Proceedings of Business and Economic Studies, 2025, Volume 8, Issue 4
http://ojs.bbwpublisher.com/index.php/PBES
Online ISSN: 2209-265X
Print ISSN: 2209-2641

Decision Framework for Reverse Logistics Models of Decommissioned Wind Turbine Blades

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Abstract: To address the recycling challenges posed by the global peak of wind turbine blade retirement, this study aims to establish a decision-making model for reverse logistics modes of decommissioned blades, resolving the multi-agent collaborative optimization problem under ultra-high logistics cost constraints. Based on the characteristics of centralized sourcing and determinable elements in blade reverse logistics, we developed three models dominated by wind power equipment manufacturers, operators, and third-party enterprises, respectively. The research analyzes influencing factors on reverse logistics mode selection and proposes a threshold decision mechanism for mode selection. Key findings reveal: technological strength serves as the core driver for manufacturer-dominated models; channel efficiency determines the applicability of operator-led models; insufficient economies of scale may hinder third-party model development. This study provides decision-making foundations for the resource utilization of decommissioned blades.

Keywords: Wind blade recycling; Reverse logistics mode; Network optimization

Online publication: September 9, 2025

1. Introduction

Amidst the global energy transition, wind energy stands as one of the most promising green energy sources [1]. With the rapid growth of global wind power installed capacity, the volume of decommissioned wind power equipment has surged significantly in recent years. Projections indicate that the global peak in wind turbine retirement will occur within the next decade, generating vast quantities of end-of-life wind turbine blades. Due to their oversized and ultra-heavy characteristics, these blades pose immense challenges for disposal and recycling. China possesses exceptional geographical conditions and ranks among the world's leaders in wind energy resources [2]. By the end of 2023, its cumulative grid-connected wind power installed capacity reached 440,000 MW [3]. In 2025, the first wave of large-scale wind turbine retirements will emerge, with aging wind farms exceeding 20 years of operation, surpassing 1.2 million kW in scale [4]. By 2026, decommissioned wind turbine blades are projected to total 8,000 tonnes [5]. This raises the critical question of how to manage such large-scale end-of-life blade waste. Globally, policies for handling decommissioned blades vary significantly. European Union nations, governed by stringent environmental regulations, largely prohibit direct landfilling of turbine blades. Countries like China and the United States have also gradually tightened restrictions on incineration and on-site landfilling of blade waste [6]. Studies confirm that recycling end-of-life blades generates higher economic returns and superior environmental benefits [7]. Consequently, recycling costs must be addressed: the oversized characteristics and low stacking density of blades result in logistics costs substantially exceeding those of conventional industrial goods. For a 200-km transport distance, transportation costs alone reach ¥1,200–1,500 per tonne [8].

2. Characteristics of decommissioned wind turbine blades

2.1. Reverse logistics features

According to China's definition, reverse logistics in the narrow sense comprises recovery logistics and waste logistics [9]. While sharing similarities with forward logistics (e.g., handling, transportation), reverse logistics exhibits distinct features:

(1) Reverse flow direction: The core characteristic where goods move opposite to forward logistics—from consumers/end-users back to manufacturers, suppliers, or recycling centers.

(2) Decentralization (Unpredictability): Reverse logistics lacks predictability in timing, location, quantity, and quality of returned products. Transport routes often deviate from conventional patterns, contrasting sharply with the planned, centralized flows of forward logistics.

(3) Gradual accumulation: Initial stages involve diverse but low-volume recoverables, hindering economies of scale. Prolonged accumulation phases reduce stakeholder engagement. Post-collection, complex sorting/reprocessing further extends cycles, limiting responsiveness to demand.

(4) Complexity:Remanufacturing(cleaning,testing,disassembly,refurbishment,reassembly) regenerates value. Diverse treatment methods yield significantly variable resource recovery outcomes.

2.2. Unique features of blade reverse logistics

Decommissioned blade reverse logistics diverges from traditional models, anchored in source concentration and determinable key factors, enabling stable network design:

2.2.1. Geographic concentration

Sources are fixed at onshore/offshore wind farms—spatially identifiable versus random origins in conventional systems.

2.2.2. Predictable drivers

(1) Retirement window: Around 20–25-year lifespan allows accurate long-term forecasting.

(2) Retirement volume: Blade counts per wind farm are pre-determinable.

(3) Material properties: Dimensional ranges and compositions (GFRP/CFRP composites) are well-defined.

2.3. Reverse logistics network typologies

China's blade recycling sector remains nascent, with three dominant models exhibiting distinct advantages and limitations:

(1) Manufacturer-dominated model: Driven by resource circularity mandates and policy compliance, manufacturers recover blades for remanufacturing. This reduces production costs, enhances product value, and

strengthens market competitiveness.

(2) Operator-dominated model: Operators/investors leverage direct source coordination for efficiency—minimizing transport costs while generating revenue streams from retirement demand.

(3) Third-party-dominated model: Specialized logistics providers handle recovery, allowing supply chain actors to focus on core operations and mitigate operational risks associated with reverse flows.

3. Research on reverse logistics models for decommissioned wind turbine blades

3.1. Model formulation

The selection of reverse logistics models for decommissioned wind turbine blades is critically important, as economic returns for participating entities vary significantly across different models. This study focuses on three manufacturer-, operator-, and third-party-dominated frameworks. Based on the operational workflow of collection → assessment → cascading utilization or material recycling pathways, mathematical models with profit maximization as the optimization objective are developed to establish a decision-making framework for optimal model selection.

3.2. Model notation and assumptions

3.2.1. Model symbols

The symbols and their meanings in the model are shown in **Table 1** below:

Table 1. Symbol model and meaning description

Symbols	Definition
k	Reverse logistics model type:k=M(manufacturer-dominated),k=O(operator-dominated),k=T(third-party-dominated)
p_k	Representing the recycling price of the recycling party under k reverse logistics modes, k=M, O, T
Q_k	The amount of retired wind turbine blades recovered under the k-th reverse logistics mode, k=M, O, T
Q_0	Recycling amount of retired wind turbine blade foundations
a	Sensitivity coefficient of the market to the price of blade recycling
λ_k	Reuse rate of retired wind turbine blades under the k-th reverse logistics mode
λ_0	Utilization rate of retired wind turbine blade foundation
β	Design efficiency coefficient
r_u	Benefits from reusing retired wind turbine blades
r_r	Renewable income from retired wind turbine blades
B	Processing scale coefficient
I_k	Investment cost under the k-th reverse logistics mode, k=M, O, T
γ	Transportation cost of retired wind turbine blades
s	Green design level
d_k	The average transportation distance under the k-th reverse logistics mode, k=M, O, T
η_k	Scale efficiency coefficient under the k-th reverse logistics mode, k=M, O, T
π_k^M	Manufacturer's total profit under model k
π_k^O	Operator's total profit under model k
π_k^T	Third-party recycler's total profit under model k

3.2.2. Model assumptions

(1) All recycling entities operate under symmetric information conditions and function as risk-neutral decision-makers.

(2) The collection volume of decommissioned wind turbine blades Q^k is assumed to follow a linear relationship with the collection price, expressed as: $Q^k = Q^0 + ap^k$, where Q^0 denotes the baseline collection volume and a represents the price sensitivity coefficient.

(3)Material recycling revenue: Units unsuitable for cascading utilization or re-decommissioned after such use generate revenue r^r per unit through recycling processes (e.g., shredding, material recovery), with $r^r < r^u$ where r^u signifies the value per unit derived from cascading utilization, confirming its superior economic benefit.

(4) Investment cost differentials among recycling entities: Recycling entities (denoted I^k, where k=M for wind equipment manufacturers, k=O for operators, and k=T for third-party recyclers) incur distinct average investment costs per unit collected, satisfying $I^0 < I^M < I^T$. This hierarchy arises because: operators (O) leverage their geographically dispersed wind farm O&M networks and spare parts warehouses for collection, minimizing investment; manufacturers (M) utilize existing sales/service networks or OEM channel resources, resulting in moderate costs; third-party recyclers (T) require dedicated infrastructure investments (transportation, storage sites, preprocessing facilities), incurring the highest costs.

3.3. Model and construction of reverse logistics mode selection

3.3.1. Reverse logistics model managed by wind power equipment manufacturers

Under the manufacturer-dominated reverse logistics model, the manufacturer handles both blade collection and processing. Its benefit function incorporates sales revenue from cascading utilization and material recycling, offset by collection costs, investment costs, eco-design expenditures, and processing costs. Thus, the comprehensive benefit function for the wind equipment manufacturer is derived as:

$$\pi_M^M = \eta_M[r_u\lambda_M Q_M + r_r(1-\lambda_M)Q_M] - (p_M + I_M)Q_M - Bs_M^2 - \gamma d_M Q_M \quad (1)$$

$$\text{constraints:}\begin{cases} Q_M = Q_0 + ap_M \\ \lambda_M = \lambda_0 + \beta s_M \end{cases} \quad (2)$$

Equation (1) is about the p_M function. By substituting the constraint conditions, the first-order partial derivative is obtained, and the partial derivative is set to 0, to obtain the optimal recycling price of retired wind turbine blades in M-mode.

$$\frac{\delta\pi_M^M}{\delta p_M} = 0 \Rightarrow p_M^* = \frac{\eta_M[(r_u - r_r)(\lambda_0 + \beta s_M) + r_r] - I_M - \gamma d_M}{2} - \frac{Q_0}{2a} \quad (3)$$

3.3.2. Reverse logistics model managed by wind power equipment operators

Under the operator-dominated reverse logistics model, decision-making is centralized: the operator exclusively controls blade collection pricing, with no manufacturer involvement or transfer payments. Its benefit function incorporates sales revenue from cascading utilization and material recycling, offset by collection, investment, and processing costs. Thus, the operator's comprehensive benefit function is derived as:

$$\pi_O^O = \eta_O[r_u\lambda_O Q_O + r_r(1-\lambda_O)Q_O] - (p_O + I_O)Q_O - \gamma d_O Q_O \quad (4)$$

$$\text{constraints:}\begin{cases} Q_O = Q_0 + ap_O \\ \lambda_O = \lambda_0 + \beta s_O \\ s_O = s_{fix}(CV) \end{cases} \quad (5)$$

Equation (4) is about the p_0 function. By substituting the constraint conditions, the first-order partial derivative is obtained, and the partial derivative is set to 0, to obtain the optimal recycling price of retired wind turbine blades in O-mode.

$$\frac{\delta\pi_O^O}{\delta p_O} = 0 \Rightarrow p_O^* = \frac{\eta_O[r_u\lambda_O + r_r(1-\lambda_O)] - I_O - \gamma d_O}{2} - \frac{Q_0}{2a} \quad (6)$$

3.3.3. Reverse logistics mode in the charge of third-party recycling enterprises

Under third-party-dominated reverse logistics, decision-making is centralized: the third-party entity holds exclusive pricing control for blade collection, with no manufacturer involvement or transfer payments. The enterprise integrates full-chain resources to autonomously set prices for profit maximization. Its benefit function comprises material recycling revenue (excluding cascading utilization), minus collection, investment, and processing costs. Thus, the comprehensive benefit function for the third-party recycler is derived as:

$$\pi_T^T = \eta_T[r_T Q_T] - (p_T + I_T)Q_T - \gamma d_T Q_T \quad (7)$$

$$\text{constraints:} Q_T = Q_0 + ap_T \quad (8)$$

Equation (7) is about the p_T function. By substituting the constraint conditions, the first-order partial derivative is obtained, and the partial derivative is set to 0, to obtain the optimal recycling price of retired wind turbine blades in T-mode.

$$p_T^* = \frac{\eta_T r_T - I_T - \gamma d_T}{2} - \frac{Q_0}{2a} \quad (9)$$

3.3.4. Comparative analysis of three mode equilibrium solutions

As shown in **Table 2**, the optimal solution under three different models contains different parameter sets, and each uncertain parameter has different effects on the optimization results. Therefore, it is necessary to analyze how these parameters affect the selection of reverse logistics model for retired fan blades.

Table 2. Optimal solution of M-mode, O-mode, and T-mode

index	M-mode	O-mode	T-mode
Recycling price	$p_M^* = \frac{\eta_M[(r_u - r_r)(\lambda_0 + \beta s_M) + r_r] - I_M - \gamma d_M}{2} - \frac{Q_0}{2a}$	$p_O^* = \frac{\eta_O[r_u\lambda_O + r_r(1-\lambda_O)] - I_O - \gamma d_O}{2} - \frac{Q_0}{2a}$	$p_T^* = \frac{\eta_T r_T - I_T - \gamma d_T}{2} - \frac{Q_0}{2a}$
Reuse rate	$\lambda_M = \lambda_0 + \beta s_M$	$\lambda_O = \lambda_0 + \beta s_{fix}$	$\lambda_T = 0$
Recovery amount	$Q_M = Q_0 + ap_M$	$Q_O = Q_0 + ap_O$	$Q_T = Q_0 + ap_T$

4. Conclusion

Wind turbine blade recycling constitutes a critical link in the green closed-loop industrial chain of renewable energy. This study, operating under three fundamental constraints—no manufacturer take-back obligations, exclusion of environmental policy variables, and distinct model advantage differentiation—reveals systemic patterns in decommissioned blade recovery through multi-agent game-theoretic modeling and a threshold decision framework. Technological superiority, channel efficiency, and economies of scale collectively form a three-dimensional coordinate for model selection. Research indicates that regional resource endowments and entity capabilities necessitate differentiated recycling pathways: the manufacturer-dominated model proves irreplaceable for high-value blade processing, the operator-dominated model demonstrates significant advantages in short-distance transport scenarios, while third-party models rely entirely on scale effects derived from concentrated wind farm clusters.

The industry's core challenge stems from the structural imbalance between recycling costs and material recovery value, requiring multi-tiered solutions: policy interventions must establish economic incentive mechanisms, technological advancements should drive eco-design innovations, and logistics systems require optimized regional consolidation networks. Future research should explore dynamic techno-economic equilibrium mechanisms and advance nationwide recycled material circulation systems. Ultimately, the green renaissance of wind turbine blades will be illuminated by technological innovation, lighting the path toward resource circularity in humanity's carbon-neutrality journey.

Disclosure statement

The author declares no conflict of interest.

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