or quantitative recycling targets in the

context of high-voltage battery waste. Vision 2050 establishes sweeping resource efficiency goals, such as aiming to cut garbage production in half by 2050 [44, 49], but remains silent on the specific legal mechanisms required to manage high-voltage battery waste. Similarly, while the exhaustive Green Growth and Climate Resilience Strategy conceptually acknowledges Extended Producer Responsibility (EPR) and allocates broad capital for general e-waste, deductive coding reveals a pervasive structural silence regarding dedicated fiscal buffer mechanisms or physical infrastructure targets specifically designed to internalize the disposal costs of electric vehicle battery components [50].

Secondary climate and industrial frameworks exacerbate this disconnect. Rwanda's Nationally Determined Contributions document heavily emphasizes government subsidies, tax exemptions, and reduced tariffs to accelerate green technology importation [51]. Furthermore, while the Climate Change Portal explicitly promotes import tax breaks to encourage the adoption of new green construction technologies, it remains structurally silent on equivalent fiscal frameworks to manage electric vehicle adoption and disposal [52].

Crucially, the Rwanda SDG Accelerator Plan proves the government possesses macro-level awareness of these threats. The document explicitly calls for larger fiscal buffers to absorb commodity price volatility. However, this awareness remains entirely siloed. Both the transit and environmental texts contain a structural silence regarding the application of these fiscal buffers to protect the national treasury from upstream lithium and cobalt price shocks. The state actively finances the hardware importation, but its official frameworks provide no mitigation infrastructure targets.

The only document within the eight frameworks analyzed containing relevant regulatory vocabulary is the National E-Waste Management Policy of 2018. This policy explicitly calls for the development of regulations and guidelines for Extended Producer Responsibility and outlines a plan to establish regional collection centres. However, a critical definitional failure renders this policy structurally irrelevant to the transit sector. The policy's explicit definition of electronic waste does not include electric vehicle or commercial motorcycle batteries. A review of policy amendments confirmed that no subsequent revision incorporating electric vehicle or commercial motorcycle batteries had been gazetted as of April 2026. Consequently, while the state possesses a theoretical framework for managing consumer electronics, the specific high-voltage hardware driving the e-mobility transition is legally orphaned. These findings are rendered analytically significant by Rwanda's recognized position as a continental e-mobility policy leader [16]; the structural silences identified here do not represent a generic regulatory failure but a specific circularity gap embedded within an otherwise progressive national framework, confirming that the Rwanda Paradox identified in this study constitutes a transnational pattern rather than an isolated national deficiency.

Primary Validation Summary

The deterministic models presented in the preceding sections rely predominantly on secondary macroeconomic and regulatory data. To ensure these models accurately reflect operational reality,

primary validation was conducted through key informant elicitations with active fleet operators and regulators. These ground truth findings empirically anchor the mathematical calculations.

Elicitation with EnviroServe confirmed the complete absence of domestic chemical processing capacity. The operator stated that recycling zero cobalt Lithium Iron Phosphate batteries remains financially unprofitable without external state subsidies. Consequently, degraded cells that cannot be repurposed are mechanically dismantled and physically exported to markets like Dubai for material recovery. This explicitly confirms that domestic circularity for lithium chemistries is presently nonviable.

The economic constraints established by this processing deficit dictate a highly probable operational outcome for the commercial transit sector. Because transboundary export remains cost-prohibitive and localized chemical processing is nonexistent, the physical stock of fully depleted commercial batteries is logically relegated to localized warehouse accumulation. Furthermore, the economic pressure to maintain fleet utility strongly indicates that operators must undertake informal reconditioning to cannibalize surviving cells and artificially extend vehicle lifespans. This deduction aligns directly with the rise of informal dismantling sectors observed in comparative emerging markets facing identical infrastructural voids [53]. Furthermore, elicitations with technical personnel confirmed total upstream dependency. Engineers stated they remain completely reliant on Asian supply chains for replacement hardware, having no active regional suppliers capable of meeting current volume demands.

Finally, consultation with the Rwanda Environment Management Authority validated the structural regulatory findings. The authority confirmed that zero legally licensed hydrometallurgical facilities currently operate within the nation. The regulator reiterated that no enforced Extended Producer Responsibility mechanisms actively mandate the repatriation of these accumulating batteries, though they confirmed such frameworks are currently in the drafting phase. Primary elicitation with REMA in April 2026 further revealed that the state has internally allocated a USD 1.7 million budget under a four-year initiative titled Accelerating the Transition to Electric Mobility in Rwanda. Media documentation of this initiative independently confirms that the project is structured across four pillars, namely institutionalization, scaling and replication, long-term environmental impact, and regulatory and market framework, with the environmental component specifically limited to drafting a national electric vehicle battery e-waste management policy [54]. No capital within the documented project scope is directed toward the construction of physical processing infrastructure of any kind. This finding is more severe than simple undercapitalization, the state has not budgeted sufficiently for a recycling facility, but has not budgeted for one at all. The USD 1.7 million funds the policy drafting exercise that would theoretically precede a future facility that currently has no construction budget and no construction timeline.

Discussion

Theoretical Validation of the Dual Exposure

The empirical findings generated by this study elevate the electric mobility transition from a technical procurement challenge into a structural macroeconomic vulnerability. The data confirms that Rwanda is currently operating under a severe Dual Exposure. However, the significance of these findings extends beyond the localized context of Kigali. When these metrics are applied to the theoretical frameworks established in the Literature Review, they validate specific structural critiques regarding the global green transition.

First, the localized stock and flow model calculated an absolute Circularity Deficit of 319.59 tonnes annually. When coupled with the verified reality of zero domestic processing capacity, this result empirically confirms the theoretical critique advanced by Korhonen et al [25]. The data proves that the Circular Economy infrastructure assumption completely fails when applied to landlocked developing economies. Because Lithium Iron Phosphate chemistry eliminates material recovery economics and the required chemical capital expenditure is prohibitive, the theoretical circular loop structurally fails. It transitions from an environmental solution into permanent toxic accumulation and absolute resource value loss. Expressed within the Material Circularity Indicator framework [27], Rwanda's current operational trajectory produces a score approaching zero, which is the fully linear end of the restorativeness scale, with the Circularity Deficit quantifying the precise mass and economic value of the gap separating that score from the Break-Even Point threshold at which domestic secondary supply becomes self-sustaining [28].

Second, the primary operational data reveals a severe temporal mismatch where the commercial motorcycle chassis outlives the battery pack by a ratio of nearly three to one. This asynchronous lifespan provides a precise empirical illustration of the structural "mis-match" defined within the Multi Level Perspective by [29], where the Niche high voltage technology physically fails years before the municipal waste Regime has time to adapt. Consequently, the imported innovation becomes physically stranded against the unprepared infrastructure of the host society. The fleet operators are trapped in a cycle of premature hardware obsolescence precisely because the Regime lacks the processing capacity to sustain the Niche technology. This friction is not solely infrastructural; it is also informational. The Regime cannot adapt its oversight capacity to a Niche degradation rate it cannot observe, since fleet operators currently hold exclusive, unaudited visibility into actual State of Health decline. Closing this friction therefore requires the Regime to acquire the same real-time degradation data the Niche already generates, which is the direct policy implication of this theoretical mismatch and the basis for the mandatory quarterly State of Health telemetry reporting mandate proposed in the Conclusions.

Third, the deductive document analysis revealed profound structural regulatory misalignment across all highest national strategies. The state possesses macro-level awareness of commodity volatility and proposes fiscal buffers in its SDG Accelerator Plan, yet remains structurally silent on infrastructure targets. While primary elicitation revealed a USD 1.7 million allocation under a four-year governance and policy initiative, independently corroborated by external project documentation [54], this budget is directed toward policy drafting and institutional coordination rather than physical processing infrastructure, confirming that no capital has been committed toward electric vehicle battery recycling

capacity of any kind. Furthermore, the revelation that Extended Producer Responsibility mandates are only now entering the legislative drafting phase provides the ultimate empirical proof of linear policy lag. This USD 1.7 million governance and policy allocation is distinct from the Green Growth and Climate Resilience Strategy's separate USD 17 million generic e-waste provision (2023; Table 3), which itself carries no infrastructure capacity target specific to electric vehicle batteries. The Rwandan state actively subsidized Niche adoption through import tax breaks, ensuring the hardware arrived years before the Regime-level regulatory mechanisms were prepared to manage the physical and financial consequences.

Extended Producer Responsibility as the Structural Solution

The results from the Results section, under Resource Value Loss Across Three Scenarios, demonstrate that linear disposal operates as a perpetual drain on national wealth: without domestic processing, the state continuously finances raw material importation while permanently forfeiting their residual value through disposal. Because Lithium Iron Phosphate chemistry holds little secondary market value and is organically unprofitable to process [55], waiting for the domestic recycling sector to mature without heavy state subsidies is a mathematically flawed strategy. The structural solution to the Dual Exposure is the immediate implementation of a mandatory pre-funded Extended Producer Responsibility escrow mechanism. This mechanism is not in tension with Rwanda's existing zero-rated import duty regime, since the two levers act on different sides of the ledger: the duty exemption is a general revenue concession that lowers acquisition price to accelerate adoption, whereas the escrow is a ring-fenced trust deposit that funds end-of-life liability the state and its operators already bear informally through warehouse stockpiling, rather than a tax on adoption itself.

An Extended Producer Responsibility escrow creates a pre-funded liability mechanism that explicitly decouples waste management from the profitability of the domestic recycling market. Under this framework, importers deposit a non-refundable fee per unit into a sovereign trust, ensuring that when each battery reaches its 3.5-year end of life, the state holds the capital required for safe disposal or chemical extraction, shifting the financial burden from the municipal taxpayer to the importing corporation. Within the established taxonomy of Extended Producer Responsibility instruments, the proposed escrow operates as an Advance Disposal Fee, a pre-collected per-unit levy imposed at the point of product importation that pre-funds end of life liability management without reliance on market profitability [36, 37]. Comparable Sub-Saharan African precedent confirms this instrument is administratively feasible at scale: South Africa published comprehensive Extended Producer Responsibility Regulations for electrical and electronic equipment in 2020 [56], Ghana's Act 917 imposes an advance eco levy on imported EEE, including batteries, at USD 0.15 to USD 15 per unit [57], and Kenya's 2024 EPR Regulations levy a flat KES 150 per imported battery under the polluter-pays principle [58], though this flat structure has drawn criticism for failing to differentiate by product value and risk [59], a flaw the fee proposed below avoids by indexing to the energy capacity method already established under Resource Value Loss and Energy Capacity Method.

Rather than adopting an arbitrary rate, this study sizes the escrow directly against the resource value loss already quantified in Table 2, so that the fee is calibrated to at minimum recapture the fiscal loss it is designed to prevent. At the floor, indexing the fee to recapture the baseline annual resource value loss of USD 42,920 (established under Resource Value Loss Across Three Scenarios) against the 29,584 kWh of annual stranded energy capacity yields a rate of approximately USD 1.45 per kWh, or USD 4.70 per imported 3.24 kWh battery pack. At the ceiling, indexing to the moderate recovery scenario of USD 118,400 yields approximately USD 4.00 per kWh, or USD 12.96 per battery. This floor sits above Kenya's implemented flat rate of approximately USD 1.16 per battery [58], a gap that is deliberate rather than incidental: the Kenyan rate was not derived from a quantified resource value loss, whereas the floor proposed here is indexed directly to Rwanda's own measured annual outflow and therefore represents the minimum rate at which the mechanism is fiscally self-justifying. Applied consistently across the 2026 to 2030 NST2 window at the fixed annual throughput of 9,131 failed packs established under Circularity Deficit, this range raises between USD 214,600 and USD 592,000 in cumulative escrow capital over five years. Table 4 presents this Min-Max escrow sizing alongside its cumulative output.

Table 4
Min-Max Extended Producer Responsibility escrow sizing (2026–2030).

Escrow Tier	Indexed Basis (Table 2)	Fee Rate (USD/kWh)	Fee per Battery (USD)	Annual Capital Raised	5-Year Cumulative Capital
Floor	Baseline resource value loss (USD 42920/year)	1.45	4.70	USD 42920	USD 214600
Ceiling	Moderate recovery scenario (USD 118400/year)	4.00	12.96	USD 118400	USD 592000

Note: Fee rates are derived by dividing the indexed annual resource value loss by the 29,584 kWh of annual stranded energy capacity established under Resource Value Loss Across Three Scenarios. Per-battery figures apply the resulting rate to the confirmed 3.24 kWh Ampersand pack capacity. Annual capital raised assumes the fixed annual throughput of 9,131 failed packs established under Circularity Deficit remains constant across the projection window; cumulative totals are undiscounted nominal sums across the five-year 2026–2030 NST2 period.

Sized against real capital benchmarks, this cumulative capital is modest relative to full hydrometallurgical infrastructure, where mid-scale plants require capital expenditure on the order of EUR 34.3 million [26], but it is adequate for a materially different and more immediate target. Techno-economic assessments of small-scale battery recycling facilities in comparable data-scarce developing economies confirm that collection, sorting, and State of Health testing infrastructure requires substantially lower capital intensity than chemical processing [60]. At the lower end, the escrow's five-year output is consistent in order of magnitude with Nigeria's Hinckley Recycling facility (USD 5 million), which itself combines cell testing, repurposing, and export logistics rather than domestic chemical refining [61], though this comparison is cross-regional and offered as an illustrative capital anchor rather than a directly transferable benchmark. This confirms the escrow's realistic first-generation output: a

national or two-to-three-site regional network for collection, State of Health testing, and safe-storage consolidation, which is the collection architecture this study identifies as the actual binding constraint, rather than a domestic hydrometallurgical processing plant.

An important qualification must be acknowledged at this point. As established in Background, under Lithium Iron Phosphate (LFP) Recycling Economics and The Alchemy Problem, alternative recovery pathways, namely direct regeneration [7] and mechanochemical processing [34], have emerged as lower-capital processing pathways specifically viable for Lithium Iron Phosphate chemistry, requiring substantially less capital expenditure than hydrometallurgical facilities. This observation strengthens rather than weakens the escrow argument: because direct regeneration lowers the per-unit capital threshold, the same fee schedule reaches processing-stage viability sooner, without requiring an upward revision of the rate. However, regardless of processing technology selected, the binding constraint in Rwanda remains the complete absence of formal collection infrastructure, the upstream architecture required to aggregate, transport, and sort end-of-life battery packs before any processing technology can receive them. An Extended Producer Responsibility escrow is the only mechanism that pre-commits the capital required to build that architecture, and Table 4 demonstrates that the fee required to do so is achievable at a rate within the range of existing regional EPR precedent (USD 0.15–15 per unit under Ghana's Act 917 [57]).

Furthermore, the Bamako Convention heavily restricts transboundary shipment of hazardous waste between African states, ruling out cross-border export as a viable long-term solution. Without escrow capital, Rwanda lacks the financial capacity to construct local processing facilities or finance the intercontinental logistics required to export waste to Asian refining nodes. By legally mandating this fee schedule, the state internalizes the environmental cost of the transition directly into the upfront procurement price at a rate that is both empirically traceable to the study's own findings and administratively consistent with regional precedent, effectively closing the regulatory vacuum that currently subsidizes linear consumption.

Alternative Explanation and the Illusion of Market Self-Correction

A rigorous assessment of these findings requires engaging the strongest counterargument available. Is the accumulation of dead batteries in Kigali warehouses merely a transitional problem that market growth will naturally self-correct?

Under this view, the profitability threshold for Lithium Iron Phosphate recycling is simply a function of scale. As Zeng et al. [62] demonstrate, the extraction of metals through urban mining is becoming more cost-effective than virgin mining. Based on this trajectory, it is theoretically plausible that once Rwanda’s commercial fleet reaches sufficient mass and throughput volume, a domestic or East African regional recycling operation will cross this profitability threshold and become economically viable. This would theoretically transform the current toxic stockpile into a temporary logistical delay rather than a permanent environmental liability.

A further self-correction argument concerns whether second-life applications, specifically stationary storage for mini-grid and off-grid deployment could absorb the waste stream before formal recycling becomes viable. Kebir et al. [46] document the technical feasibility of lithium-ion second-life systems in comparable East African contexts, and this study acknowledges second-life as a legitimate intermediate circularity pathway. However, it does not resolve the Circularity Deficit. Second-life deployment requires formal collection, State of Health testing, and redistribution infrastructure equally absent from Rwanda's current system the same infrastructure gap generating the deficit in the first instance. It defers rather than eliminates accumulation. Moreover, the informal reconditioning documented under Circularity Deficit Model already, approximates second-life in unstructured form, confirming market demand exists but cannot be captured without the collection architecture an EPR escrow would finance. Second-life therefore reinforces rather than replaces the EPR argument.

However, three specific empirical realities observed in this study invalidate the broader market self-correction hypothesis. First, the accelerated 3.5-year replacement cycle dictates that physical compounding is happening immediately. The state does not have the luxury of waiting for future market scale to arrive because the environmental burden is accumulating rapidly in real time. Second, the Bamako Convention heavily restricts the transboundary movement of hazardous waste between African states [63]. This creates a rigid legal barrier preventing Kigali from simply exporting its problem to a hypothetical regional processing hub in neighboring countries without severe logistical friction.

Third, and most critically, scale alone does not build chemical refineries. Capital builds refineries. As established through primary elicitation, the State’s proposed USD 1.7 million intervention is a fraction of the necessary capital. Without a mandatory Extended Producer Responsibility escrow to guarantee a revenue stream, private investors will not deploy USD 50 million to build a true hydrometallurgical plant in a landlocked economy just to process little value lithium chemistries. The market will not self-correct because current national policy fails to mandate the accumulation of the required mitigation capital.

Generalizability of the Analytical Framework

While grounded in Rwandan data, the analytical framework generalizes to any peripheral electric mobility adopter deploying Lithium Iron Phosphate fleets without domestic hydrometallurgical infrastructure. The deterministic stress test executed in Kigali is not an isolated geographical anomaly. It is a structural blueprint for evaluating the systemic friction occurring across the broader Global South.

The operational similarities observed in comparative emerging markets confirm this generalizability. In sub-Saharan Africa, the accelerated battery degradation of commercial electric motorcycles is compounded by local driving conditions, as heavy payloads drastically increase energy consumption [64], and poor road quality induces destructive mechanical vibrations [65]; broader deployments across the region reveal the same financial and operational hurdles documented here, scaling high-voltage commercial networks without the requisite supporting infrastructure [10]. This forces an asynchronous lifespan, a differential degradation rate between the battery pack and motorcycle chassis triggering

premature hardware replacement cycles before the broader municipal waste regime has adapted. Similarly, India's rapid electrification of its three-wheeler transit network [66, 67] has encountered its own transition friction, with a documented battery recycling infrastructure gap and unresolved Extended Producer Responsibility challenges for retired packs [11, 12]. Furthermore, the rise of highly dangerous informal dismantling sectors for e-waste in Vietnam [68, 69], where the pace of battery imports has outstripped the development of formal recycling infrastructure, leads to hazardous exposures for workers and residents due to a lack of formal chemical processing capacity [13, 14, 70]. The Dual Exposure model, as applied in this study, refers specifically to the simultaneous exposure of a peripheral electric mobility adopter to upstream supply chain price volatility for critical minerals and downstream circularity failure arising from absent recycling infrastructure and Extended Producer Responsibility frameworks. These comparative cases illustrate the Dual Exposure model's applicability as a transnational diagnostic phenomenon rather than an artefact of the Rwandan context.

Consequently, the mathematical logic of this study is highly adaptable for future research. The Circularity Deficit equation is portable. Applying it requires only fleet volume, battery mass, lifespan, and verified domestic capacity. By utilizing this framework, neighboring states can quantify their own localized exposure before their incoming battery stock transitions into unmanageable toxic accumulation [20].

Study Limitations

This methodology provides a robust physical and economic stress test within defined boundaries. First, informal reconditioning of degraded cells for off-grid solar reuse is observable in East Africa but unquantified in municipal tracking systems [46], which may marginally skew reported tonnage. Key informant lifespan figures from Ampersand and Spiro, who have a commercial incentive to report high fleet utilization, were cross-validated against published corporate telemetry rather than accepted uncritically.

Second, resource value loss relies on historically verified price extremes rather than continuous statistical variance, necessitated by proprietary paywalls on lithium spot price data and the opacity of private corporate procurement contracts [39, 71]. This yields a measure of absolute sovereign risk exposure rather than a probabilistic forecast.

Third, the 3.5-year urban lifespan is a central empirical estimate from primary telemetry, not a deterministic constant; degradation is inherently stochastic across topography, thermal environment, and cycling intensity. Because the annual failure rate is the inverse of lifespan, the Circularity Deficit is not strictly linear across this parameter; recalculating the inflow at the full 3.0 to 5.0 year range confirmed during Spiro elicitation yields an annual inflow of 364.93 tonnes at the lower bound and 238.00 tonnes at the upper bound, against the 319.59-tonne central estimate. Because domestic hydrometallurgical processing capacity is verified at zero tonnes per year across this entire range, the qualitative finding of a complete Circularity Deficit is unaffected by where the true lifespan falls within the informant-confirmed range, even though the absolute tonnage carries a real sensitivity of approximately − 25 to + 14 percent around the central estimate.

Fourth, this model treats fleet volume as static at the 2025–2026 baseline of 34,000 units; because NST2 targets further electrification through 2030, the reported Circularity Deficit and cumulative figures should be read as a conservative floor rather than an upper bound on the transition's true waste trajectory. Fifth, this is a single-country design. Rwanda's status as a continental e-mobility policy leader [16] means the regulatory gap documented here represents a best-case scenario among Sub-Saharan African adopters rather than an average, a qualification relevant to the generalizability discussion above, under Generalizability of the Analytical Framework.

Boundary of Evidence

Rigorous scholarship requires distinguishing empirical measurement from theoretical advocacy. This study can empirically prove that a structural policy gap exists between Rwanda's electric mobility adoption targets and its end-of-life regulatory capacity as of April 2026: verified zero domestic processing capacity and cost-prohibitive export barriers confirm that depleted batteries are structurally forced into localized warehouse accumulation, and deductive coding confirms that enforced Extended Producer Responsibility mandates and dedicated transit stabilization funds remain entirely absent from active policy, leaving the state reliant on a USD 1.7 million governance and policy initiative that allocates no capital toward recycling infrastructure of any kind [54].

Conversely, this study cannot prove that a specific upstream price shock will occur within the 2026 to 2030 window the stress test calculates absolute maximum exposure from historical anchors rather than forecasting market behavior nor that the current stockpile will remain unaddressed if the state accelerates policy implementation, nor that Rwanda's broader green growth targets will fail as a direct consequence of this single variable. The Dual Exposure model isolates the specific risk generated by the intersection of supply chain volatility and circularity deficits; it functions as a diagnostic tool identifying systemic friction, giving policymakers the empirical basis to act before theoretical vulnerability becomes permanent macroeconomic loss.

Conclusions

First, the localized stock and flow model confirms an annual Circularity Deficit of 319.59 tonnes, representing a complete recycling shortfall confirmed by zero domestic processing capacity across all chemical recovery modalities, including direct regenerative pathways. Second, the linear disposal of these high voltage packs strips between USD 42,920 and USD 245,680 of unrecovered lithium value from the domestic economy annually, compounding to a cumulative loss of up to USD 1,228,400 under peak historical stress across the 2026 to 2030 NST2 window. Third, systematic deductive coding combined with primary validation confirms a dangerous linear policy lag. While primary elicitation revealed a USD 1.7 million state allocation under a governance and policy initiative independently confirmed as directed toward policy drafting and institutional coordination rather than physical recycling infrastructure [54], no capital has been committed toward electric vehicle battery processing capacity of any kind, and Extended Producer Responsibility mandates governing high voltage battery waste are only now entering

the legislative drafting phase. Fourth, the economic constraints of this processing deficit logically force operators into informal reconditioning and cell cannibalization to artificially extend battery lifespans, leaving the sector fully exposed to upstream market shocks.

To secure the transition against these systemic vulnerabilities, the sovereign government must execute three targeted interventions. (1) The Rwanda Environment Management Authority must accelerate its legislative drafts into a mandated, pre-funded Extended Producer Responsibility escrow, indexed at USD 1.45 to USD 4.00 per kilowatt hour of imported high voltage battery, a range shown under Extended Producer Responsibility as the Structural Solution to raise between USD 214,600 and USD 592,000 in cumulative capital over the 2026 to 2030 window to capitalize localized collection and waste management infrastructure. (2) The Ministry of Trade and Industry should legally condition all electric vehicle import licenses upon demonstrated end of life disposal agreements to prevent informal stockpiling. (3) The Ministry of Infrastructure must mandate quarterly State of Health telemetry reporting to a centralized national registry to eliminate information asymmetry regarding actual fleet degradation rates.

Future research should conduct a dedicated chemical engineering cost-benefit analysis comparing the minimum throughput volume and capital requirements at which both hydrometallurgical processing and direct regenerative pathways become economically viable in a landlocked East African economy, given the emerging literature's identification of direct regeneration as the lower capital option for Lithium Iron Phosphate chemistry [7, 34]. An actuarial study is also required to calculate the precise insurance and freight costs of Class 9 hazardous battery waste export under the Bamako Convention, clarifying the financial burden of the international disposal pathway. Collectively, these findings offer the first quantified diagnostic and costed policy instrument for a Circularity Deficit in a Lithium Iron Phosphate commercial fleet, providing a replicable framework for peripheral e-mobility adopters confronting the same structural conditions across the Global South.

Abbreviations

BaaS
Battery-as-a-Service
EPR
Extended Producer Responsibility
LFP
Lithium Iron Phosphate
MINICOM
Ministry of Trade and Industry
NST2
Second National Strategy for Transformation
REMA
Rwanda Environment Management Authority

SDG
Sustainable Development Goals
USD
United States Dollar

Declarations

Ethics approval and consent to participate

Key informant elicitations were conducted with technical personnel at Ampersand, Spiro, EnviroServe, and the Rwanda Environment Management Authority (REMA), acting in their professional institutional capacity. All participants were briefed on the academic purpose of the study prior to elicitation and provided informed consent to participate. All informant data were anonymized at the individual level and attributed broadly to institutional role rather than named individuals, and no personal or vulnerable-population data were collected. Formal ethics committee review was therefore not required under UNILAK's research governance framework.

Consent for publication

Not applicable. This manuscript does not contain any individual person's data, images, or identifying details.

Availability of data and materials

The macroeconomic datasets analysed during the current study are publicly available from the United States Geological Survey (USGS) Mineral Commodity Summaries and the London Metal Exchange (LME). The primary key informant elicitation data supporting the findings of this study are available from the corresponding author on reasonable request.

Competing interests

JSK, AOM, and ABMJ declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Authors' contributions

J.S. K conceptualized the study, developed the methodology, conducted the investigation and formal analysis, and wrote the original draft. A.O. M supervised the study, contributed to the methodology,

validated the findings, and reviewed and edited the manuscript. A.B.M.J contributed to the investigation and reviewed and edited the manuscript. All authors read and approved the final manuscript.

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Figures

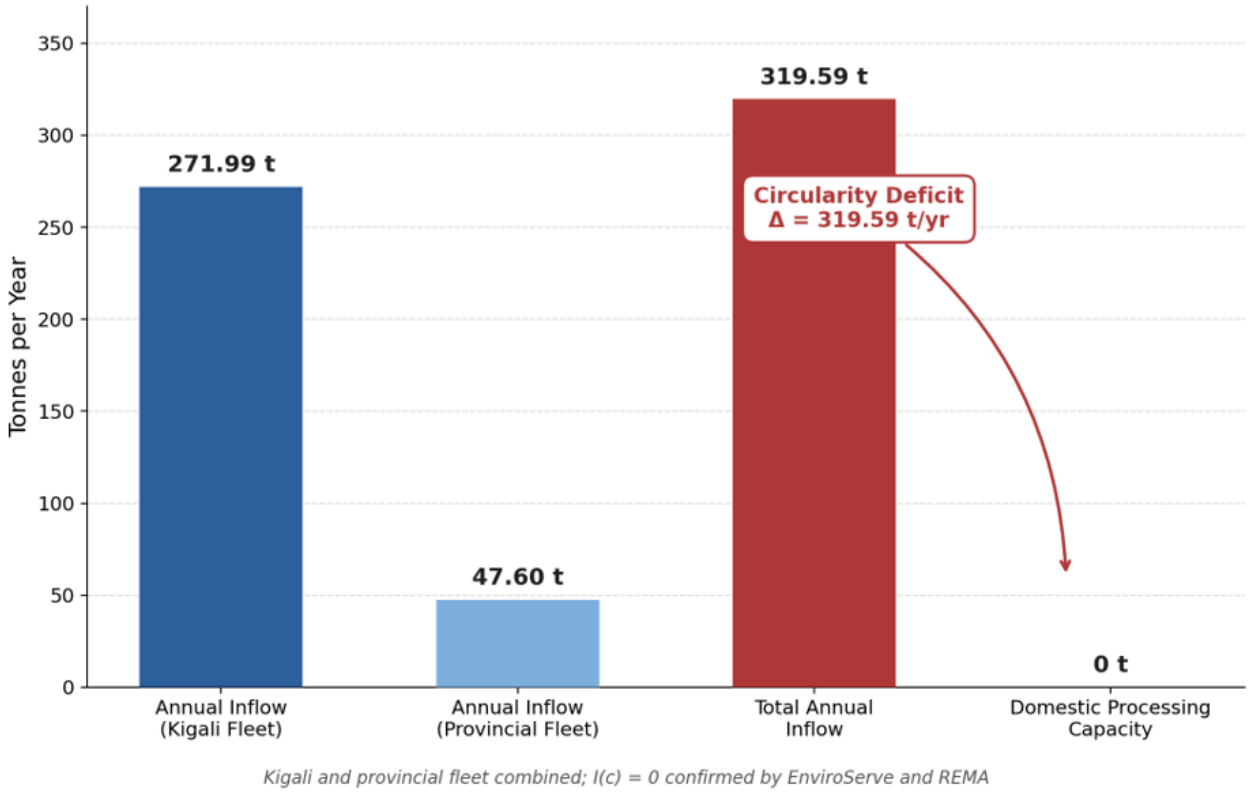

Figure 1

Annual Circularity Deficit against domestic processing capacity.

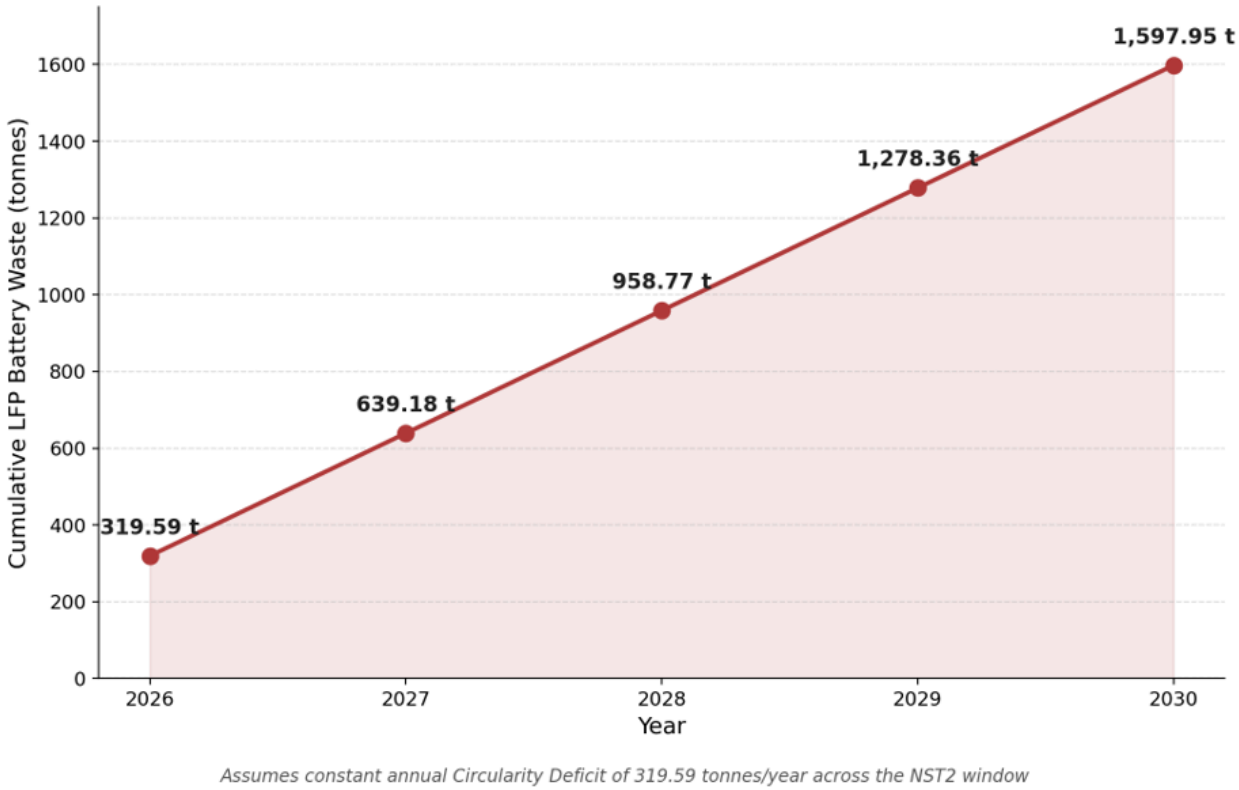

Figure 2

Projected cumulative LFP battery waste accumulation, 2026-2030.

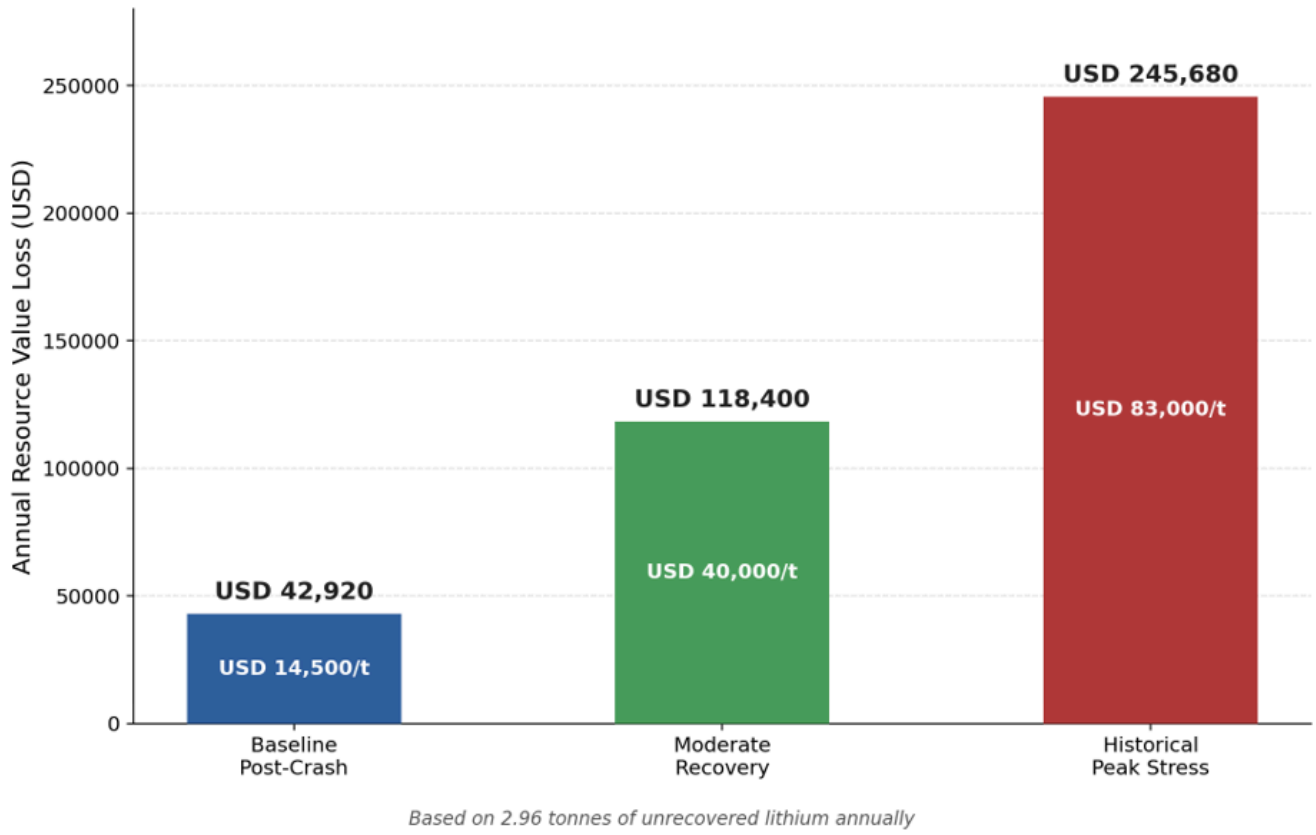

Figure 3

Annual unrecovered lithium resource value loss across three price scenarios.

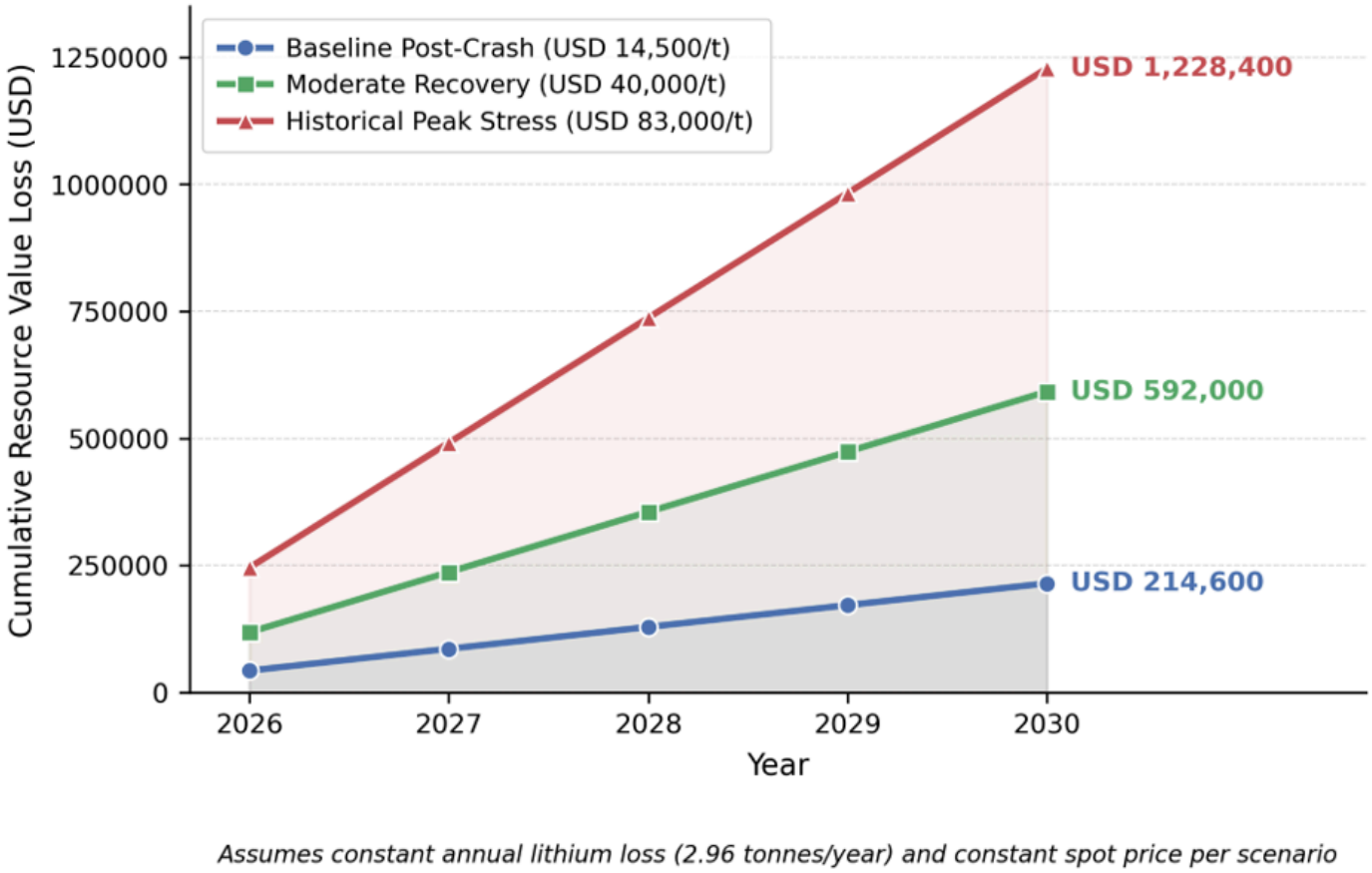

Figure 4

Projected cumulative resource value loss, 2026-2030 NST2 window.