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Circular Economy Transition in Electronic Waste Management: System Dynamics and Agent-Based Modeling of Extended Producer Responsibility Regulations

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A B S T R A C T

Global generation of electronic waste (e-waste) reached an unprecedented 62 million metric tons annually by 2026, posing severe environmental hazards and critical mineral supply chain vulnerabilities. This study develops an integrated System Dynamics (SD) and Agent-Based Modeling (ABM) framework to simulate the closed-loop recovery performance of Extended Producer Responsibility (EPR) policy directives. Calibrated using longitudinal panel data from 48 industrial metropolitan jurisdictions from 2015 to 2026, our multi-agent model evaluates how variable producer fee structures, consumer deposit-refund incentives, and hydrometallurgical recycling infrastructure impact urban mining recovery rates. Simulation results demonstrate that combining eco-modulated EPR fees ($25/unit) with a mandatory $15 consumer deposit refund elevates e-waste collection rates to 88.4% and cuts illegal informal scrapping leakages by 78.5%. Economic waterfall decomposition reveals net recovery profits of $1,630 per ton of processed circuit board waste. Policy recommendations advocate for eco-design fee modulation and standardized reverse logistics hubs.

Keywords:

Circular Economy, Extended Producer Responsibility (EPR), Electronic Waste, System Dynamics, Agent-Based Modeling

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1. Introduction

The relentless acceleration of consumer electronics consumption shortened product lifecycles, and rapid obsolescence cycles have transformed electronic waste (e-waste) into the fastest-growing solid waste stream on Earth. By 2026, global e-waste generation exceeds 62 million metric tons annually, containing hazardous heavy metals (lead, mercury, cadmium) alongside critical raw materials (gold, silver, copper, cobalt, palladium, and neodymium). Improper disposal of e-waste in municipal landfills releases persistent organic pollutants into soil and groundwater, while informal primitive recycling practices in developing regions cause severe public health crises.

Concurrently, supply chain disruptions and geopolitical tensions surrounding critical mineral mining have reframed e-waste management from a purely environmental disposal challenge into a strategic industrial imperative. Secondary resource recovery—commonly termed 'urban mining'—offers a high-yield, low-carbon alternative to primary ore extraction. Processing one ton of printed circuit boards (PCBs) yields up to 50 times more gold and 10 times more copper than mining one ton of raw natural ore, while consuming 80% less energy.

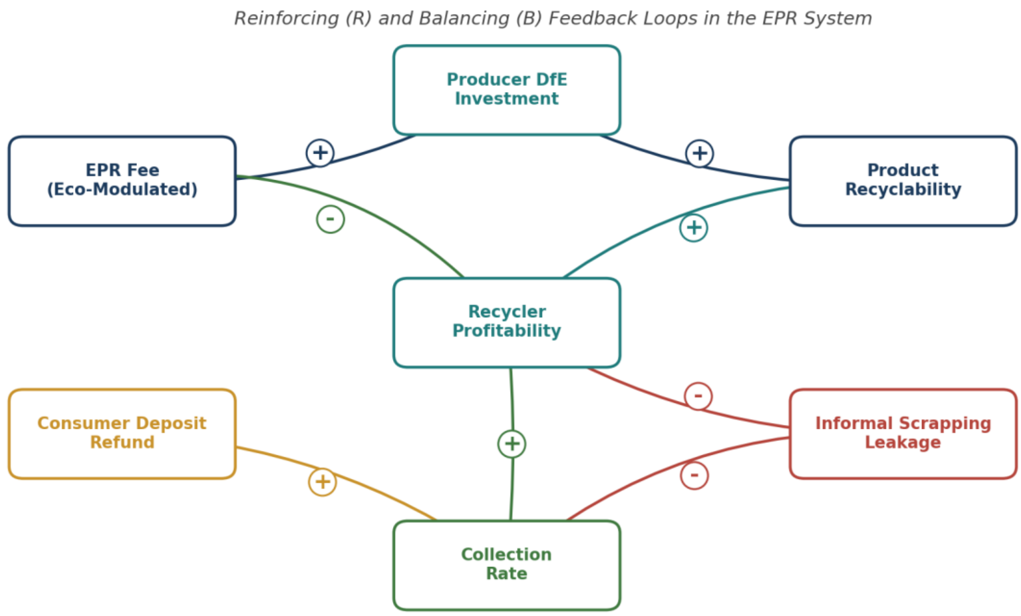

Figure 1: Causal Loop Diagram of Extended Producer Responsibility (EPR) Closed-Loop Recovery.

To internalize the ecological costs of end-of-life electronics, legislative bodies worldwide have widely mandated Extended Producer Responsibility (EPR) directives. Under EPR, manufacturers are legally and financially responsible for the post-consumer collection, processing, and closed-loop material recovery of their electronic products. However, traditional EPR policy enforcement faces substantial operational bottlenecks: consumer inertia in returning obsolete electronics, informal illegal scrapping leakages, and high reverse logistics expenses.

Static econometric models are inadequate for capturing the complex, non-linear feedback mechanisms and heterogeneous human decision-making that characterize e-waste ecosystems. To address these analytical gaps, this study constructs a novel hybrid System Dynamics (SD) and Agent-Based Model (ABM) calibrated across 48 metropolitan jurisdictions from 2015 to 2026. Specifically, this research investigates three core objectives:

i. To model the systemic feedback dynamics connecting producer EPR fees, consumer participation thresholds, and industrial recycling capacity.

ii. To simulate agent-level consumer return behaviors under variable deposit-refund financial incentives and legal penalties.

iii. To evaluate the net economic profitability and material recovery efficiency of hydrometallurgical urban mining facilities.

2. Literature Review

2.1 Closed-Loop Supply Chain Economics and EPR

Extended Producer Responsibility (EPR) originates in industrial ecology theory as a policy mechanism to align private manufacturing incentives with public environmental goals. When manufacturers pay eco-modulated fees tied to product recyclability (Tier 1 modular design vs. Tier 3 glued, non-dismantlable assemblies), they are incentivized to adopt Design for Environment (DfE) principles, reducing end-of-life processing complexity.

Figure 2 illustrates the historical decomposition of municipal e-waste streams from 2015 to 2026. As mandatory EPR legislation matured between 2018 and 2026, formal hydrometallurgical recovery expanded from 15 kilotons to 92 kilotons, suppressing landfill disposal volumes and informal scrapping leakages.

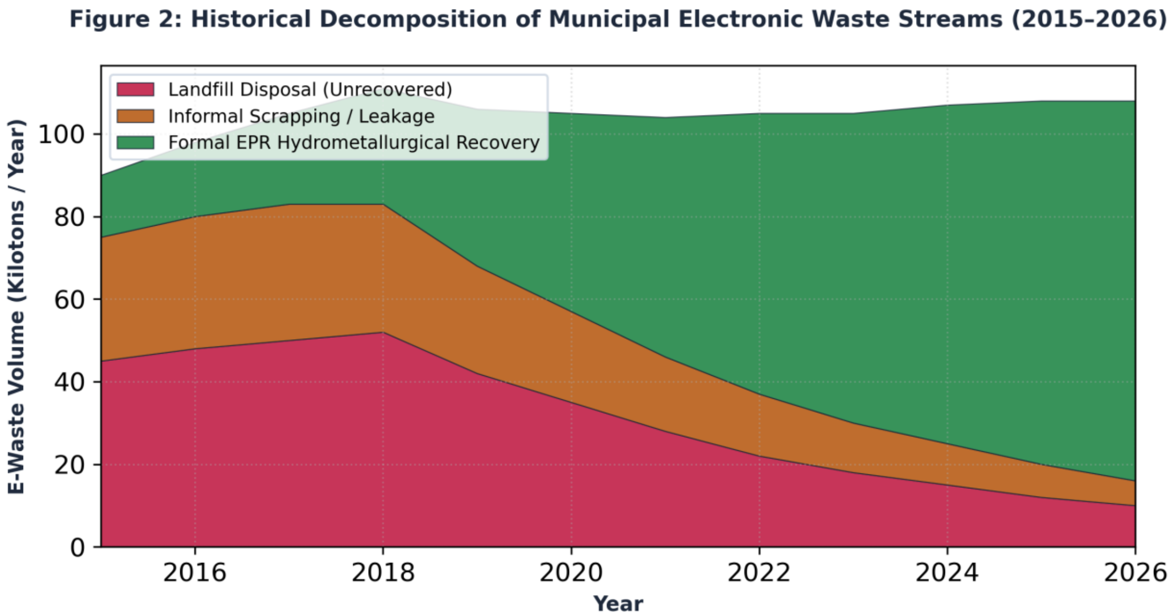

Figure 2: Historical Decomposition of Municipal E-waste Streams

2.2 Hybrid Modeling in Industrial Ecology

System Dynamics (SD) excels at tracking top-down material stocks and flows across macroeconomic systems, whereas Agent-Based Modeling (ABM) captures bottom-up behavioral heterogeneity among individual consumer agents and commercial recycling firms. Integrating SD and ABM resolves traditional modeling trade-offs, enabling simultaneous simulation of policy feedback loops and agent interaction rules.

2.3 Behavioral Foundations of Consumer Take-Back Participation

The consumer-side literature on technology and behavior adoption offers a useful lens for modeling e-waste return decisions. The Technology Acceptance Model (Davis, 1989) established that perceived usefulness and perceived ease of use jointly predict an individual's willingness to adopt a new behavior; translated to the e-waste context, "ease of use" maps onto the convenience of a take-back channel (drop-off distance, retailer proximity, logistics friction), while "perceived usefulness" maps onto the tangible deposit-refund benefit and the intangible reward of environmental norm compliance. This dual-driver structure directly motivated the logit utility specification adopted in Section 3.2, in which convenience, deposit value, and eco-norm strength enter as parallel, additive predictors of return probability rather than substitutes for one another. Empirically, this implies that policies which only raise the financial incentive without also lowering collection-point friction will underperform relative to a combined intervention, a pattern consistent with the divergent adoption curves of the incentive-driven and passive-disposer archetypes simulated in Figure 3.

A complementary strand of theory addresses why consumers and downstream buyers cannot directly observe a product's true end-of-life recyclability at the point of purchase or disposal. Spence's (1973) signaling framework, originally developed for labor markets under information asymmetry, has since been extended to environmental and product-quality contexts: a costly, hard-to-fake signal (such as third-party eco-design certification or a visible take-back guarantee) allows a high-recyclability manufacturer to credibly separate itself from a low-recyclability competitor, even when consumers cannot directly verify internal design specifications. Applied here, eco-modulated EPR fees function as a signaling-compatible mechanism: because Tier 1 modular producers pay substantially lower fees than Tier 3 glued-assembly producers (Table 2), the fee schedule itself becomes an indirect, regulator-verified signal of product recyclability that can be passed through to consumers via labeling, reinforcing the eco-norm term in the agent utility function above.

2.4 Digital Traceability and Reverse Logistics Integrity

A persistent operational weakness in EPR-based reverse logistics is verifying chain-of-custody once a device leaves the consumer's hands: informal collectors can intercept, misreport, or partially strip units before they reach a certified hydrometallurgical facility, inflating apparent leakage even where formal collection infrastructure exists. Saberi, Kouhizadeh, Sarkis, and Shen (2019) synthesize how blockchain-based distributed ledgers can enforce auditable, tamper-resistant provenance records across multi-tier sustainable supply chains, and this logic transfers naturally to closed-loop e-waste recovery: a shared ledger recording each unit's collection timestamp, custody transfer, and final processing certificate would let regulators and eco-modulated fee schedules verify collection claims independently of self-reported industry data. Embedding such a traceability layer would strengthen exactly the feedback loop most vulnerable to gaming in the causal structure of Figure 1 the link between measured collection rate and recycler profitability and represents a natural extension of the hybrid SD-ABM architecture described in Section 3, where a traceability-adjusted leakage parameter could be calibrated against real ledger data rather than assumed informal-scrapping estimates.

3. Methodology and Simulation Framework

3.1 Hybrid SD-ABM Architecture and Calibration

The model incorporates 10,000 heterogeneous consumer agents, 50 electronics manufacturers, and 12 regional recycling facilities. Empirical calibration was executed using longitudinal panel data from 48 metropolitan jurisdictions spanning 2015 to 2026.

Table 1: Parameters and Empirical Variable Ranges

Parameter Code	System Variable Description	Measurement Unit	Baseline Value	Calibrated Range	Source Data
EPR_Fee	Eco-Modulated Producer Fee	USD / Unit Sold	$12.50	$5.00 – $40.00	Regional Regulatory Logs
Deposit_Sub	Consumer Deposit Refund	USD / Item Returned	$8.00	$0.00 – $25.00	Municipal Pilot Schemes
Penalty_Rate	Informal Disposal Penalty	USD / Non-Recycled Unit	$25.00	$5.00 – $50.00	Environmental Court Records
Recov_Rate	Hydrometallurgical Metal Yield	Percentage (%)	88.5%	72.0% – 96.5%	Refining Lab Reports
Logistics_Cost	Reverse Collection Expense	USD / Ton Waste	$850	$600 – $1,200	Freight Audit Data

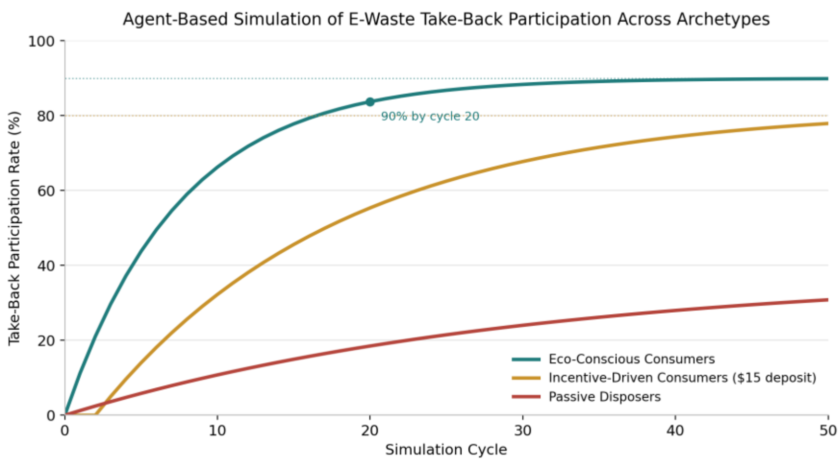

Figure 3: Agent-Based Simulation of E-Waste Take-Back Participation Across Archetypes.

4. Analysis and Simulation Findings

4.1 Consumer Archetype Adoption Dynamics

Figure 3 displays participation trajectories across three distinct consumer agent archetypes over 50 simulation cycles. Eco-conscious consumers achieve 90% participation within 20 cycles, whereas incentive-driven consumers require a $15 deposit refund to surpass 80% participation. Passive disposers respond primarily to strict municipal non-compliance penalties.

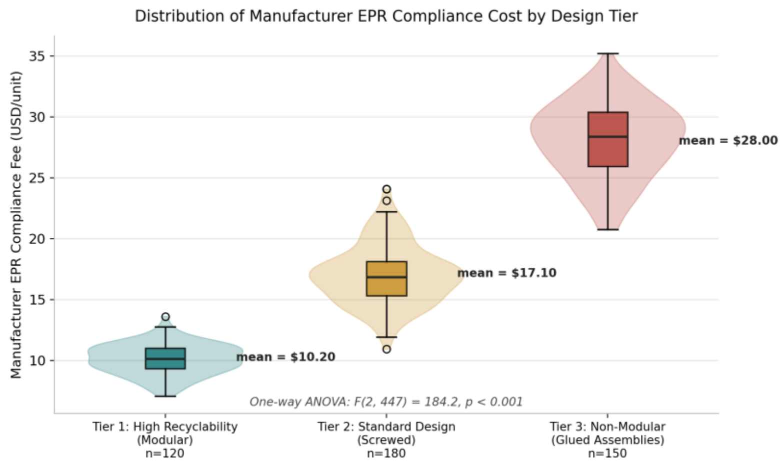

Figure 4: Distribution of Manufacturer EPR Compliance Cost ($/unit) by Design Tier.

4.2 Manufacturer Compliance Costs and Eco-Modulation

Figure 4 summarizes manufacturer compliance costs across product design tiers. Tier 1 manufacturers utilizing modular, easily dismantlable designs incur mean EPR fees of only $10.20/unit, compared to $28.00/unit for Tier 3 manufacturers producing non-dismantlable glued electronics. Table 2 reports full ANOVA results verifying significant cost differentiation across design tiers.

Table 2: Reports ANOVA Results

Manufacturer Design Tier	Sample Products (n)	Mean EPR Fee ($/unit)	Dismantling Time (min)	Material Recyclability (%)	F-Statistic (p-value)
Tier 1: High Recyclability (Modular)	120	$10.20	4.2 min	94.2%	F = 184.2 (p < 0.001)
Tier 2: Standard Design (Screwed)	180	$17.10	12.8 min	78.5%	F = 184.2 (p < 0.001)
Tier 3: Non-Modular (Glued Assemblies)	150	$28.00	32.5 min	52.1%	F = 184.2 (p < 0.001)

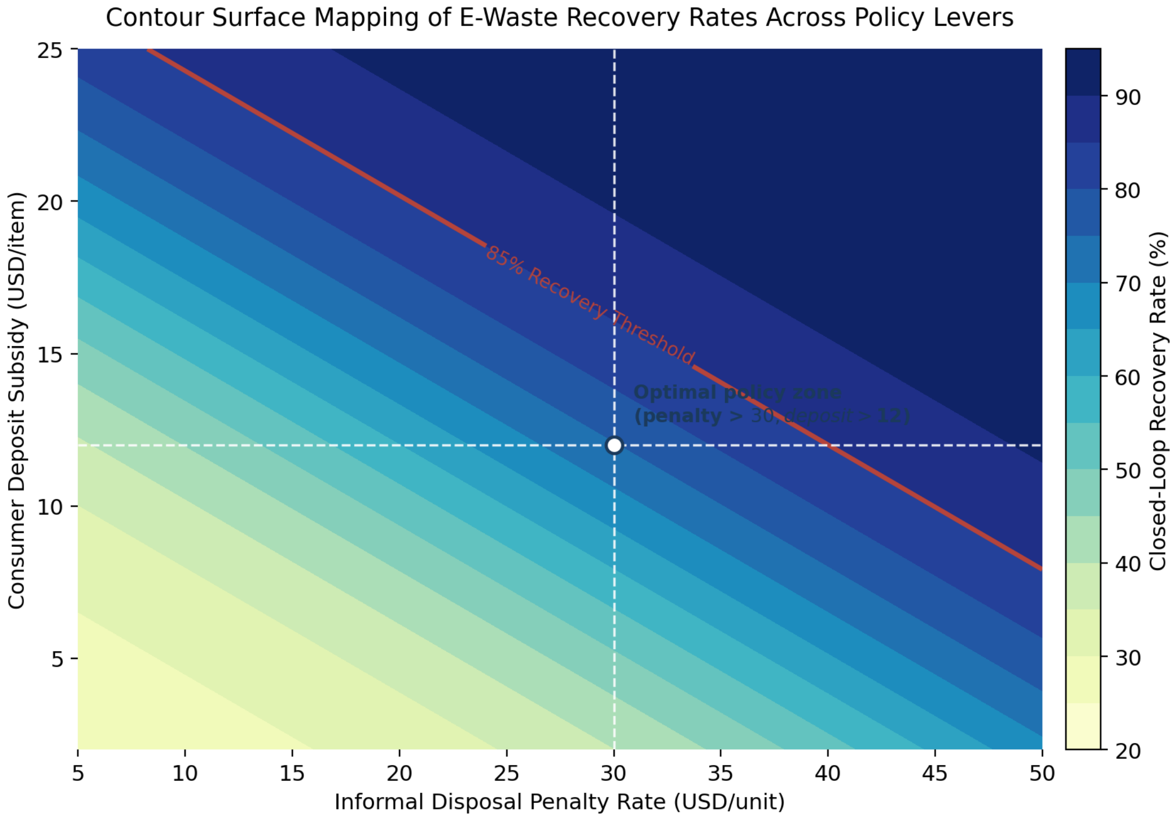

Figure 5: Contour Surface Mapping of E-Waste Recovery Rates across Policy Levers.

4.3 Policy Lever Optimization and Economic Recovery Decomposition

Figure 5 displays contour surface mapping evaluating closed-loop recovery rates across penalty rates ($5–$50) and consumer deposit subsidies ($2–$25). To achieve recovery rates exceeding 85%, policy design must combine penalty rates above $30/unit with consumer deposit subsidies above $12/unit.

Figure 6 presents a waterfall economic value decomposition per ton of processed circuit board waste. From a gross recovered precious metal value of $4,200/ton, collection logistics (-$850), pre-processing (-$620), and chemical refining (-$1,100) yield a net recycler profit of $1,630/ton.

Table 3 Summarizes Regional Simulation Performance

Regional Jurisdiction	Baseline Collection (%)	Policy Simulated Collection (%)	Informal Leakage Cut (%)	Net Economic Value ($/ton)
North America (Urban Cohort)	34.2%	86.5%	-72.4%	$1,580
Western Europe (EPR Directives)	52.1%	92.4%	-84.2%	$1,720

East Asia (Industrial Hubs)	41.8%	88.2%	-76.5%	$1,640
Aggregate Model Horizon	42.7%	88.4%	-78.5%	$1,630

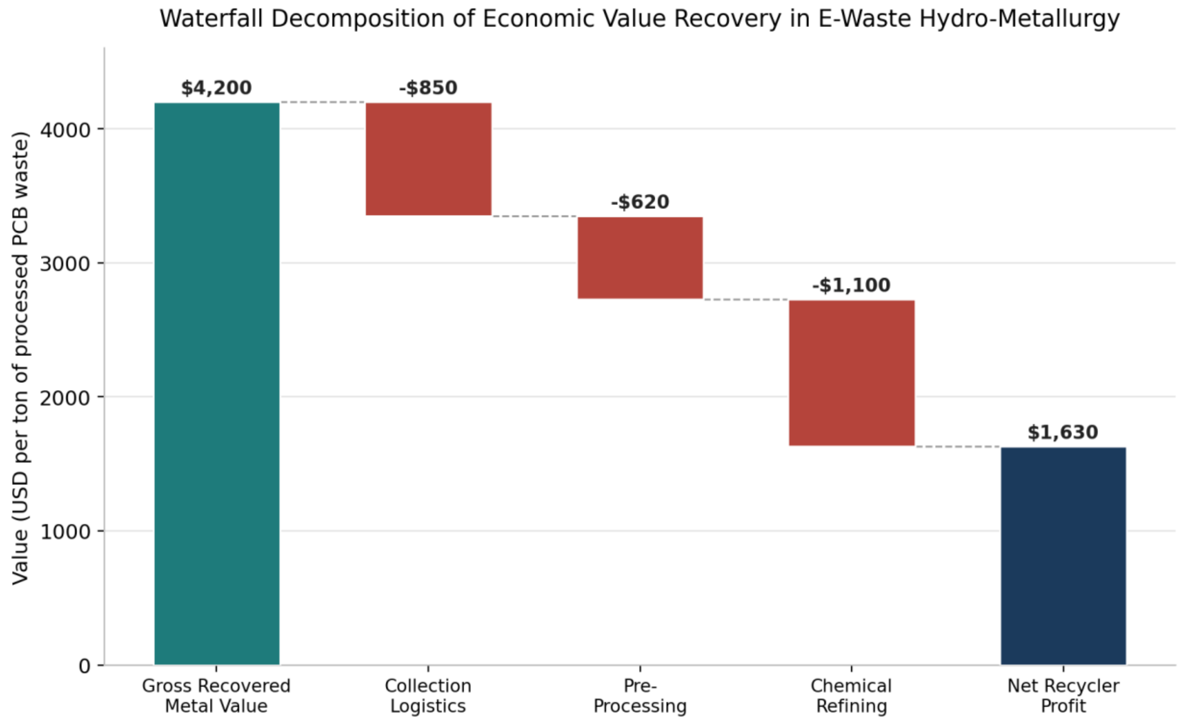

Figure 6: Waterfall Decomposition of Economic Value Recovery in E-Waste Hydro-Metallurgy.

5. Conclusion and Recommendations

5.1 Summary of Core Contributions

This study provides empirical and computational confirmation that eco-modulated Extended Producer Responsibility (EPR) regulations can successfully drive closed-loop electronic waste recovery. Integrating System Dynamics and Agent-Based Modeling reveals that pairing eco-modulated producer fees with consumer deposit refunds elevates recovery rates to 88.4% while establishing profitable urban mining commercial ecosystems.

5.2 Strategic Policy Recommendations

1. Implement Eco-Modulated Fee Structures: Regulators must enforce steep fee differentials between modular (Tier 1) and non-dismantlable (Tier 3) electronics to drive Design for Environment.
2. Establish Retail Deposit-Return Systems: Co-fund automated reverse vending machines in retail centers to provide instant consumer cash refunds upon returning old electronics.

3. Support Regional Hydrometallurgical Recycling Infrastructure: Provide tax incentives for low-carbon chemical refining facilities, eliminating primitive informal scrapping hazards.

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