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Capacity-Constrained Pathways to Formal EV Battery Recycling in China

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Abstract

China's retired electric vehicle (EV) battery recycling system faces rapidly increasing end-of-life supply, persistent formal–informal competition, and uncertainty over policy withdrawal. Existing models often equate strategy probabilities with formalization and overlook unreturned stocks, consumer channel choice, and processing capacity. This study develops a 2020–2050 system dynamics model linking a cohort–Weibull retirement module with material-conserving battery flows, channel allocation, capacity expansion, authorized integration, metal recovery, relative environmental burden, and adaptive policy withdrawal. All scenarios share a fixed 25% formal-processing share in 2025. Under current policy, the formal share reaches only 52.95% by 2050, while informal processing and unreturned stocks remain substantial. Among single pathways, subsidy plus capacity support accelerates early formalization, whereas enforcement achieves the highest nominal 2050 share (60.83%). Integration is conditional on licensed capacity: 108.50 GWh yr^{-1} is requested for transfer in 2050, but only 51.27 GWh yr^{-1} is realized. Fixed, life-cycle, and staged portfolios reach 68.32%, 65.77%, and 66.49%, respectively. Relative to the fixed portfolio, the adaptive portfolios reduce model-accounted government expenditure by 29.68% and 45.14%, with endpoint losses of 2.55 and 1.82 percentage points. Across 200 Latin-hypercube draws centered on the nominal settings, suppression is the leading single pathway in 97.5% of cases, while each portfolio exceeds the best single pathway in every draw. The results support sequential governance that combines early capacity building, persistent baseline enforcement, capacity-constrained integration, and gradual withdrawal after observable maturity conditions are met.

Keywords: Retired EV batteries, Formal and informal recycling, System dynamics, Extended producer responsibility, Policy portfolio, Capacity constraint.

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1. Introduction

The electrification of road transport is simultaneously expanding battery production, use, and retirement. As the world's largest market for new energy vehicles and traction batteries, China will encounter a large and increasingly heterogeneous stream of retired batteries earlier than most countries. These batteries contain lithium (Li), cobalt (Co), and nickel (Ni), and their controlled recovery can reduce demand for primary resources and mitigate the environmental, safety, and health risks associated with inappropriate dismantling. Conversely, prolonged storage by owners or processing without pollution controls can forfeit both resource value and environmental benefits. Recycled-content targets also need to be aligned with the physical availability of recoverable material and the conditions of metal circularity; otherwise, formally ambitious targets may create new allocation constraints (Zhou et al., 2024). Retired-battery recycling is therefore not merely an end-of-pipe waste-management problem. It connects the EV industry, critical-material security, and the transition toward a circular economy.

China has progressively developed an extended producer responsibility (EPR) framework for traction-battery recycling. The 2018 Interim Measures assigned primary responsibility to vehicle producers and promoted life-cycle governance through coding, traceability, service networks, and the management of comprehensive-utilization enterprises (Ministry of Industry and Information Technology of China et al., 2018). The 2024 industry specification raised requirements for safety, environmental protection, and resource utilization (Ministry of Industry and Information Technology of China, 2024). In 2025, the State Council issued an action plan to improve legislation and collection networks (General Office of the State Council of China, 2025), while the six-ministry Order No. 73, which took effect on 1 April 2026, further specified collection responsibilities, information reporting, and penalties (Ministry of Industry and Information Technology of China et al., 2025). Yet institutional reinforcement does not automatically direct retired batteries to licensed processors. Informal actors can remain competitive because of dense networks, flexible collection, higher purchase offers, and lower compliance costs. Consumers consequently operate as the system's decisive allocation valve (Tang et al., 2023a; Yang et al., 2025; Wang et al., 2026a).

Formal–informal competition is not reducible to price alone. Licensed firms incur environmental, safety, transport, traceability, and administrative costs and generally achieve higher recovery performance, but may be less competitive in purchase prices, door-to-door service, and network density. Informal actors provide convenient collection, while self-processing can generate greater environmental damage. Evidence from Chinese residents indicates that perceived behavioral control, economic incentives, subjective norms, and self-identity all affect recycling intentions; better prices, denser service networks, and stronger environmental awareness increase participation in formal recycling (Tang et al., 2023a). Agent-based simulations similarly show that publicity, price support, and policy

combinations alter formal collection through heterogeneous interactions between households and collectors (Tang et al., 2023b). Government thus influences, rather than directly determines, final battery destinations by changing relative channel utility, processing capacity, and institutional constraints.

Most policy studies on retired batteries employ evolutionary games, supply-chain games, or system dynamics. Tu et al. (2020) and He and Sun (2022) show that rewards, penalties, and dynamic regulation change strategic evolution among governments, firms, and the public. Nie et al. (2024) and Tan et al. (2025) extend this reasoning to central and local governments, producers, and third-party recyclers. Complex-network studies demonstrate that coevolution among residents and recyclers, information interaction, and network structure can change diffusion speed and generate diminishing policy returns (Wang et al., 2025a, 2026b). Similar multi-stakeholder coevolution is observed in other waste-recycling chains (Long et al., 2019). These studies explain strategic incentives, but a probability of choosing a positive strategy is not the same as a physical quantity of batteries reaching licensed treatment.

A related literature investigates competition and cooperation between formal and informal recyclers. Wang et al. (2024) show that cooperation can generate economic and environmental synergies under particular cost and market conditions. Closed-loop supply-chain studies compare subsidy recipients, recovery modes, and coordination mechanisms. Production, collection, and capacity subsidies produce different price, technology, and fiscal outcomes (Zhang et al., 2024; Chu et al., 2025), while tax–subsidy packages, dynamic incentives, and consumer low-carbon preferences change government and firm decisions (Chen et al., 2025; Guo and Yang, 2026; Sun et al., 2026). Coalition formation, channel leadership, carbon trading, and joint environmental policies also alter recovery volumes and profits (Zhang and Wang, 2025; Wu, 2025; Lin et al., 2026). These models establish policy complementarity, but their principal outputs are usually equilibrium prices, profits, or recovery rates; they rarely track unreturned inventories and capacity feedback after policy withdrawal.

Long-horizon simulations have begun comparing subsidies, technological progress, carbon trading, and policy packages. Wei (2025) finds that phased subsidies can outperform fixed subsidies, while Wu et al. (2025) report that policy portfolios often improve recovery and closed-loop supply-chain performance relative to single instruments. Wang et al. (2026a) show that strategic EPR can substantially increase formal flows and propose repositioning some informal recyclers as flexible collectors. Three gaps nevertheless remain. First, formalization is commonly approximated by strategy probabilities or exogenous shares, which cannot jointly represent retired supply, unreturned stock, and processing constraints. Second, informal integration frequently assumes that licensed firms can accept all requested transfers, potentially overstating its effect. Third, policies are often maintained indefinitely or withdrawn at preset dates, rather than in response to observed system maturity.

This study addresses three questions. RQ1 asks how rapidly growing retired-battery

supply is dynamically divided among unreturned stock, formal processing, and informal processing under continuation of current policy. RQ2 asks when suppression, substitution, and integration are most effective, and whether integration retains its relative advantage once the residual capacity of licensed processors constrains actual transfers. RQ3 asks how fixed, state-triggered life-cycle, and staged portfolios trade off formalization gains, resource and environmental outcomes, and model-accounted government expenditure.

The study contributes in three ways. First, it tracks batteries from retirement through immediate and delayed return, collection inventory, channel allocation, and final processing under explicit material conservation, rather than equating strategy probabilities with formal-processing shares. Second, it separates the collection function of informal actors from the risks of informal processing, and constrains authorized transfers by residual licensed capacity. Third, it compares fixed and adaptive withdrawal strategies under identical peak instruments and reports formal processing, cumulative volume, critical-metal recovery, relative environmental burden, and model-accounted expenditure. The policy question consequently shifts from identifying a universally best instrument to determining when instruments should be combined, when they should be withdrawn, and which capacities must be in place for integration to work.

2. Methods and data

2.1 Research design and system boundary

The model covers 2020–2050 with a time step of 0.125 years. The period 2020–2025 initializes the system and calibrates historical boundaries. All scenarios share the same state in 2025, after which new policies are activated gradually. Battery flows are measured in energy-equivalent GWh, with parallel mass-flow accounts for Li, Co, and Ni. Retired supply is generated by an upstream cohort–Weibull module. Annual in-use cohorts follow a Weibull lifetime distribution with shape parameter $k = 3.5$ and a scale parameter derived from mean lifetime. The probability of retirement at a given age equals the difference between cumulative failure probabilities in adjacent years. The baseline BS–Mixed–LFP-only pathway preserves an evolving chemistry mix with increasing dominance of lithium iron phosphate (LFP). In the incomplete second-use case, only LFP batteries enter second use and remain there for three years before retirement.

The upstream retirement module supplies annual retired-energy and Li, Co, and Ni flows to the governance model. The linkage is one-way: recycling policy does not alter the assumed vehicle-sales, lifetime, or chemistry pathways. Therefore, every governance scenario encounters identical retired supply. This separation retains time-varying material composition while preventing changes in vehicle demand or battery lifetime from being misattributed to recycling policy.

The downstream boundary begins when batteries reach end of life and ends with formal or informal processing and metal recovery. Direct formal collection is not the only path to formal treatment. Informal collectors may transfer batteries to

licensed processors under authorized integration. The formal-processing share is consequently defined as the quantity ultimately treated by licensed processors divided by total processed batteries. This outcome differs from the consumer-side share initially directed to a formal collector and corresponds more directly to environmental burden and metal-recovery performance.

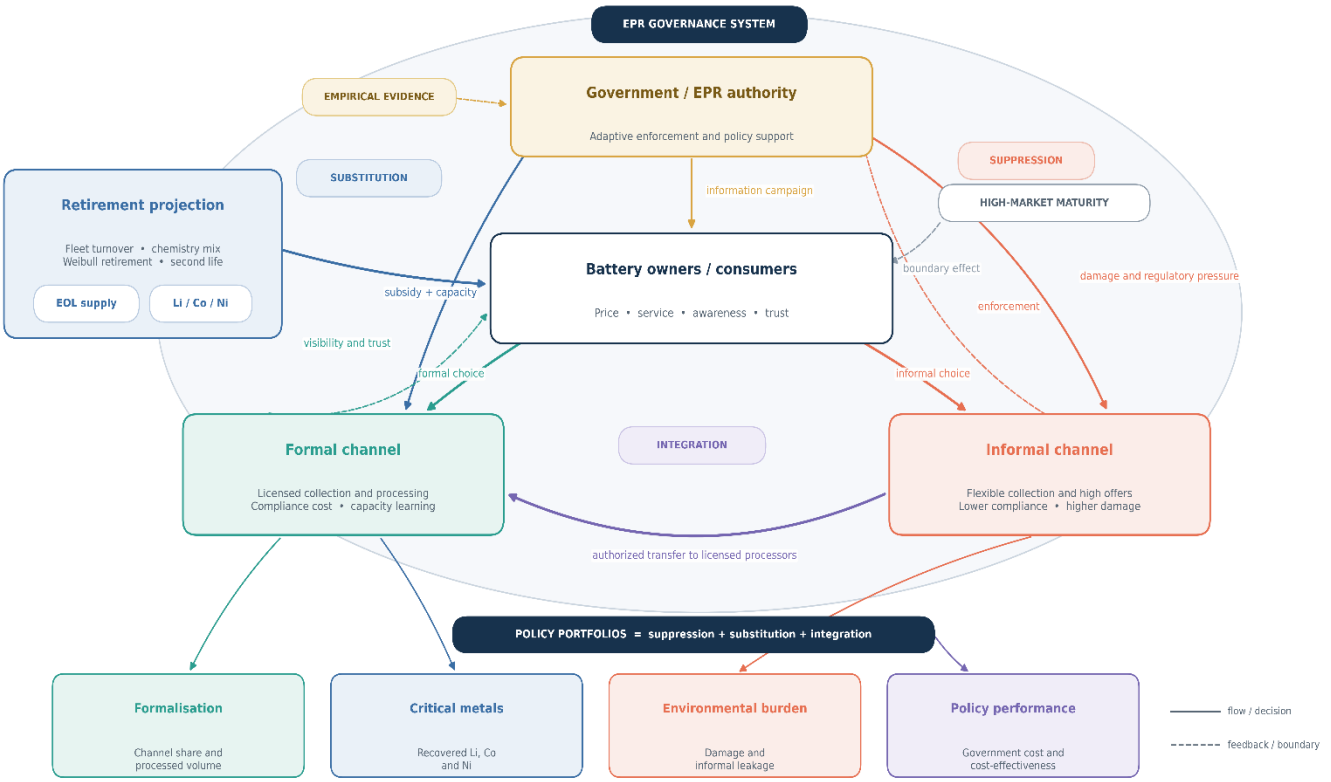


Figure 1: Integrated research framework linking retired-battery supply, channel competition, capacity constraints, and policy outcomes

2.2 Model structure and feedbacks

The model comprises retired supply, unreturned stock, collected inventory, consumer channel choice, formal and informal capacity, policy response, and resource–environmental outputs (Figure 2). Retired batteries enter either immediate return or the unreturned stock. Once available for collection, they are allocated between channels according to relative price, service, awareness, trust, regulation, and market maturity. A portion collected informally may request authorized transfer, but realized transfer cannot exceed formal residual capacity after direct formal demand has been processed.

Four feedbacks organize system behavior. First, formal processing raises channel visibility and trust, which strengthens subsequent formal choice. Second, formal demand stimulates licensed capacity; improved service then increases formal utility. Third, a larger informal share raises the target level of enforcement, which reduces

informal offer capacity and informal capacity expansion. Fourth, integration creates additional demand for licensed processing, but insufficient residual capacity prevents all requested transfers from being realized. This balancing loop prevents the model from treating contractual integration as equivalent to actual formal treatment.

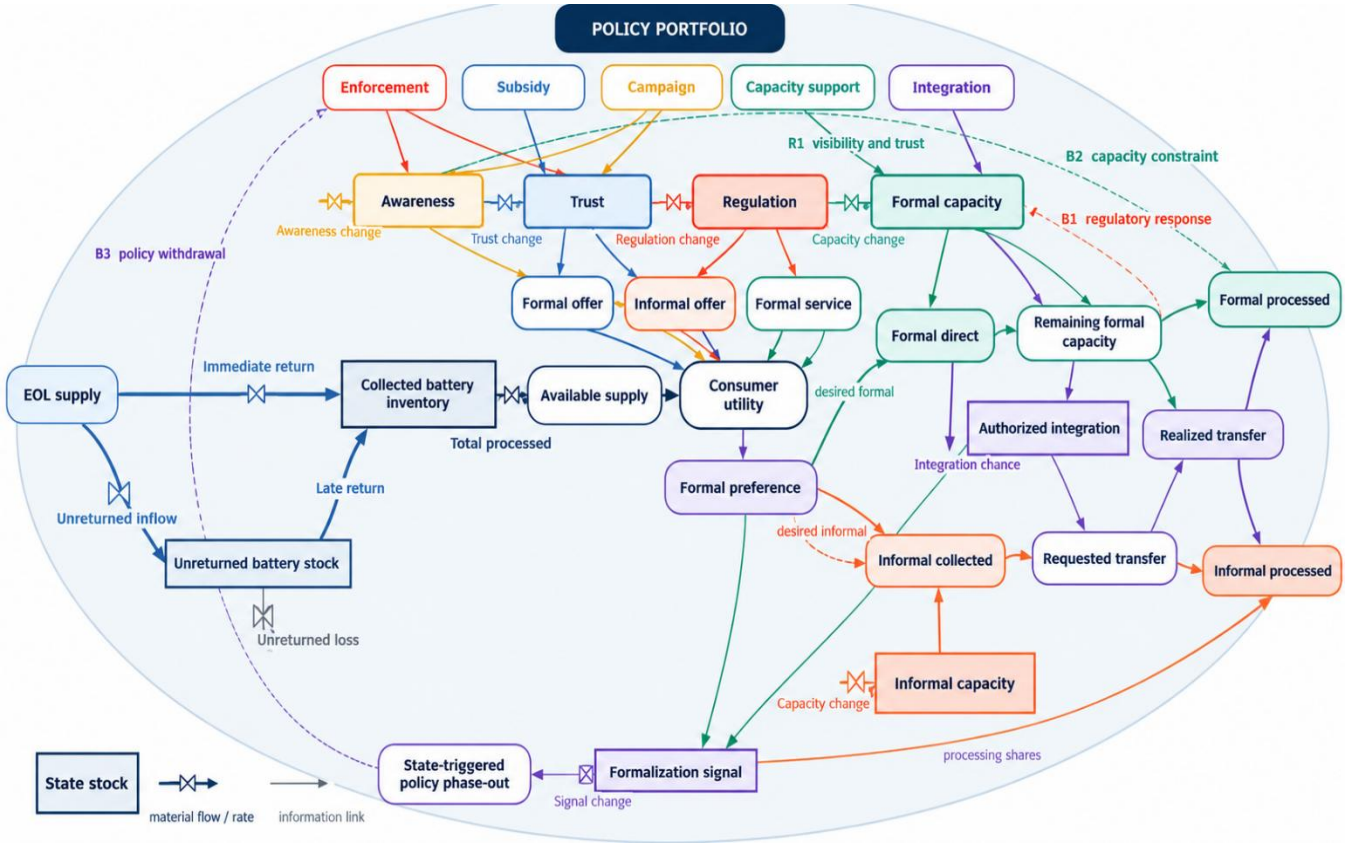


Figure 2: Stock–flow and feedback structure of the capacity-constrained formal–informal recycling model

2.3 Governing equations

Let E(t) denote annual retired-battery supply, r(t) immediate return propensity, B(t) unreturned stock, and C(t) collected but unprocessed inventory. The clip(x,a,b) operator bounds x to [a,b], and Δt is the integration step. Table 1 summarizes the principal symbols.

Table 1: Principal variables and symbols

Symbol	Meaning	Unit
E	Annual retired-battery supply	GWh yr^{-1}
B	Unreturned battery stock	GWh
C	Collected, unprocessed inventory	GWh
Q	Supply available for channel matching	GWh yr^{-1}
pF	Consumer preference for the formal channel	Dimensionless
KF, KI	Formal/informal processing capacity	GWh yr^{-1}
F, I	Final formal/informal processing	GWh yr^{-1}
Xreq, X	Requested/realized authorized transfer	GWh yr^{-1}
A, T, G, Z	Awareness, trust, regulation, integration states	Dimensionless
H	Policy withdrawal progress	Dimensionless
Rm	Recovered metal m	t yr^{-1}
GC	Model-accounted government cost	GWh yr^{-1}

2.3.1 Return behavior and material conservation

Baseline return propensity r0(t) increases gradually as the collection system matures; awareness A and campaign effect CE provide bounded adjustments. Immediate return Q_0 and the flow into unreturned stock UB are:

$$r(t)=\mathrm{clip}[r_0(t)+0.05(A-0.30)+0.05CE,\ 0.25,\ 0.85] \quad (1)$$

$$Q_0(t)=E(t)r(t), \qquad UB(t)=E(t)-Q_0(t) \quad (2)$$

Unreturned batteries are governed by a four-year baseline return-adjustment time and a stock loss of 0.5% yr−1. Because the realized return rate is additionally moderated by awareness, four years is a model time constant rather than the realized mean waiting time. Outflows are bounded by $B/\Delta t$ so that no time step removes more stock than is available.

$$dB/dt=UB-LR-Loss \quad (3)$$

$$LR=\min\{B/\tau B\cdot(0.35+0.30A),\ B/\Delta t\} \quad (4)$$

Immediate return, delayed return, and release of previously collected inventory form the quantity available for processing. Collected inventory increases through returns and decreases through realized formal and informal processing:

$$Q=Q_0+LR+C/\tau C \quad (5)$$

$$dC/dt=Q_0+LR-F-I \quad (6)$$

2.3.2 Consumer choice and channel allocation

The formal offer PF combines a baseline price and subsidy effect SE, while the informal offer PI declines with enforcement effect EF and regulation G. The formal utility difference U includes the standardized price gap, market maturity M, awareness A, trust T, regulation G, and formal service SF. Coefficients calibrate relative mechanism strength and are not interpreted as survey elasticities.

$$PF=PF,0+SE, \quad PI=PI,0-KE\cdot EF\cdot G \tag{7}$$

The coefficient K_E represents the pass-through of enforcement pressure to the purchase offer of informal recyclers. Its nominal value is set at CNY 22 kWh^{-1}. At unit enforcement and regulation states, this corresponds to a maximum reduction of 12.6% relative to the baseline informal offer of CNY 175 kWh^{-1}. Under the suppression scenario, where the enforcement effect peaks at 0.35, the direct reduction cannot exceed CNY 7.7 kWh^{-1}, equivalent to 4.4% of the baseline informal offer. Because no national time series directly measures this pass-through effect, K_E is treated as a calibration and scenario parameter rather than an observed national coefficient.

$$U=\alpha+0.95(PF-PI)/100+M+0.70(A-0.30)+0.55(T-0.50)+0.45(G-0.20)+0.55(SF-0.50) \tag{8}$$

$$pF=1/[1+\exp(-U)], \quad DF=QpF, \quad DI=Q(1-pF) \tag{9}$$

Consumer intentions do not automatically become processing flows. Direct formal processing FD and informal collection IC are limited by their respective capacities:

$$FD=\min(DF,KF), \quad IC=\min(DI,KI) \tag{10}$$

2.3.3 Authorized integration under capacity constraints

The integration state Z and regulation G determine the fraction of informal collection requesting authorized transfer, capped at 55%. Licensed processors first meet direct formal demand; only remaining capacity can accept transfers.

$$fX=\min\{\mathrm{clip}[Z(0.45+0.35G),0,1],0.55\} \tag{11}$$

$$Xreq=IC\cdot fX, \quad Krem=\max(KF-FD,0) \tag{12}$$

$$X=\min(Xreq,Krem) \tag{13}$$

$$F=FD+X, \quad I=IC-X, \quad sF=F/(F+I) \tag{14}$$

Equation (13) is central to the analysis. If requested transfer exceeds residual formal capacity, the unmet request is not treated as a battery loss. Those batteries remain in the informal-processing flow. Integration therefore improves formalization only when authorized collection is matched by licensed end-processing capacity.

2.3.4 Capacity and behavioral adjustment

Target formal capacity includes direct formal demand and expected transfer requests; capacity support CS raises the planning margin. Target informal capacity is compressed by enforcement. Formal and informal capacities adjust with time constants of 1.2 and 2.5 years, respectively.

$$KF^*=(DF+Xreq)(1.05+CS), \quad dKF/dt=(KF^*-KF)/1.2 \tag{15}$$

$$KI^*=DI(1.05-0.35EF), \quad dKI/dt=(KI^*-KI)/2.5 \tag{16}$$

Awareness, trust, regulation, integration, and the formalization signal follow first-order delays with adjustment times of 6, 5, 4, 3, and 3 years. These delays ensure that policy effects propagate through behavior and capacity rather than appearing immediately.

$$dY/dt=[Y^*(t)-Y(t)]/\tau Y, \quad Y\in\{A,T,G,Z,S\} \tag{17}$$

2.4 Policy scenarios and withdrawal rules

Policy instruments include enforcement, a formal purchase-price subsidy, consumer campaigns, formal-capacity support, and authorized integration. The realized effect of instrument j combines peak strength PSj, a linear ramp Rj, and policy multiplier Mj. Enforcement, subsidy, campaign, capacity support, and integration reach peak strength over 4, 3, 3.5, 5, and 6 years, respectively, reflecting the time required for institutional implementation, investment, and network formation.

$$PEj(t)=PSj\cdot Rj(t)\cdot Mj(t), \quad Rj=clip[(t-2025)/\tau j,0,1] \tag{18}$$

The life-cycle portfolio first smooths the formal-processing share over three years. Withdrawal is prohibited before 2036. Thereafter, a target begins when the smoothed share reaches 55% and is complete at 68%; realized withdrawal H adjusts toward the target over five years. At full withdrawal, enforcement, subsidy, campaign, capacity support, and integration retain 80%, 10%, 35%, 45%, and 85% of their peak levels, respectively. Withdrawal therefore does not mean eliminating all governance. The staged portfolio instead reduces the subsidy by 5% per year from 2030 while retaining the other portfolio instruments.

$$h^*=I(t\geq 2036)\cdot clip[(S-0.55)/(0.68-0.55),0,1], \quad dH/dt=(h^*-H)/5 \tag{19}$$

$$Mj=1-(1-\rho j)H \tag{20}$$

Table 2: Policy scenarios

Scenario	Core instruments	Strength or rule	Interpretation
Current policy	No new instrument	Shared 2025 anchor	Continuation benchmark
Suppression	Enforcement	Peak 0.35	Reduces informal offer and capacity
Substitution	Subsidy + capacity	CNY 20 kWh^{-1} + 0.15	Expands formal competitiveness
Integration	Authorized transfer	Peak 0.35	Informal collection, formal treatment
Fixed portfolio	All five instruments	0.25/15/0.20/0.15/0.15	Peak levels maintained
Life-cycle portfolio	Same as fixed	State-triggered withdrawal	Withdrawal after maturity
Staged portfolio	Same package	Subsidy −5% yr^{-1} after 2030	Preset phase-down
High-market frontier	High market maturity	External consistency bound	Not a core policy scenario

2.5 Metal recovery, environmental burden, and policy cost

Li, Co, and Ni are allocated to formal and informal flows according to their concentration in the contemporaneous processing pool and then multiplied by channel-specific recovery efficiencies. The formal technical scenario uses 90% for Li and 98% for Co and Ni; the informal path is lower but improves over time. These values support relative channel comparisons and are not claimed as uniform measurements for every enterprise.

$$R_m = c_m[F \cdot \eta_{F,m} + I \cdot \eta_{I,m}] \tag{21}$$

Environmental outcomes use a relative burden-weighted processing quantity. Formal processing has weight 1 and informal processing weight 3. The index compares changes caused by channel reallocation; it is not an absolute life-cycle assessment, emissions inventory, or monetized damage estimate.

$$D^* = F + 3I, \quad d = D^*/(F+I) \tag{22}$$

Model-accounted government cost includes subsidies to directly formal processing, support for authorized transfer, campaign spending, and enforcement expenditure. It excludes capacity-investment capital, firm compliance costs, and broader social welfare. Reported savings therefore refer only to this fiscal boundary.

$$GC = FD \cdot SE \cdot 10^6 + X \cdot 30 \cdot 10^6 + CE \cdot 15 \times 10^6 + EF \cdot 20 \times 10^6 \tag{23}$$

2.6 Parameterization, calibration, and model testing

Parameters are classified as upstream scenario inputs, literature-constrained quantities, boundary-calibration terms, or transparent policy-design assumptions. Retired supply is generated by the cohort–Weibull module. Prices, behavioral directions, and policy magnitudes are constrained by the reviewed evidence. The utility intercept and historical maturity offset reproduce formal-processing shares of 20% in 2020 and 25% in 2025. The latter is treated as a fixed historical anchor, not as a model forecast or a separate validation observation. Policy ramp times, withdrawal thresholds, and retained fractions are explicit scenario parameters and are varied in sensitivity tests.

The enforcement-to-price coefficient K_E is set to CNY 22 kWh^{-1} in the nominal model and tested over a range of CNY 11–33 kWh^{-1}, corresponding to 50%–150% of its nominal value.

Table 3: Key parameters and evidence status

Parameter	Baseline	Evidence status	Treatment
Simulation/time step	2020–2050 / 0.125 yr	Model setting	Numerical convergence test
Formal share, 2020/2025	20% / 25%	Boundary calibration	Endpoint constraints only
Formal/informal offer	100 / 175 CNY kWh^{-1}	Literature + calibration	Price sensitivity tested
Capacity adjustment	1.2 / 2.5 yr	Mechanism parameter	Global uncertainty
Policy ramp time	3–6 yr	Policy design	Not claimed as national measurement
Transfer cap	55%	Scenario boundary	Also limited by residual capacity
Withdrawal thresholds	55%–68%	Policy design	Timing combinations tested
Informal burden weight	3	Relative scenario value	No absolute LCA claim
Enforcement-to-price coefficient K_E	22 CNY kWh^{-1}	Calibration/scenario parameter	One-at-a-time sensitivity:11-33 CNY kWh^{-1}

Structural and behavioral tests follow standard system-dynamics practice for dimensional consistency, extreme conditions, conservation, time-step convergence, and parameter sensitivity (Barlas, 1996; Sterman, 2000). At each time step, the model checks mass balance for unreturned batteries, collected batteries, and metals; all flows must remain non-negative and all shares within [0,1]. All policy scenarios use identical retirement trajectories. Numerical convergence compares the 0.125-

and 0.0625-year steps against 0.03125 years. Global robustness is evaluated with 200 independent Latin-hypercube draws. Utility weights vary by ±20%, channel offers by ±10%, and capacity, behavioral, regulatory, integration-adjustment times and the transfer ceiling by ±20% around their nominal settings. Every draw is recalibrated to the same 25% formal-processing share in 2025; the nominal parameter vector is simulated separately and is not included in the percentile calculation. Alternative withdrawal timings and an integration–capacity boundary grid provide additional mechanism tests. Reported ranges are model outcome intervals under declared parameter perturbations, not statistical confidence intervals.A separate one-at-a-time sensitivity test varies K_E between 50% and 150% of its nominal value to examine whether the policy ranking depends on this calibrated coefficient.

3. Results

3.1 Evolution under current policy

Under current policy, annual retired batteries increase from 20.73 GWh in 2025 to 108.97 GWh in 2030, 326.91 GWh in 2035, and 1,538.36 GWh in 2050. Total processed volume rises from 10.48 to 1,321.01 GWh yr−1 over the same interval. Processing expands substantially, yet the unreturned stock grows from 19.23 GWh in 2025 to 425.90 GWh in 2035 and 2,467.03 GWh in 2050. Rapidly growing retirement therefore outpaces the combined development of return and treatment systems (Figure 3A,D).

The formal-processing share is anchored at 25% in 2025 and then increases gradually to 33.68% in 2030, 42.88% in 2035, and 52.95% in 2050. By 2050, formal and informal processing reach 699.44 and 621.57 GWh yr−1, respectively. Formal processing therefore equals 45.47% of that year's retired supply, which is lower than its 52.95% share of processed batteries because some retired batteries remain unreturned or awaiting treatment. The direction of change is consistent with strengthening EPR, maturing networks, and increasing awareness, but the trajectory does not imply automatic displacement of the informal sector. A larger formal share can coexist with growth in absolute informal volume when total retired supply expands rapidly.

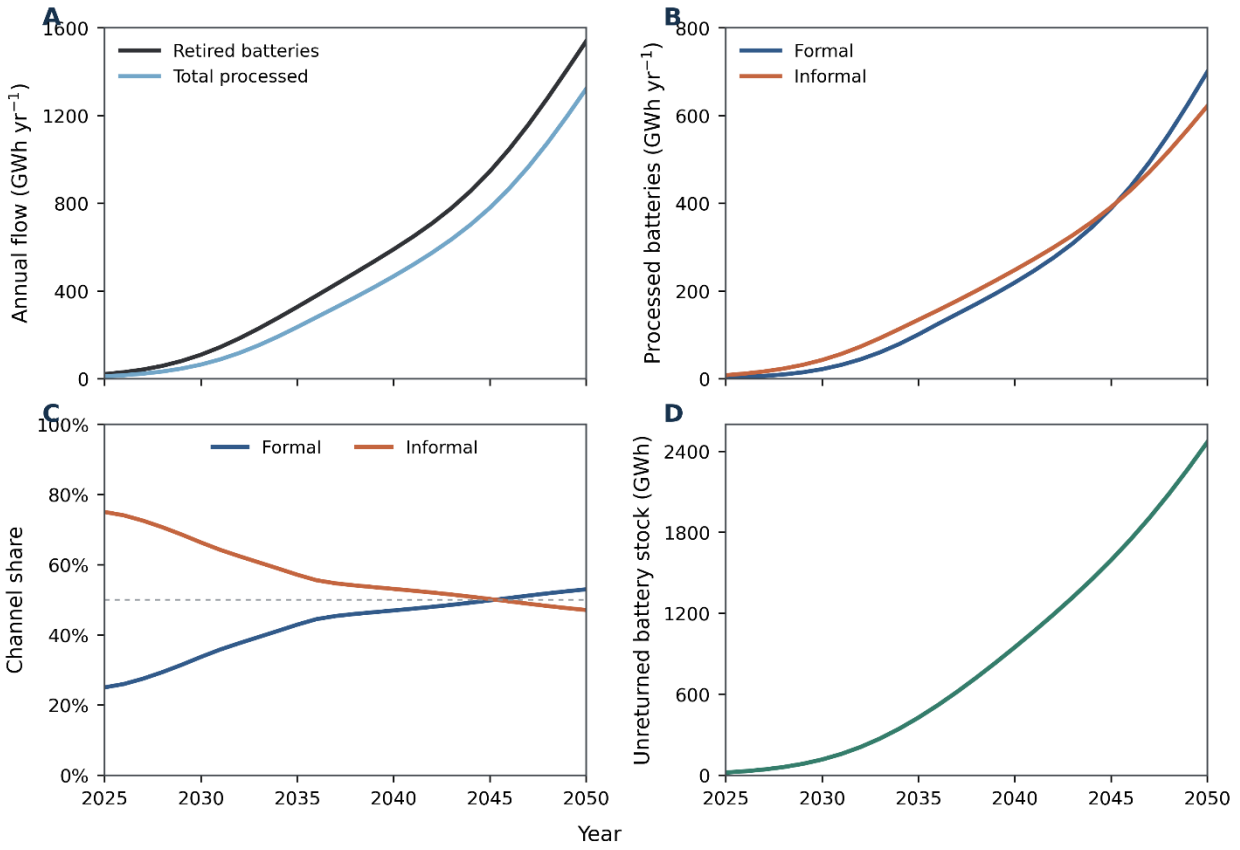


Figure 3: Retired supply, processing flows, formalization, and unreturned stock under current policy

3.2 Single governance pathways

All single pathways increase the formal-processing share, but their timing differs (Figure 4A). In 2030, substitution reaches 42.67%, above suppression at 38.31% and integration at 36.02%. Subsidy and capacity support therefore improve the formal channel's relative offer and service quickly. By 2050, the ranking changes: suppression, substitution, and integration reach 60.83%, 59.44%, and 58.72%, respectively. The long-run result does not support integration as inherently superior; persistent enforcement is more stable when licensed capacity is constrained.

The timing decomposition explains the crossover. The substitution path acts through both price and capacity and therefore produces the largest initial gain. Suppression accumulates more slowly as regulation affects informal offers and capacity targets, but its effect persists. Integration acts last because authorized networks take six years to reach peak strength and because realized transfers require residual formal capacity. In 2050, requested transfer is 108.50 GWh yr−1, whereas only 51.27 GWh yr−1 can be realized. In 2030 and 2035, realized transfer is zero despite requests of 3.25 and 20.08 GWh yr−1 because direct formal demand already uses the available licensed capacity.

Cumulative gains and costs reveal distinct mechanisms. Over 2025–2050, suppression, substitution, and integration add 810.04, 818.76, and 663.69 GWh of formal processing relative to current policy. Suppression has low model-accounted fiscal cost because enforcement expenditure is represented directly, whereas substitution requires approximately CNY 121.19 billion in subsidies and integration approximately CNY 11.03 billion in transfer support and associated measures. These figures should not be read as complete social costs, because private investment and compliance expenditure lie outside the accounting boundary.

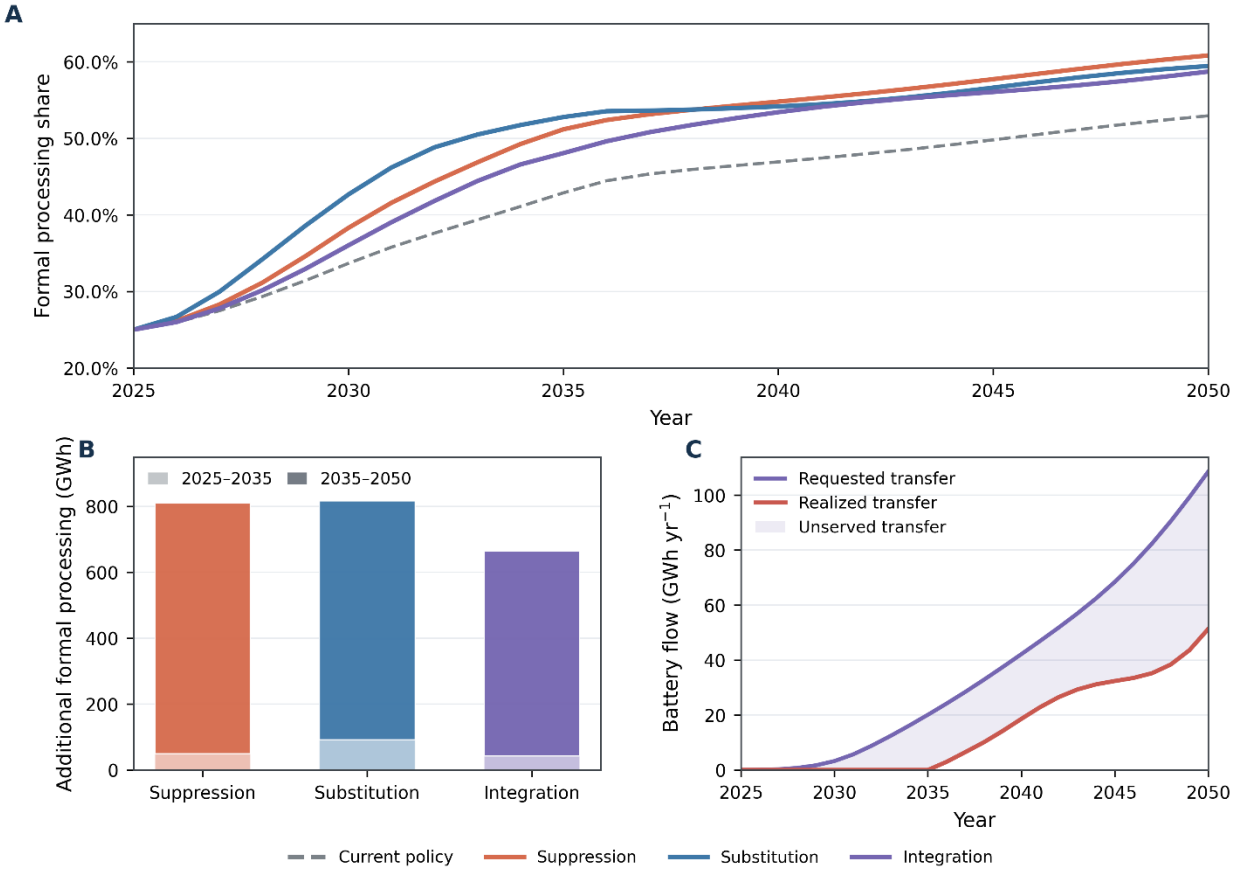


Figure 4: Performance, timing, and capacity-constrained mechanisms of suppression, substitution, and integration pathways

3.3 Policy portfolios and withdrawal trade-offs

Portfolios operate simultaneously on price, service, regulation, awareness, capacity, and transfer networks and consequently outperform individual pathways in the baseline. The fixed, life-cycle, and staged portfolios all reach 46.32% in 2030. Their shares in 2035 are 59.39%, 59.39%, and 58.92%. After 2036, state-triggered withdrawal and scheduled subsidy phase-down separate the trajectories. By 2050, the formal shares are 68.32%, 65.77%, and 66.49%, respectively.

Differences in effect are smaller than differences in fiscal cost. The fixed portfolio adds 1,838.30 GWh of cumulative formal processing during 2025–2050 and incurs CNY 111.42 billion in model-accounted government cost. The life-cycle portfolio adds 1,671.03 GWh at CNY 78.34 billion, saving 29.68% while losing 2.55 percentage points of final formal share. The staged portfolio adds 1,683.54 GWh at CNY 61.13 billion, saving 45.14% while losing 1.82 percentage points. Under baseline parameters, the staged portfolio provides the strongest cost–effect compromise, but its advantage depends on a prespecified calendar. The life-cycle portfolio instead withdraws support when observed formalization crosses maturity thresholds.

The withdrawal rule also clarifies which instruments should persist. Baseline enforcement and the legal architecture for traceability and authorized transfer remain largely in place, while general subsidies retreat most strongly. This is consistent with a transition from market formation to institutional maintenance: fiscal support creates capacity and participation early, but mature markets still require monitoring, authorization, and credible penalties.

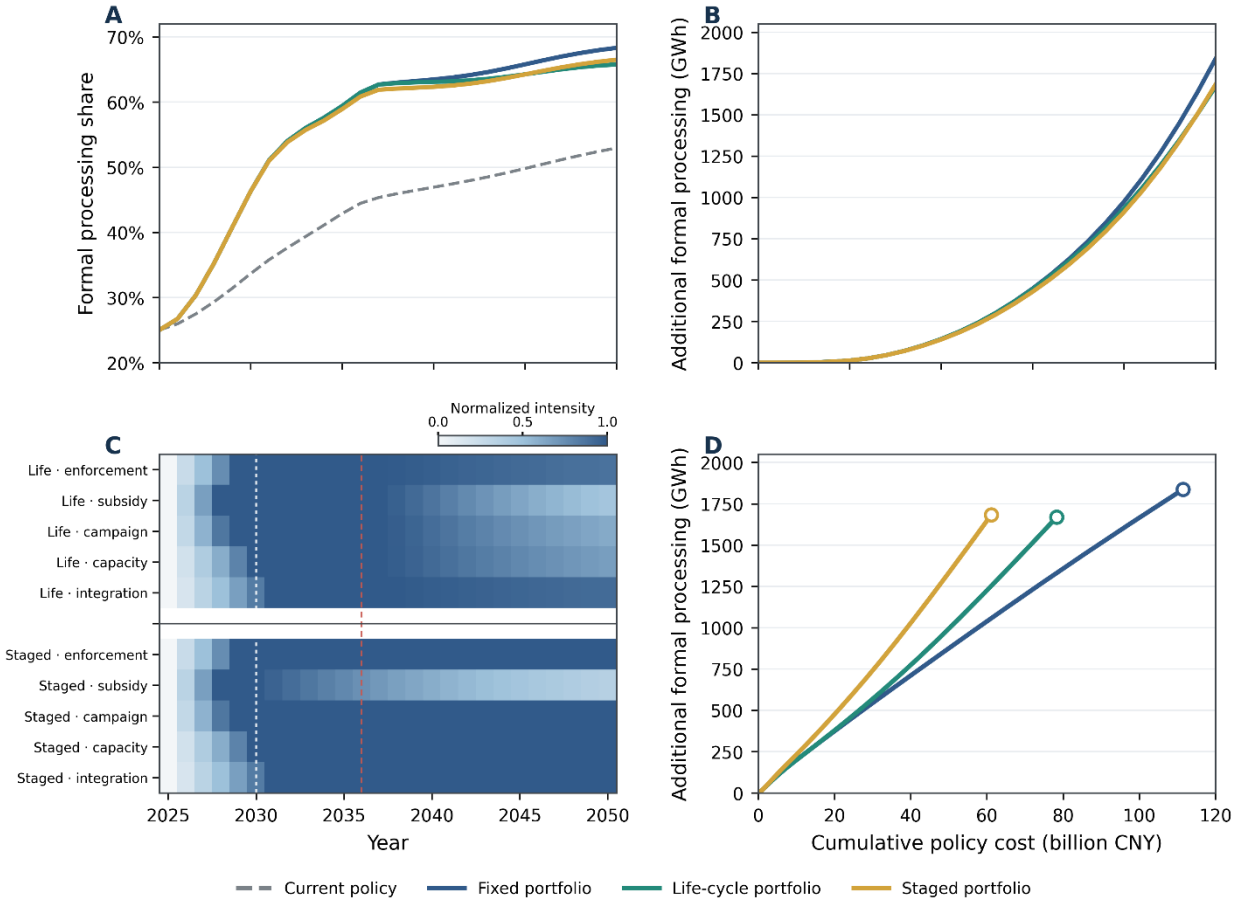


Figure 5: Outcome trajectories and model-accounted fiscal trade-offs of fixed, life-cycle, and staged policy portfolios.

3.4 Environmental and critical-metal outcomes

Formalization lowers the relative environmental burden. In 2050, annual burden indices under the fixed, life-cycle, and staged portfolios are 2,178.54, 2,234.83, and 2,225.77, respectively, corresponding to reductions of approximately 15.04%, 12.84%, and 13.20% relative to current policy. Cumulative avoided burden during 2025–2050 is 3,122.55, 2,902.60, and 2,841.84 relative units. Because the indicator is calculated from channel weights, it identifies consequences of changing treatment destinations, not pollutant-specific emissions or monetized social benefits.

Metal gains differ across chemistries because the composition of the processing pool changes over time and because the formal–informal recovery-efficiency gap is metal specific. Relative to current policy in 2050, the fixed portfolio increases Li, Co, and Ni recovery by 9.41%, 2.72%, and 2.89%. Corresponding gains are 7.45%, 1.89%, and 2.04% under the life-cycle portfolio and 8.34%, 2.43%, and 2.59% under the staged portfolio. The larger modeled Li response reflects the interaction between the increasing LFP share, inventory composition, and the wider formal–informal efficiency advantage assumed for lithium; it should not be attributed to chemistry shares alone. Moreover, increasing the formal share among processed batteries does not recover material that remains in the growing unreturned stock.

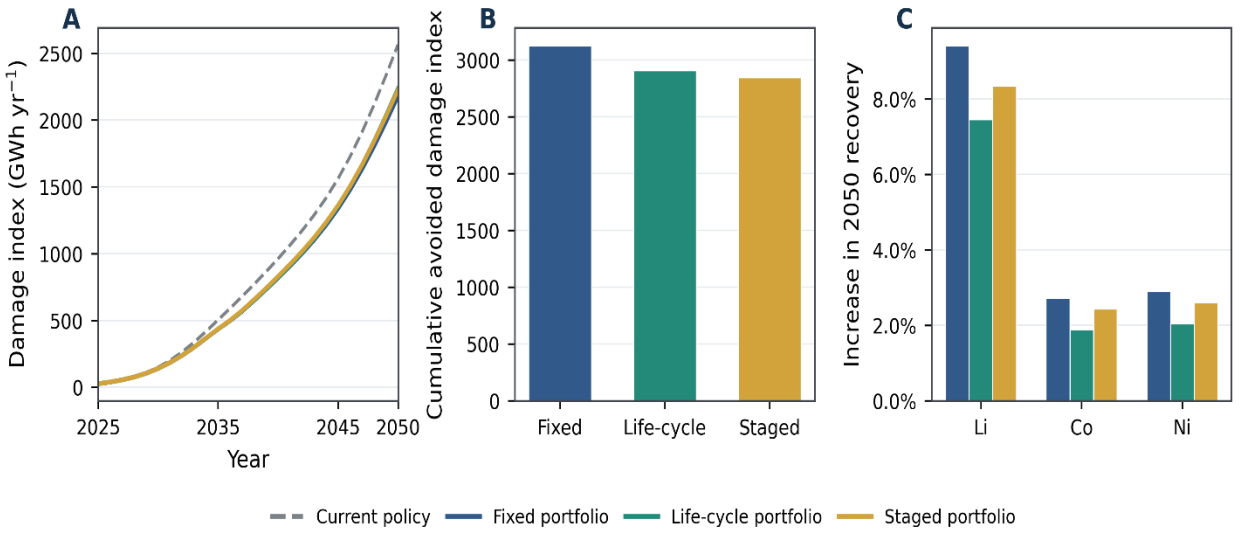


Figure 6: Relative environmental burden and critical-metal recovery outcomes of policy portfolios

3.5 Uncertainty, rankings, and the capacity boundary

The corrected global uncertainty experiment yields intervals centered on the declared nominal settings. Across 200 Latin-hypercube draws, the 5th–95th percentile range of the 2050 formal-processing share is 65.64%–70.94% for the fixed portfolio, with a median of 68.37% and a nominal value of 68.32%. The life-cycle portfolio ranges from 63.80% to 67.64%, with a median of 65.80% and a nominal value of 65.77%; the staged portfolio ranges from 63.83% to 69.06%, with a median of 66.53% and a nominal value of 66.49%. These are model distributions under parameter perturbation, not statistical confidence intervals.

Suppression ranks first among the three single pathways in 195 of 200 draws (97.5%); substitution ranks first in four draws and integration in one. Each of the fixed, life-cycle, and staged portfolios exceeds the contemporaneous best single pathway in all 200 draws. This result supports policy complementarity within the tested ranges, but it does not establish universal dominance outside the model boundary or under omitted cost and capacity conditions.

The integration–capacity grid shows that integration can surpass nominal suppression only when formal capacity adjusts sufficiently quickly or receives strong support. The boundary in Figure 7C is a mechanism frontier rather than a statistical significance contour. Numerical tests also converge: relative to the 0.03125-year benchmark, maximum deviations in core outcomes are approximately 1.36% at 0.125 years and 0.45% at 0.0625 years. Across alternative life-cycle withdrawal timings, model-accounted cost savings relative to the fixed portfolio range from 20.54% to 38.54%, while the 2050 share loss ranges from 1.92 to 3.02 percentage points; the nominal rule lies within these bounds.

A separate one-at-a-time sensitivity test varies K_E from CNY 11 to 33 kWh^{-1}. Across this range, the 2050 formal processing share under the suppression pathway changes from 60.35% to 61.30%, compared with 60.83% at the nominal value. The maximum deviation is only 0.48 percentage points. Suppression remains the leading single pathway in all five runs, while each policy portfolio remains above the best-performing single pathway. Therefore, the principal policy ranking is not driven by the nominal value of K_E=22.

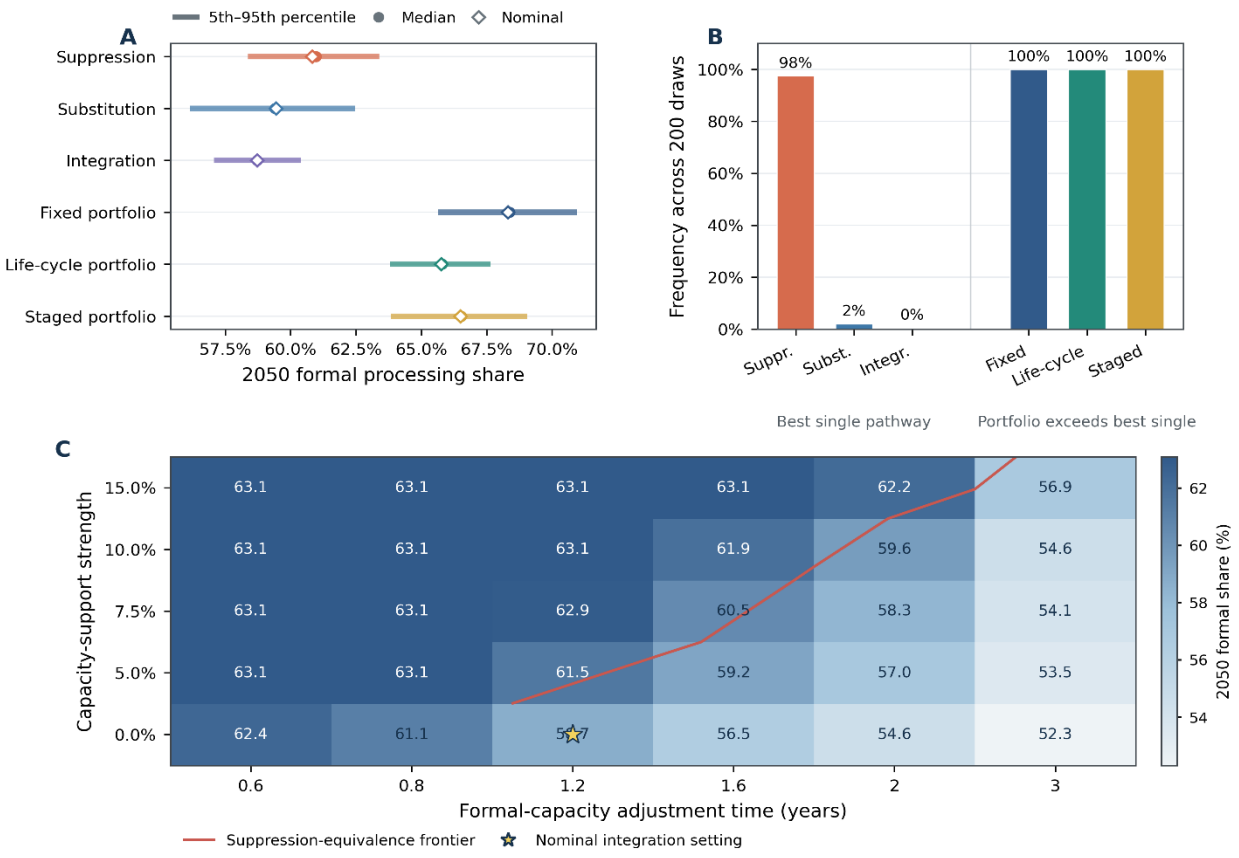


Figure 7: Parameter uncertainty, pathway ranking, and the formal-capacity boundary of authorized integration. (A) The 5th–95th percentile intervals from 200 Latin-hypercube draws over symmetric parameter ranges; circles and diamonds denote medians and separately simulated nominal values. (B) Frequencies with which a pathway ranks first within the single-pathway class or a portfolio exceeds the best single pathway. (C) The 2050 formal share across capacity-support strengths and adjustment times; the red line is the nominal suppression-equivalence frontier.

4. Discussion

4.1 Gradual formalization rather than automatic substitution

The current-policy pathway combines a rising formal share with persistent informal processing and an expanding unreturned stock. This pattern is consistent with Wang et al. (2026a), who argue that existing EPR and market conditions do not rapidly establish overwhelming formal-channel dominance, and with Tang et al. (2023a, 2023b), who emphasize prices, convenience, awareness, and actor heterogeneity. The two-layer network results of Wang et al. (2025a) further imply that policy effects coevolve among residents and recyclers and can exhibit diminishing returns. The present model adds that return and channel allocation are separate decisions.

Even when the formal share among processed batteries improves, retired supply can expand faster than return, increasing the stock outside the collection system. Formal share alone is therefore an incomplete performance metric.

The endpoint shares should not be compared mechanically with those reported in One Earth. The studies differ in retired-supply trajectories, actor definitions, formalization metrics, and assumptions about market maturity. The high-market-maturity run is used here as an external consistency frontier rather than a calibration target. Its higher formal share demonstrates that the model can reproduce an optimistic pathway, while the main scenarios preserve a more conservative maturity trajectory and avoid back-calibrating current policy to a favorable future endpoint.

The continued growth of the unreturned battery stock reveals an upstream policy gap. The policy portfolios simulated in this study mainly reallocate batteries after they enter the collection system. Consequently, downstream processing-capacity expansion and authorized integration cannot by themselves eliminate delayed return or prolonged storage by vehicle owners and enterprises. A complete formalization strategy should therefore combine downstream formalization with return-activation instruments, including deposit–refund schemes, trade-in incentives, mandatory take-back through dealerships and maintenance outlets, convenient door-to-door collection, and digital battery traceability. The growth rate of the unreturned stock should also be considered before policy withdrawal, because a high formal share among processed batteries may coexist with a large quantity of batteries remaining outside the collection system.

4.2 Why single pathways have different timing

The early advantage of substitution arises because subsidy and capacity support jointly improve the formal offer and service. This mechanism accords with Wei (2025), who finds that collection subsidies can expand formal capacity in the short term. Subsidy, however, does not directly remove the informal network's convenience advantage. As both channels expand, its final-share advantage narrows. Suppression persistently reduces informal offer capacity and informal target capacity and therefore yields the strongest long-run single-path performance in the nominal run and 195 of 200 uncertainty draws. This direction is consistent with He and Sun (2022), who show that dynamic rewards, penalties, and high informal prices alter formal participation.

Integration reveals a frequently overlooked condition. Incorporating informal collection networks into EPR does not imply that licensed processors can absorb the associated batteries. Wang et al. (2024) and Wang et al. (2026a) provide theoretical support for formal–informal cooperation, but the capacity constraint shows that authorized networks and licensed end-processing capacity must be built together. Once transfer requests exceed residual capacity, increasing authorization creates unmet requests rather than proportional formal-processing gains. Integration remains valuable, but its superiority is conditional on infrastructure rather than universal.

4.3 Portfolios, withdrawal, and policy design

All three portfolios exceed the best single pathway in every corrected uncertainty draw, consistent with evidence that policy combinations frequently outperform isolated instruments (Chen et al., 2025; Wu et al., 2025). The effect is not simply additive. Enforcement reduces informal returns; subsidy improves the formal offer; campaigns increase awareness and trust; capacity support creates acceptance space; and integration preserves convenient collection while redirecting batteries to licensed processing. Chu et al. (2025) similarly support the proposition that collection incentives and capacity building are not fully substitutable. Within the tested ranges, sustained formalization emerges when behavior, enterprise capacity, and end processing reinforce one another.

The fixed portfolio also has the highest fiscal cost. Both adaptive portfolios show that withdrawal can reduce model-accounted expenditure substantially, but their governance logics differ. Staged withdrawal is easy to administer and produces the lowest cost, yet it may withdraw too early where regional maturity is uneven. Life-cycle withdrawal responds to a smoothed system state and better represents support ending after conditions are met, but requires reliable monitoring. A practical hybrid would establish an earliest review date and maximum annual reduction while using formal-processing share, residual capacity, transfer realization, and unreturned-stock growth as conditions for proceeding or pausing.

The national-average results should not be interpreted as implying a uniform provincial implementation schedule. Provinces with dense formal collection networks, shorter transport distances, stronger enforcement capacity, and larger retired-battery volumes may reach the conditions for policy withdrawal earlier. In contrast, regions with dispersed retirement sources, longer transport distances, weaker licensed processing capacity, or more active informal markets may require longer capacity support, stronger logistics coordination, and a slower subsidy phase-down. If provincial data were introduced, the life-cycle portfolio would therefore generate region-specific withdrawal times, whereas a nationally synchronized withdrawal schedule could remove support prematurely in less-developed recycling markets. Regional implementation should recalibrate retired-battery supply, transport distance, channel prices, licensed capacity, and enforcement effectiveness.

4.4 Theoretical contribution and limitations

The theoretical contribution is not the addition of more actors, but a different representation of formalization. Evolutionary-game models commonly store probabilities of positive strategies and analyze convergence through replicator dynamics. This study stores batteries and metals, while preferences, policies, and capacities determine physical flows. It can therefore distinguish willingness to recycle formally, direct formal collection, requested authorized transfer, realized transfer, and final formal processing. The distinction demonstrates why strategic willingness cannot be realized when physical capacity is insufficient.

Four limitations define the interpretation of the results. First, China lacks a unified

national time series for formal and informal channel shares, actual purchase prices, and authorized transfer volumes. The 25% value in 2025 is a single boundary anchor rather than a multi-point external validation dataset. Second, ramp times, capacity adjustment, withdrawal thresholds, and retained fractions are transparent scenario assumptions and should not be interpreted as measured national averages. Third, the environmental indicator uses relative weights rather than a complete life-cycle inventory, and the government-cost account excludes capacity capital, compliance expenditure, and social welfare. Fourth, the national-average structure does not represent provincial variation in retired supply, transport distance, technology, prices, and enforcement capability. Future work should use enterprise flow data, regional quotations, and observed public expenditure for Bayesian calibration and couple the material-flow model with spatial or agent-based networks.

5. Conclusions and policy implications

This study develops a capacity-constrained system dynamics model linking retired-battery supply, consumer return, formal–informal competition, authorized transfer, enterprise capacity, metal recovery, and policy withdrawal. The purpose is not to provide a single forecast of China's future formal rate, but to identify timing advantages, infrastructure conditions, and model-accounted fiscal trade-offs under a common retired-supply boundary.

First, continuation of current policy produces gradual formalization but does not eliminate coexistence. The formal-processing share reaches 52.95% in 2050, while informal treatment and unreturned stocks remain substantial. Policy assessment should report both stocks outside the collection system and final processing structure, not only the formal fraction of processed batteries.

Second, the three single pathways solve different constraints. Substitution acts fastest in the early period; suppression is the most stable single pathway in the baseline and uncertainty draws; and integration is constrained by residual formal capacity. Informal actors may be retained as authorized collectors, but network authorization must be synchronized with licensed capacity, traceability, and transfer standards.

Third, portfolios provide the most robust formalization within the tested parameter ranges. The fixed portfolio reaches a nominal 68.32% in 2050, while the life-cycle and staged portfolios reach 65.77% and 66.49%. Each portfolio exceeds the best single pathway in all 200 uncertainty draws, although the adaptive portfolios accept modest endpoint losses relative to the fixed portfolio in exchange for lower model-accounted expenditure. The results support a sequence of early capacity and service development, middle-stage enforcement plus authorized integration, and gradual withdrawal after maturity.

Fourth, withdrawal should respond to system state rather than to a date alone. In the present model, the life-cycle rule is triggered by a smoothed formal-processing share; residual capacity, transfer realization, unreturned-stock growth, and consumer trust are not additional trigger variables. These indicators are therefore

proposed as extensions for implementation and future testing, not as mechanisms already validated here. In practice, subsidy phase-down could begin only after several indicators remain above their thresholds and pause if capacity shortages or informal shares rebound. Baseline enforcement, traceability, and authorization rules should remain, whereas general subsidies and exceptional support can retreat first. Overall, the analysis does not advocate eliminating informal collection. It supports reducing informal-processing risk, retaining collection convenience where useful, and ensuring that licensed end-processing can accept redirected batteries. The numerical findings remain conditional on available evidence and the declared model boundary. When continuous channel, price, transfer, and fiscal data become available, behavioral parameters and policy rankings should be re-estimated.

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