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End-of-Life Recycling of New Energy Equipment: Challenges, Policy Frameworks, and Circular Economy Pathways—A Case Study of Henan Province, China

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Abstract

Rapid deployment of new energy technologies is generating growing volumes of end-of-life equipment. In Chinese policy discourse, three such waste streams are grouped as the "new trio": electric vehicle (EV) lithium-ion batteries, photovoltaic (PV) modules, and wind turbine blades. Under the International Energy Agency net-zero emissions scenario, global renewable capacity must more than triple by 2030, implying a proportional acceleration in end-of-life equipment flows that few national waste management systems are currently equipped to absorb. This study combines material flow analysis (MFA) to quantify waste generation, lifecycle assessment (LCA) to evaluate recycling pathways, and policy text quantitative analysis (PTQA) to benchmark technology maturity and policy frameworks in China, the EU, and Japan. A case study of Henan Province identifies systemic bottlenecks and policy responses. Global "new trio" waste is projected to exceed 16.7 million tons by 2030 under baseline assumptions, with China accounting for approximately 45% of total generation. The embedded resource value is estimated at USD 28 billion in 2025, growing to USD 75 billion by 2030. EV battery recycling demonstrates the highest technology maturity (3.5/5), while PV modules (1.8/5) and wind turbine blades (1.5/5) remain at early developmental stages constrained by fundamental technical bottlenecks. The EU leads in extended producer responsibility (EPR) implementation with over 90% recovery rates, followed by Japan at 85% and China at approximately 60%. The case study of Henan Province reveals significant imbalances between upstream manufacturing scale and downstream recycling capacity. Five systemic barriers—incomplete regulation, technological bottlenecks, market failure, fragmented governance, and underdeveloped industrial ecosystems—are identified, and seven policy recommendations are proposed to advance circular economy transitions for sustainable new energy waste management.

Keywords: new trio e-waste; extended producer responsibility; circular economy; material flow analysis; Henan province

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1. Introduction

The global energy transition has driven unprecedented expansion of renewable energy infrastructure over the past decade [1]. By 2024, global installed solar photovoltaic capacity exceeded 1600 GW, wind power reached 1000 GW, and the electric vehicle stock surpassed

40 million units [2,3]. Recent global waste assessments accordingly stress the urgency of proactive end-of-life governance [4,5]. China has emerged as the primary engine of this growth, accounting for approximately 40% of global new energy installations and 60% of EV production [6]. However, this rapid deployment has created a looming sustainability challenge: a wave of end-of-life equipment retirement. Chinese policy groups three such waste streams as the "new trio": EV lithium-ion batteries, PV modules, and wind turbine blades.

Distinct from conventional waste electrical and electronic equipment (WEEE), the "new trio" exhibits unique characteristics: massive unit scale, complex multi-material composition, high intrinsic resource value, and significant environmental hazard potential. A single wind turbine blade can exceed 80 m in length and weigh over 20 t [7], while a typical EV battery pack contains 8–15 kg of lithium, 10–15 kg of cobalt, and 30–40 kg of nickel [8]. These metals are strategic minerals with pronounced supply chain vulnerabilities [9]. These waste streams have a dual nature: they constitute both a critical secondary raw material reserve and a potential environmental liability, presenting significant valorization opportunities alongside formidable governance challenges. For instance, fluorine-based backsheet materials in PV modules can release persistent organic pollutants during uncontrolled disposal. Brominated flame retardants in battery packs pose a similar hazard. Epoxy resins in wind turbine blades, by contrast, resist biological degradation and persist in landfills for decades [10]. These material-specific hazards require treatment technologies distinct from those applied to conventional WEEE.

The existing literature on new energy waste management remains fragmented across technology domains, with limited cross-category comparative analysis and insufficient attention to institutional and market dynamics. Recycling technologies vary substantially in technological readiness. EV battery recycling has achieved the highest maturity, with mechanical processing, hydrometallurgy, pyrometallurgy, and cascade utilization as principal pathways [11,12]. Hydrometallurgical processes achieve metal recovery rates exceeding 95% for lithium, cobalt, and nickel, but generate substantial wastewater requiring treatment [13]. PV module recycling remains at an earlier developmental stage, a key technical challenge remains: separating the EVA encapsulant film from silicon cells at commercial scale, which limits the economic viability of PV recycling [14]. Wind turbine blade recycling faces the most formidable barriers, as the thermosetting nature of epoxy composites renders conventional thermal reprocessing infeasible, with chemical depolymerization remaining at laboratory scale [15,16]. For PV modules, thermal delamination at 450–550 degrees Celsius can remove the EVA encapsulant but incurs high energy costs and potential cell damage, whereas chemical delamination using organic solvents offers gentler separation but faces solvent recovery challenges [17]. For wind blades, mechanical shredding produces fiber-rich powders with reduced mechanical properties that limit high-value reuse, while solvolysis and supercritical fluid depolymerization show promise for clean fiber recovery but remain at pilot scale [18].

Extended producer responsibility (EPR) is a foundational policy instrument for sustainable waste management, as demonstrated by international experience [19]. The EU has implemented comprehensive EPR legislation through the WEEE Directive and the Batteries Directive, establishing mandatory recovery targets [20,21]. Japan has developed a distinctive industry-led model achieving recovery rates of approximately 85% for home appliances [5]. China has progressively expanded its EPR framework since 2012, but EPR coverage has not been extended to PV modules or wind turbine blades, creating regulatory gaps that contribute to disordered recycling practices [22,23]. The EU 2023 Batteries Regulation further introduces mandatory carbon footprint declarations and recycled content thresholds for battery producers, representing a new generation of EPR instruments that

internalize lifecycle environmental costs [21]. Japan's approach, by contrast, relies on industry consortia such as the Battery Association of Japan [24] to manage collection and recycling, leveraging high consumer compliance and dense urban logistics networks.

This study addresses these research gaps through three contributions. First, it employs MFA to quantify waste streams and resource recovery potential. Second, it applies PTQA to benchmark policy frameworks across China, the EU, and Japan. Third, it presents a case study of Henan Province, a leading province in central China by new energy installed capacity, to identify systemic bottlenecks and propose targeted policy interventions. The findings advance understanding of sustainable solid waste management (SSWM) in emerging economies and inform circular economy (CE) strategy formulation. Combining material flow modeling, policy text analysis, and a provincial case study, this study links global waste trajectories to subnational implementation. This addresses a recognized gap, since most studies examine technology or policy in isolation rather than their interaction.

2. Materials and Methods

2.1. Research Design

This study integrates three methods: MFA to quantify waste generation, LCA to evaluate recycling pathways, and PTQA to benchmark regulatory frameworks across jurisdictions. This triangulation approach enhances the robustness of findings by cross-validating results across multiple methodological perspectives [25]. This multi-method design serves two purposes. First, each method captures a different dimension of the sustainability challenge: physical flows, environmental impacts, and institutional frameworks. Second, convergence across methods strengthens the credibility of the conclusions in a domain where controlled experiments are generally infeasible.

2.2. Material Flow Analysis (MFA)

MFA is employed to quantify the flows of "new trio" waste through the economy, from manufacturing through use phase to end-of-life management [26]. The analysis covers 2018–2030, with 2018–2025 based on observed data and 2026–2030 based on projection models. Waste generation is calculated as follows:

$$W(\mathrm{t}) = \sum S_{i(t-L_i)} \times R_i \times (1 - \partial_i) \quad (1)$$

where $W(\mathrm{t})$ represents waste generation in year t, S_i represents sales of category i in year t–L_i, $\mathrm{L_i}$ represents average lifespan, R_i represents the retirement rate, and α_i represents the cascade utilization rate. The retirement rate R_i integrates an early-retirement component driven by technology repowering and failure-induced replacement, calibrated to industry-reported annual failure rates of 1–3 percent for PV modules and 0.5–1.5 percent for wind turbines [27]. The cascade utilization rate gamma i accounts for the proportion of retired batteries that enter second-life stationary storage applications [28] before material recycling, reducing the primary recycling stream by an estimated 10–15 percent for EV batteries. Lifespan parameters are set at 7 years for EV batteries, 25 years for PV modules, and 20 years for wind turbine blades, based on the IEA Global EV Outlook 2025 for EV batteries and on IRENA and IEC 61215/61400 design standards for PV modules and wind turbine blades, respectively [2,3]. To test the robustness of the projections, a three-scenario sensitivity analysis was conducted by varying average lifespan (±20%), the early-retirement rate (5–15%), and the cascade utilization rate (5–15%) around baseline values. Under the low and high scenarios, global "new trio" waste generation in 2030 ranges from 12.8 to 21.3 million tons, and Henan Province ranges from 195 to 318 kilotons (Table 1). A Weibull-based lifetime distribution model and Monte Carlo uncertainty propagation are identified as priorities for future work. The baseline scenario uses central estimates from industry

forecasts. The low scenario applies conservative retirement assumptions, and the high scenario applies aggressive ones, so that the three scenarios bound a plausible range for policy planning under uncertainty.

Table 1. Three-scenario sensitivity analysis of "new trio" waste generation in 2030 (lifespan ± 20%; early-retirement and cascade utilization rates varied between 5% and 15%).

Scenario	Lifespan Variation	Early-Retirement Rate	Cascade Utilization Rate	Global 2030 (Mt)	Henan 2030 (kt)
Low	+20%	5%	15%	12.8	195
Baseline	Design specification	10%	10%	16.7	252
High	−20%	15%	5%	21.3	318

2.3. Lifecycle Assessment (LCA)

LCA provides a systematic framework for evaluating the environmental performance of recycling technologies across their full lifecycle, following ISO 14040/14044 standards [29,30]. The functional unit is defined as the treatment of one ton of "new trio" waste. Impact categories include climate change (CO_2-eq), resource depletion, human toxicity, ecotoxicity, and cumulative energy demand. Inventory data are sourced from the Ecoinvent database supplemented with primary data from recycling facility surveys [31]; results are reported in Section 3.3. The system boundary encompasses collection, transportation, mechanical preprocessing, and the core recovery process, with end-of-life treatment of process residues included. Economic allocation is applied to multi-output processes, and cut-off rules follow the ecoinvent consequential system model. SimaPro 9.5 was used for inventory construction and impact calculation, with the ReCiPe 2016 midpoint method [32] adopted for impact characterization.

2.4. Policy Text Quantitative Analysis (PTQA)

Quantitative analysis of policy texts (PTQA) was employed to systematically evaluate regulatory frameworks across jurisdictions. The corpus comprises 87 policy documents issued between 2015 and 2026, selected from official databases (State Council/MIIT/NDRC/MEE portals for China; EUR-Lex for the EU; e-Gov for Japan) using the criterion that documents directly regulate at least one waste stream or its recycling value chain. Documents were coded along six dimensions: legal hierarchy and enforceability, coverage scope, EPR mechanism design, standardization level, economic incentive instruments, and supervision capacity. Each dimension is scored on a 1–5 scale using the rubric in the Supplementary Materials (Table S4), with equal weighting. Two independent coders coded all documents after a 10-document calibration exercise; inter-coder reliability was high (weighted kappa = 0.82; raw exact agreement = 84.1%) [33]. The complete document list, coding manual and raw scores are provided in the Supplementary Materials (Tables S1 and S2), and aggregate regional results are reported in Section 3.4. Discrepancies were resolved through discussion with a third senior researcher, and documents with unresolved disagreements were re-coded jointly. The six-dimension framework was developed inductively from the policy literature on extended producer responsibility and waste governance, and validated through two expert interviews with senior regulatory officials prior to full coding.

2.5. Data Sources and Limitations

Primary data sources include national and provincial statistical yearbooks, industry association reports, government policy documents, and peer-reviewed research. International data are drawn from Eurostat, IRENA, and the IEA. Several limitations should be

acknowledged: official statistics on waste generation are incomplete for PV modules and wind blades; technological performance data are based on demonstration projects; and policy analysis may not capture local implementation realities. These limitations are addressed through triangulation across multiple data sources. For Henan Province, primary data were complemented by semi-structured field interviews conducted in 2025 with eight recycling enterprise managers and three provincial regulatory officials. These interviews provided qualitative context for the quantitative findings. All monetary values are expressed in constant 2025 US dollars to facilitate cross-year comparison.

3. Results and Discussion

3.1. Global Retirement Trends and Projections

Global "new trio" waste generation is projected to increase rapidly over the coming decade. Total retirement volume is estimated at approximately 3.5 million tons in 2025, with projections indicating growth to over 16.7 million tons by 2030—a nearly fivefold increase [33,34]. Under the low and high scenarios (Section 2.2; Table 1), the 2030 estimate ranges from 12.8 to 21.3 million tons. This trajectory reflects the combined effect of cumulative installations from the 2015–2020 expansion period and the aging of equipment commissioned during that period. Across waste categories, retired EV batteries dominate in the near term because of their shorter service life. PV module waste, by contrast, accelerates sharply after 2027 [35], when the 2015–2020 installation cohort reaches end of life. Wind blade waste grows more gradually but poses outsized logistical challenges due to the 80-plus-meter length of individual blades, which typically require on-site segmentation before transport to recycling facilities.

The composition is shifting over time (Figure 1). EV batteries currently represent the largest stream at approximately 1.2 million tons in 2025, driven by first-generation EVs reaching retirement age [33]. PV module waste is growing most rapidly and is projected to surpass EV batteries as the largest stream by 2030 at approximately 8 million tons, reflecting the massive scale of global solar deployment, the post-2018 installation cohort reaching end-of-life, and an early-loss rate of approximately 10% consistent with IRENA/IEA-PVPS benchmarks [34,36]. Wind turbine blade waste, while smaller in absolute volume at approximately 1.2 million tons by 2030, presents disproportionate challenges due to large unit size and composite material recycling difficulty.

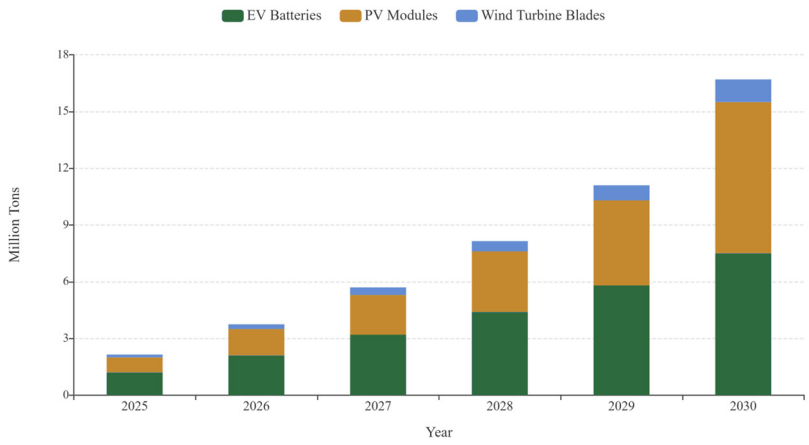

Figure 1. Global "New Trio" E-Waste Retirement Volume Forecast (2025–2030). Bars represent annual retirement volumes (flows), not cumulative stocks.

China is expected to account for approximately 45% of global generation by 2030, reflecting its position as the world's largest producer and user of new energy equipment [6].

China's projected 45% share of global waste generation creates both significant management challenges and favorable conditions for achieving economies of scale in recycling operations.

3.2. Resource Value and Environmental Risk

The economic value of recoverable materials from "new trio" waste is substantial (Table 2). Based on 2025 market prices, the total global resource value is estimated at approximately USD 28 billion annually, projected to reach USD 75 billion by 2030 under constant 2025 prices (volume-driven; an upper bound for planning purposes) [37]. EV batteries account for approximately 70% of total value, reflecting high concentrations of lithium, cobalt, and nickel. PV modules contribute approximately 20% through silver, copper, and aluminum recovery, while wind turbine blades represent approximately 10% primarily through glass fiber recovery.

Table 2. Resource Value and Environmental Risk of "New Trio" E-Waste.

Waste Category	Key Recoverable Materials	Estimated Value per Ton (USD)	Primary Environmental Risks
EV Lithium-Ion Batteries	Li, Co, Ni, Mn, Cu, Al	USD 5000–12,000	Heavy metal leaching, electrolyte toxicity, fire hazard
PV Modules	Ag, Cu, Si, Al, glass	USD 800–2000	Heavy metal contamination, fluorine compounds, glass waste
Wind Turbine Blades	Glass fiber, carbon fiber, epoxy resin	USD 200–500	Landfill volume, microfiber release, incineration emissions

The resource grade advantage of waste streams over primary ores is significant. For lithium, the concentration in spent EV batteries is approximately 3–8 wt% depending on cathode chemistry [8,9], compared to 0.05–0.2% in brines and 0.5–1.5% in hard rock ores [9]. This grade differential is favorable but does not by itself establish economic competitiveness, which further depends on collection logistics, disassembly, energy and waste-treatment costs; a full techno-economic analysis is required [8,9].

3.3. Technology Maturity Assessment

The assessment covers six dimensions (Figure 2): technical maturity, standardization, economic viability, recovery efficiency, environmental impact, and industrial scale. It reveals a clear hierarchy among the three waste categories. Scores were elicited through a Delphi-style two-round survey with 12 domain experts (four per category), scored on the 1–5 rubric in Table 3 with equal weighting; a weight sensitivity analysis under three alternative weighting schemes confirms that the ranking (EV batteries > PV modules > wind blades) is robust, with overall scores varying by less than 0.3.

EV battery recycling demonstrates the highest overall maturity with an average score of 3.5/5 (Table 3) [11,12]. Standardization of EV battery recycling processes is most advanced, with over 20 national standards published in China covering classification, testing, and safety protocols. However, economic viability remains a challenge at 2.8/5, reflecting high hydrometallurgical processing costs and competitive pressure from informal recycling networks.

PV module recycling scores an average of 1.8/5 (Table 3), indicating early-stage development [38]. Standardization is particularly weak at 1.5/5, as dedicated pollution control specifications have not been issued. Wind turbine blade recycling is the least mature category at 1.5/5 (Table 3), with standardization and industrial scale at 1.0/5, reflecting the near absence of regulatory frameworks and commercial operations [7,16,39]. The uneven

development creates a policy challenge: extending lessons from EV battery recycling to PV and wind while avoiding technology lock-in on suboptimal approaches.

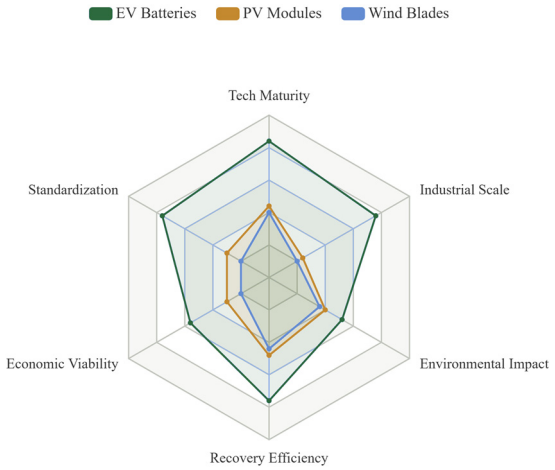

Figure 2. Recycling technology maturity radar comparison across the three waste categories (scores 1–5). Scores are the mean panel ratings per dimension shown in Table 3; the full scoring rubric is provided in the Supplementary Materials (Table S4).

Table 3. Technology maturity scores across six dimensions (1–5 scale; equal weighting; Delphi two-round survey with 12 experts). Full rubric in Supplementary Materials (Table S4).

Dimension	Weight	EV Batteries	PV Modules	Wind Blades
Technical maturity	1/6	4.2	2.2	2.0
Standardization	1/6	3.8	1.5	1.0
Economic viability	1/6	2.8	1.5	1.0
Recovery efficiency	1/6	3.8	2.4	2.2
Environmental impact	1/6	2.6	2.0	1.8
Industrial scale	1/6	3.8	1.2	1.0
Overall (equal weights)		3.5	1.8	1.5

Screening-level LCA results (Table 4) substantiate the environmental assessment. Hydrometallurgical EV battery recycling yields net benefits for climate change and resource depletion when displaced primary production is credited. However, wastewater treatment remains a material burden. PV module recycling currently exhibits net costs in climate change and cumulative energy demand categories, driven by the energy intensity of EVA film separation, while delivering avoided-landfill benefits. Mechanical recycling of wind turbine blades yields moderate benefits, dominated by avoided landfill. Chemical depolymerization remains too immature for quantitative assessment. These screening-level results are based on Ecoinvent inventories supplemented with literature data (Section 2.3). They should therefore be interpreted with caution and updated as commercial facilities scale up. The net climate benefit of hydrometallurgical EV battery recycling is primarily driven by avoided primary production of nickel and cobalt, which together account for approximately 70 percent of the credited emissions reduction [40]. For PV modules, the energy penalty of EVA thermal separation currently outweighs avoided glass and aluminum production, though this balance could shift with low-carbon electricity grids and improved separation efficiency.

Table 4. Screening-level LCA comparison of the three recycling pathways (qualitative net assessment).

Impact Category	EV Battery Recycling (Hydrometallurgical)	PV Module Recycling	Wind Blade Recycling (Mechanical)
Climate change	Net benefit	Net cost	Moderate benefit
Resource depletion	Net benefit	Minor benefit	Minor benefit
Human toxicity/ecotoxicity	Cost (wastewater treatment)	Cost (EVA separation)	Low
Cumulative energy demand	Net benefit	Net cost	Moderate benefit

3.4. International Comparative Analysis

A systematic comparison across the EU, Japan, and China reveals both common patterns and divergent approaches (Figure 3; Table 5). All three jurisdictions recognize EPR as the foundational principle, but implementation varies significantly in scope, stringency, and institutional design.

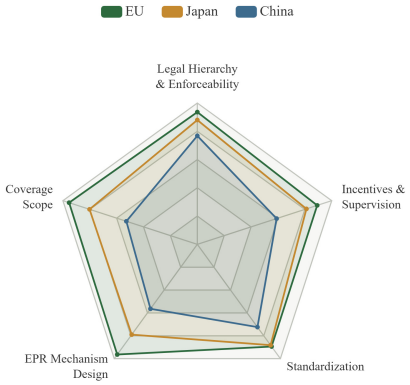

Figure 3. International comparison of "new trio" e-waste policy frameworks across the EU, Japan, and China (scores 1–5). The five displayed dimensions map directly onto the six-dimension PTQA coding framework: legal hierarchy and enforceability, coverage scope, EPR mechanism design, and standardization correspond one-to-one, while the fifth dimension (incentives and supervision) aggregates economic incentive instruments and supervision capacity. Underlying regional means are provided in the Supplementary Materials (Table S3).

Table 5. International Comparison of "New Trio" E-Waste Management Systems.

Dimension	European Union	Japan	China
EPR Coverage	Comprehensive: WEEE, Batteries, ELV directives	Appliances, automobiles, emerging for PV	Appliances, EV batteries; PV and wind pending
Recovery Targets	Mandatory: 45% WEEE, 50% batteries, 85% ELV	Mandatory: 80%+ for appliances and ELV	Guidance only for EV batteries; none for PV/wind
Standardization	High: Harmonized EU-wide standards	High: JIS standards across categories	Moderate: 20+ standards for batteries; gaps for PV/wind
Funding Mechanism	Producer responsibility + visible fee at purchase	Consumer fee at disposal + producer obligation	Recycling fund (appliances) + producer responsibility (batteries)
Enforcement	Strong: EU-level monitoring + member state enforcement	Strong: Industry self-regulation + government oversight	Moderate: Multi-departmental coordination challenges
Informal Sector	Minimal: Strong regulatory enforcement	Minimal: High compliance culture	Significant: Estimated 30–50% of battery recycling is informal

The comparison reveals that China lags behind the EU and Japan primarily in EPR coverage breadth, recovery target stringency, and informal sector enforcement [22,34]. The EU's comprehensive regulatory framework and Japan's industry-led collection systems offer relevant models, though direct transferability to China's institutional context requires careful consideration. The most transferable lessons include the importance of comprehensive EPR legislation, progressively increasing mandatory recovery targets, and digital traceability systems [21,41].

3.5. Henan Province Case Study

Henan Province occupies a strategic position in China's new energy landscape (Figure 4). As of June 2026, total installed renewable energy capacity reached 101 GW, representing approximately 60% of total provincial installed capacity. Wind and solar installed capacity reached 90.19 GW, ranking first in central China and among the top six provinces nationally, comprising approximately 42 GW of wind power and 48 GW of solar PV.

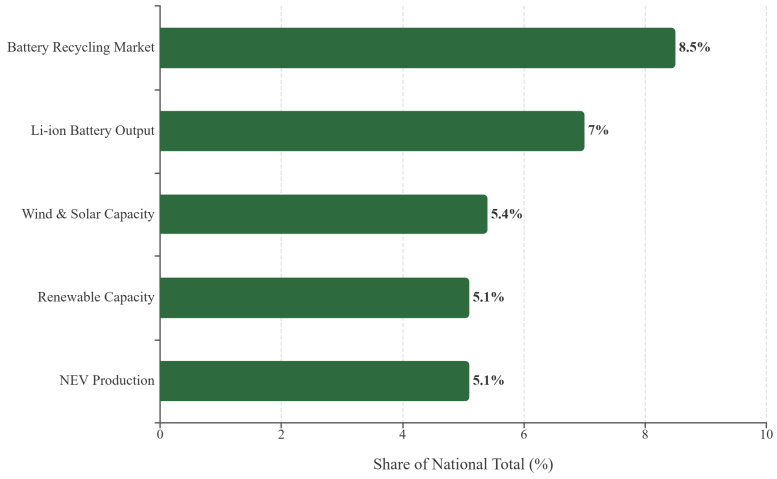

Figure 4. Henan Province New Energy Industry Key Metrics (2025). Metrics are expressed as a percentage of China's national total, enabling comparison across indicators. National totals (2025) used as denominators: renewable capacity approx. 2000 GW; wind and solar capacity approx. 1670 GW; NEV production approx. 13.0 million units; Li-ion battery output approx. 1230 GWh; battery recycling market approx. CNY 40 billion.

The EV battery industry has emerged as a strategic pillar. In 2025, the province produced 660,100 new energy vehicles, up 49.9% year on year, and lithium-ion battery output reached 86.32 GWh, up 53.8% [37]. The CATL Luoyang production base, when fully operational, will achieve annual output value exceeding CNY 100 billion, cementing Henan's position as a national battery manufacturing center.

Based on installed capacity data and equipment lifespan parameters, "new trio" waste generation in Henan is estimated using material flow analysis (MFA). By 2030, total waste generation is projected to reach approximately 252 kilotons, with EV batteries accounting for 71.4% (Table 6), PV modules for 23.8%, and wind turbine blades for 4.8%. This composition differs from the national average, where PV modules represent a larger share by 2030, reflecting Henan's particularly strong position in EV and battery manufacturing.

The "new trio" recycling industry in Henan is at an early developmental stage, with significant variation across categories. EV battery recycling is most advanced, supported by the province's strong manufacturing base. The market value of lithium battery recycling in Henan reached approximately CNY 3.4 billion in 2025, representing about 8.5% of the

national market. However, the overall recycling industry remains underdeveloped relative to the scale of new energy deployment, with a significant imbalance between upstream manufacturing scale and downstream recycling capacity.

Table 6. Estimated "new trio" E-Waste Generation in Henan Province (2025–2030).

Category	2025	2027	2029	2030	2030 Share
EV Batteries (kt)	12.5	45.0	120.0	180.0	71.4%
PV Modules (kt)	2.0	8.5	35.0	60.0	23.8%
Wind Blades (kt)	1.5	4.0	9.5	12.0	4.8%
Total (kt)	16.0	57.5	164.5	252.0	100%

3.6. Systemic Challenges and Root Causes

Five interconnected systemic barriers constrain the development of the "new trio" recycling industry [42]. First, the regulatory framework is incomplete. In the absence of EPR for PV modules and wind turbine blades, manufacturers bear no legal obligation for end-of-life management, and no dedicated funding mechanism supports recycling operations. The interrupted transmission of responsibility within the EPR system constitutes the most fundamental institutional barrier [22]. Without producer obligation, recycling costs fall on municipalities and informal operators, creating a funding gap estimated at 8–12 billion yuan [43] annually for PV and wind waste management at the national level.

Second, recycling technology development significantly lags behind new energy technology advancement. Research and development investment in recycling technology is structurally imbalanced. The field faces high technical barriers, long development cycles, and elevated commercialization risk, which together deter private sector investment. University–industry collaboration mechanisms are underdeveloped, with academic research often remaining at the theoretical stage without clear pathways to industrial application.

Third, structural market failure characterized by the dominance of informal recycling networks creates adverse selection dynamics. Informal operators achieve 30–50% cost advantages by externalizing environmental costs, creating a perverse incentive structure where the most environmentally harmful operators are the most economically competitive [44].

Fourth, governance is fragmented across the National Development and Reform Commission, the Ministry of Industry and Information Technology, the Ministry of Commerce, and the Ministry of Ecology and Environment. Overlapping mandates and unassigned responsibilities produce a segmented supervisory system with regulatory gaps [44]. Information isolation compounds this challenge, with no unified platform for full lifecycle data management.

Fifth, the industrial ecosystem remains underdeveloped. Value chains from production through consumption and recycling to regeneration are fragmented, and standardized specifications for recycled materials are lacking. Together these conditions limit demand for such materials and undermine economic viability [45]. These five barriers reinforce each other in a negative feedback loop, requiring coordinated, multi-dimensional policy interventions.

3.7. Policy Recommendations

To translate the diagnostic findings into actionable governance, seven policy recommendations are proposed, each linked to the five systemic barriers (Section 3.6) and informed by the international comparison (Section 3.4).

(1) Extend EPR coverage and complete the regulatory framework. EPR obligations should be extended to PV modules and wind turbine blades, with explicit producer responsibilities, registration requirements, and progressive recovery targets modeled on

Regulation (EU) 2023/1542 [21]. This would close the institutional gap identified as the most fundamental barrier.

(2) Strengthen technological innovation support. Dedicated national R&D programs should target two decisive technical bottlenecks: EVA encapsulant separation and thermosetting composite depolymerization. Support should take the form of pilot and demonstration funding, university–industry platforms, and long-cycle risk-sharing instruments that offset the structural R&D imbalance.

(3) Cultivate formal recycling markets. Compliance costs for informal operators should be raised through consistent enforcement. Formal networks should meanwhile receive subsidies and tax credits conditional on environmental performance. Both measures should be underpinned by standardized specifications for recycled materials that build downstream demand.

(4) Enhance environmental supervision. Unified supervision across departments, strict enforcement of hazardous waste transfer rules, and an enterprise credit system would internalize environmental costs. Together they would also eliminate the adverse selection that currently rewards the most polluting operators.

(5) Build digital governance platforms. The national power-battery traceability platform should be extended to PV modules and wind turbine blades, enabling full lifecycle data management, collection scheduling and enforcement.

(6) Optimize industrial layout. Regional recycling bases should be co-located with retirement clusters. Henan's battery manufacturing base provides an exemplary foundation, and such bases should be supported by cascade utilization pilots and second-life application markets.

(7) Deepen regional and international cooperation. Inter-provincial coordination mechanisms should govern cross-regional waste transfer. Continued learning from EU and Japanese regulatory experience would further support a coherent national recycling ecosystem.

4. Conclusions

This study has systematically analyzed the recycling of "new trio" e-waste, comprising EV lithium-ion batteries, PV modules, and wind turbine blades. The analysis applies a hybrid methodology that integrates MFA, LCA, and PTQA. Five key findings emerge. First, the scale of the waste challenge is accelerating rapidly: global generation is projected to exceed 16.7 million tons by 2030 under baseline assumptions (range: 12.8–21.3 million tons), with China accounting for approximately 45%. In Henan Province alone, waste volumes are projected to reach approximately 252 kilotons by 2030, with EV batteries representing the dominant share at 71.4%. The embedded resource value is substantial—estimated at USD 28 billion globally in 2025, growing to USD 75 billion by 2030—representing both a significant economic opportunity and a critical supply chain security consideration.

Second, recycling technology maturity varies markedly across categories. EV battery recycling is the most advanced and already operates at industrial scale. PV module valorization remains at the demonstration stage, constrained by EVA separation and wind blade valorization by thermosetting composite depolymerization.

Third, international comparison reveals that China lags behind the EU and Japan in EPR coverage breadth, recovery target stringency, and informal sector enforcement.

Fourth, the Henan case study demonstrates both the scale of the challenge and the opportunities for proactive intervention. The province leads the country in new energy installed capacity and battery manufacturing, which provides a strong foundation for recycling. However, recycling capacity lags substantially behind manufacturing growth, and the gap is widening.

Fifth, the causes of industry underdevelopment are systemic and interconnected. Incomplete regulation, technological bottlenecks, market failure, fragmented supervision, and underdeveloped ecosystems reinforce one another in a self-reinforcing cycle. To address these barriers, Section 3.7 proposes seven policy recommendations spanning EPR extension, innovation support, formal market development, environmental supervision, digital governance, industrial layout and regional cooperation.

Future research could address these limitations through Monte Carlo uncertainty propagation, primary data collection at recycling facilities, and longitudinal tracking of waste generation. Detailed case studies of policy implementation at the municipal level would complement these efforts. Despite these limitations, this study provides a sound analytical foundation for understanding the "new trio" e-waste challenge. Proactive policy, targeted investment, and institutional innovation could turn this emerging waste stream into a strategic resource. The choice is not whether retirement will occur, but whether it is managed as a liability or as an asset.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su182211495/s1, Table S1. Policy document corpus (87 documents, 2015–2026); Table S2. Raw coding scores (two independent coders, six dimensions). Table S3. Inter-coder reliability. Table S3b. Mean scores by region. Table S4. Scoring rubric.

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Abbreviations

The following abbreviations are used in this manuscript:

EV	Electric vehicle
PV	Photovoltaic
MFA	Material flow analysis
LCA	Lifecycle assessment
PTQA	Policy text quantitative analysis
EPR	Extended producer responsibility
WEEE	Waste electrical and electronic equipment
SSWM	Sustainable solid waste management
CE	Circular economy

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