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Development of a Recycling Technology Selection Framework for Sustainable Metal Recycling

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ABSTRACT
The growing global demand for metals due to industrialisation, infrastructure development, and technological progress has led to serious challenges such as resource depletion, high energy use, and environmental impacts. Conventional metal recycling systems are widely used to reduce dependence on primary metal resources. However, they mainly focus on end-of-life recovery and rely on energy-intensive processes. These systems also suffer from material losses, downcycling, and poor long-term value retention, which limit their overall sustainability. This study reviews and analyses conventional metal recycling systems and proposes an alternative recovery framework that prioritises value retention throughout the product life cycle. A qualitative, literature-based approach was used to examine previous studies on metal recycling technologies, circular economy principles, and value retention strategies. Key weaknesses of recycling-dominant systems were identified through literature synthesis and comparative analysis. Based on these findings, a Recycling Technology Selection Framework (RTSF) was developed by integrating design-stage considerations, performance maintenance during use, condition-based assessment at end-of-use, and a hierarchical selection of recovery options. The RTSF prioritises reuse, refurbishment, and remanufacturing before recycling, while treating disposal and material leakage as system failures. The comparative evaluation suggests that the RTSF can improve value retention, enhance energy efficiency, and better align metal recovery systems with circular economy principles, contributing to a more sustainable and resource-efficient metal recovery system. Although conceptual in nature, the RTSF provides a structured decision-support foundation for manufacturing industries. However, the framework remains conceptual and has not yet been validated through industrial case studies or quantitative life-cycle assessment. Future research should validate the framework through empirical industrial applications and quantitative evaluation to confirm its practical applicability.
Keywords: Metal recycling, Circular economy, Value retention, Recycling Technology Selection Framework (RTSF), Sustainable manufacturing, Energy efficiency.

1 INTRODUCTION

Metal resource depletion has emerged as a critical global sustainability challenge, driven by rapid industrialisation, infrastructure development, and increasing demand for metals. Global metal consumption continues to rise steadily, placing significant pressure on primary resources and resulting in high energy consumption, greenhouse gas emissions, and environmental degradation associated with mining and refining activities (Graedel et al., 2011). In Malaysia, the manufacturing, construction, and automotive sectors generate substantial quantities of metal waste each year; however, a large proportion of this waste is still managed through energy-intensive recycling or disposal pathways, indicating inefficiencies in current recovery practices (Reck & Graedel, 2012). These challenges are particularly pronounced in developing economies, where recovery systems remain largely focused on end-of-life material recycling rather than value retention across the product life cycle.

Despite continuous improvements in metal recycling technologies, conventional recovery practices remain dominated by smelting and refining processes. While effective for material recovery, these approaches are constrained by high energy demand, material losses, alloy contamination, and downcycling, which reduce the long-term availability of high-quality secondary metals (Allwood et al., 2011). Advanced recovery strategies such as reuse, refurbishment, and remanufacturing offer significantly higher value retention and energy savings; however, their adoption is limited by design incompatibilities, lack of structured decision-making, and insufficient integration between product design and recovery stages (Bocken et al., 2016). Existing decision frameworks for metal recycling

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are either overly simplistic focusing primarily on cost or recycling rates or overly complex, limiting their practical applicability in industrial contexts.

To address these limitations, this study proposes a Recycling Technology Selection Framework (RTSF) for metal recovery that evaluates recovery options using a structured, value-oriented approach. The RTSF integrates four key evaluation pillars: technical feasibility, environmental sustainability, innovation and technological advancement, and system efficiency. Unlike conventional recycling-centric frameworks, the RTSF introduces multiple decision points across the product life cycle and prioritises higher-value recovery strategies before recycling. This structured yet accessible framework enables qualitative comparison of metal recovery technologies using a three-tier scoring system, supported by radar chart visualisation to enhance interpretability and decision support. The primary objectives of this study are threefold:

- To review and analyse conventional metal recycling systems and identify their limitations.
- To compare the proposed RTSF with conventional metal recycling frameworks and evaluate its potential advantages.

2 METHODOLOGY

This study develops and applies the Recycling Technology Selection Framework (RTSF) to evaluate and compare metal recovery strategies within industrial and manufacturing contexts. Rather than focusing solely on end-of-life recycling, the RTSF adopts a value-oriented and life-cycle-based perspective to assess the suitability of different metal recovery technologies. The framework is designed to support structured decision-making by prioritising value retention, energy efficiency, and sustainability performance across the product life cycle. This methodology section outlines the research design, evaluation structure, and analytical approach used to develop and apply the RTSF.

2.1 Introduction

This section describes the research methodology adopted for the development and application of the Recycling Technology Selection Framework (RTSF) for metal recovery systems. The methodology is designed to support a conceptual and qualitative evaluation of recovery options by integrating circular economy principles and value retention concepts. Rather than focusing solely on end-of-life recycling performance, the RTSF evaluates recovery options across the product life cycle to identify pathways that maximise sustainability and resource efficiency.

Given the objective of framework development and comparative evaluation, a qualitative, literature-based research approach was adopted. This approach is widely used in sustainability and circular economy studies where system-level understanding, conceptual synthesis, and decision-framework development are prioritised over numerical optimisation or experimental validation (Allwood et al., 2011; Kirchherr et al., 2017).

2.2 Research Design

The research adopts an exploratory and qualitative research design, suitable for analysing complex systems and developing conceptual frameworks. The study does not involve experimental testing, numerical modelling, or industrial case studies. Instead, it relies on systematic literature synthesis and analytical comparison of existing metal recovery practices.

The methodological workflow consists of the following stages

1. Identification of limitations in conventional metal recycling systems
2. Review of circular economy principles and value retention strategies
3. Development of the Recycling Technology Selection Framework (RTSF)
4. Qualitative evaluation of metal recovery options using the RTSF
5. Interpretation and discussion of results

This structured approach ensures logical progression from problem identification to framework validation, as recommended in previous framework-development studies in material sustainability research (Bocken et al., 2016; Reuter, 2012).

2.3 Framework Development

The RTSF was developed through synthesis of findings from peer-reviewed literature on metal recycling, circular economy implementation, and value retention hierarchies. Previous studies have highlighted that recycling-dominant systems prioritise material recovery at the expense of embedded energy and functional value (Allwood et al., 2011; Reck & Graedel, 2012). These insights formed the foundation for restructuring recovery decision-making within the RTSF.

The framework evaluates four metal management strategies within the metal value chain:

- Reuse
- Recycling
- Recovery
- Landfill (final disposal)

In this study, recovery refers specifically to energy or material recovery processes that do not preserve product functionality. Landfill is considered a final disposal pathway rather than a recovery option. These options are arranged in descending order of value retention, consistent with circular economy hierarchies proposed in earlier studies (Bocken et al., 2016; Kirchherr et al., 2017).
The RTSF integrates input indicators (enabling conditions) and output indicators (performance outcomes), which are organised into four evaluation pillars:

1. Technical Feasibility – practicality, process complexity, and compatibility with existing systems
2. Environmental Sustainability – relative energy demand, emissions potential, and material losses
3. Innovation and Technological Advancement – support from design-for-circularity and recovery-enabling technologies
4. System Efficiency – effectiveness of value retention and alignment with circular economy goals

This structure addresses gaps in existing frameworks that either focus narrowly on recycling rates or lack practical decision hierarchies (Reuter, 2012; Kirchherr et al., 2017).

2.4 Data Collection

This study relies exclusively on secondary data, as primary data collection was beyond the scope of the research. Data were obtained through a systematic literature review of academic and authoritative sources published between 2011 and 2024.
The main sources of data include:

- Peer-reviewed journal articles related to metal recycling, materials engineering, and sustainability (e.g., *Resources, Conservation and Recycling*, *Journal of Cleaner Production*)
- Review papers and conceptual studies on circular economy and value retention strategies (Allwood et al., 2011; Bocken et al., 2016)
- Authoritative reports and academic books addressing material efficiency and metal resource management

These sources provided qualitative evidence on energy intensity, material degradation, system inefficiencies, and recovery hierarchy effectiveness. The literature was screened and synthesised to ensure relevance to metal recovery systems and framework development objectives.

2.5 Data Analysis and Evaluation

A qualitative three-level scoring system (*High, Medium, Low*) was used to evaluate each recovery option across the four RTSF pillars. This approach enables structured comparison while avoiding reliance on uncertain or context-specific numerical data.
Each recovery option was assessed as follows:

- Reuse – evaluated for its ability to preserve product form, function, and embedded energy
- Recycling – assessed based on material recovery effectiveness and associated energy and material losses
- Recovery – examined as a lower-value option with limited circularity contribution
- Landfill – treated as a system failure with no value retention

Scoring was based on comparative interpretation of findings from the literature, following approaches used in previous qualitative sustainability assessments (Bocken et al., 2016; Reuter, 2012). To enhance interpretability, results were synthesised and presented using radar chart visualisation, allowing clear comparison across evaluation pillars.

2.6 Policy and Regional Fit Consideration

While no policy compliance assessment was conducted, the RTSF was developed with consideration of regional industrial realities, particularly those relevant to developing and manufacturing-based economies. Previous studies highlight that recovery strategies must be compatible with existing infrastructure, skills availability, and industrial practices to be effective (Allwood et al., 2011).

The framework's emphasis on reuse and value retention supports broader sustainability and resource-efficiency objectives promoted in industrial development policies. By positioning landfill as a failure and recovery as a lower-priority option, the RTSF reinforces long-term sustainability goals without requiring immediate large-scale technological investment.

2.7 Methodological Limitations

This study is limited to **conceptual framework development and qualitative analysis** based on secondary data. No quantitative life-cycle assessment, economic modelling, or industrial validation was performed. While this limits numerical comparison, the methodology provides a strong theoretical foundation for understanding system-level recovery decisions.

Future research may extend this work by applying the RTSF to industrial case studies, integrating life-cycle assessment, or developing quantitative weighting schemes for decision-making.

2.8 Current Existing RTSF and Proposed RTSF

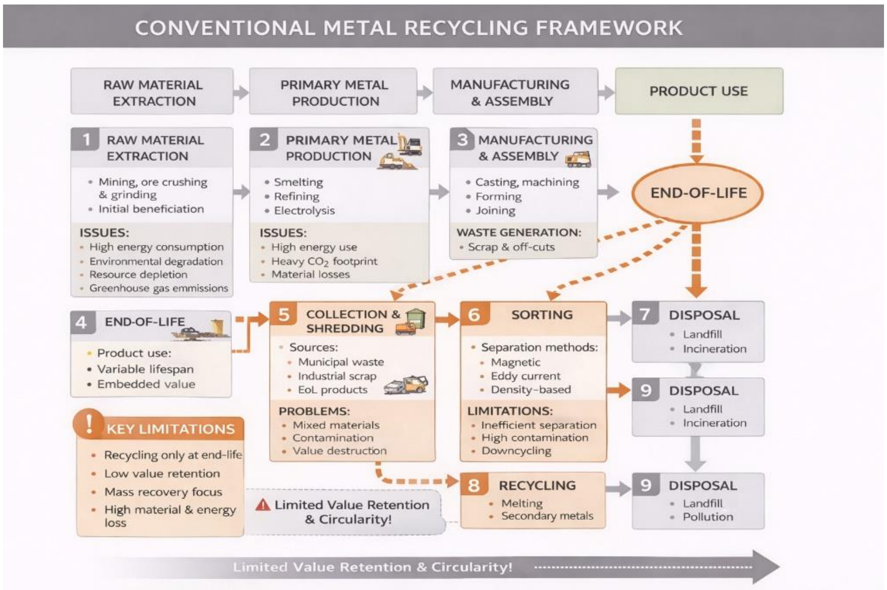

Figure 1 illustrates the structure of the existing recycling-dominant framework, where recovery decisions are primarily concentrated at the end-of-life stage and recycling is treated as the default strategy.

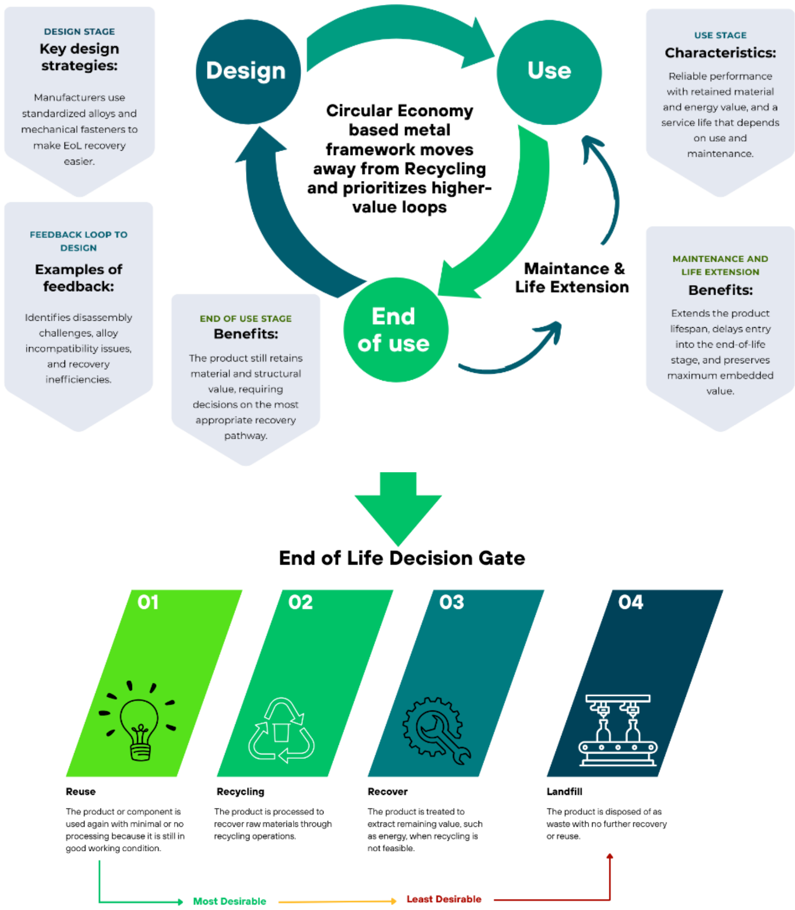

Figure 2 presents the proposed RTSF structure, which introduces multiple decision points across the product life cycle and prioritises higher-value strategies such as reuse and refurbishment before recycling.

3 RESULTS AND DISCUSSION

3.1 Introduction

This section presents and discusses the results obtained from applying the Recycling Technology Selection Framework (RTSF) to evaluate metal recovery options within a circular economy context. The purpose of this analysis is to demonstrate how the RTSF differentiates recovery pathways based on value retention, sustainability performance, and system efficiency, rather than relying solely on end-of-life recycling metrics.

The evaluation focuses on four metal management strategies Reuse, Recycling, Recovery, and Landfill assessed across four RTSF pillars: technical feasibility, environmental sustainability, innovation and technological advancement, and system efficiency. The results are derived from qualitative synthesis of peer-reviewed literature and authoritative reports, consistent with the methodology described in Chapter 2. This section first presents the RTSF evaluation outcomes and subsequently discusses their implications for sustainable metal resource management.

3.2 Overview of RTSF Application Results

Application of the RTSF reveals a clear hierarchical pattern in the performance of metal management strategies. Recovery strategies that preserve product form and embedded energy consistently outperform those relying on destructive processing. This finding aligns with earlier studies which argue that recycling-dominant systems underestimate the sustainability benefits of value retention strategies (Allwood et al., 2011; Bocken et al., 2016).

Across all four evaluation pillars, Reuse achieves the strongest overall performance, followed by Recycling, Recovery, and finally Landfill. The radar-chart-based comparison highlights those differences between recovery options are most pronounced in environmental sustainability and system efficiency, where energy demand and value loss play a critical role.

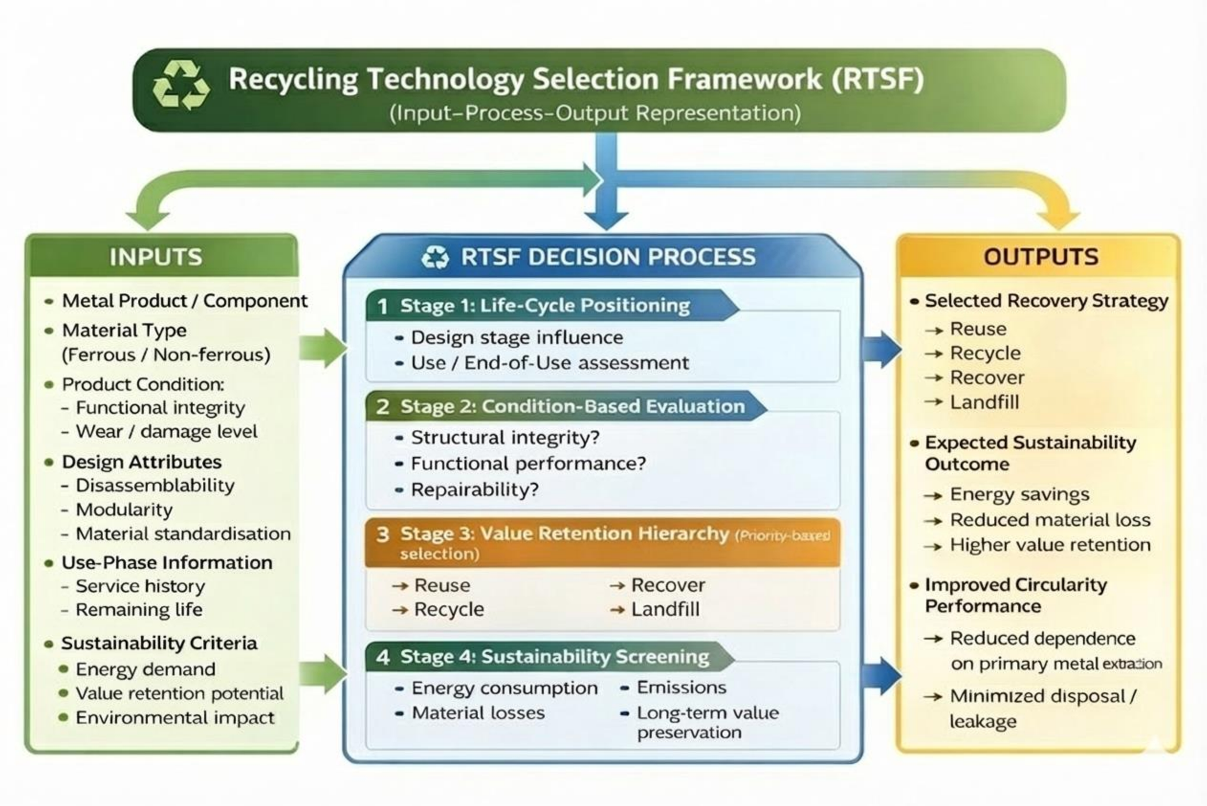

Figure 3: Recycling Technology Selection Framework (RTSF)

As illustrated in Figure 3, the radar chart comparison clearly differentiates the performance of the four metal management strategies across the RTSF evaluation pillars, highlighting the superior sustainability performance of reuse.

3.3 Evaluation of Metal Recovery Options

3.3.1 Reuse

Reuse demonstrates the highest performance across all RTSF pillars. From a technical perspective, reuse requires minimal processing and is compatible with existing industrial practices when product integrity and safety requirements are met. Previous studies indicate that reuse can often be implemented with limited technological intervention, relying mainly on inspection and quality verification processes (Allwood et al., 2011).

In terms of environmental sustainability, reuse offers the greatest benefits by avoiding energy-intensive operations such as smelting and refining. The preservation of embedded energy results in substantially lower emissions compared to recycling or recovery pathways (Bocken et al., 2016).

While reuse does not inherently rely on advanced processing technologies, innovation in design-for-durability and standardisation enhances its feasibility. From a system efficiency perspective, reuse achieves near-complete value retention, making it the most desirable recovery option within the RTSF hierarchy.

3.3.2 Recycling

Recycling remains the most widely implemented metal recovery option and exhibits high technical feasibility due to established infrastructure and industrial familiarity. However, the RTSF results indicate that recycling performs moderately rather than optimally across the evaluation pillars. Although recycling reduces dependence on primary metal extraction, its environmental performance is constrained by high energy consumption during smelting and refining, as well as oxidation losses and slag formation (Reck & Graedel, 2012). Repeated recycling cycles often lead to downcycling, reducing long-term material quality and functional value (Cullen & Allwood, 2013).

In terms of innovation, recycling systems tend to rely on conventional technologies with limited integration of recovery-enabling design principles. Consequently, system efficiency is moderate, as material value is only partially retained and product functionality is lost. These findings reinforce arguments that recycling should not be treated as the default recovery strategy (Allwood et al., 2011).

3.3.3 Recovery

Recovery represents lower-value pathways that do not preserve product form and offer limited contribution to circular material flows. RTSF evaluation indicates moderate to low technical feasibility, as recovery routes often involve complex processing and limited applicability to high-value metal products. From an environmental perspective, recovery options generally require significant energy input and result in indirect emissions, reducing their sustainability advantages compared to reuse or recycling (Reuter, 2012). Although some recovery processes incorporate advanced technologies, innovation in this context does not necessarily translate into improved value retention. The system efficiency of recovery is low, as most embedded energy and functional value are lost. As a result, recovery is positioned as a transitional option within the RTSF, suitable only when higher-value strategies are infeasible.

3.3.4 Landfill

Landfill consistently performs worst across all RTSF pillars and is classified as a system failure rather than a recovery option. Technically, landfill requires minimal effort, but it provides no material or functional value recovery. Landfilling metals results in permanent loss of resources and embedded energy, contradicting circular economy principles (Kirchherr et al., 2017). From both environmental and system efficiency perspectives, landfill represents the least sustainable outcome and highlights the consequences of ineffective recovery decision-making.

3.4 Discussion of Key Findings

3.4.1 Effectiveness of RTSF in Guiding Recovery Decisions

The results demonstrate that the RTSF is effective in structuring recovery decisions according to value retention rather than convenience. By explicitly comparing reuse, recycling, recovery, and landfill across multiple dimensions, the framework exposes the limitations of recycling-centric systems and supports a shift toward higher-value recovery pathways. This finding is consistent with previous literature, which emphasises that sustainability gains are maximised when recovery strategies prioritise preservation of product form and embedded energy (Allwood et al., 2011; Bocken et al., 2016).

3.4.2 Implications for Circular Economy Implementation

The RTSF operationalises circular economy principles by embedding them directly into recovery technology selection. Instead of treating circularity as a conceptual goal, the framework provides a practical mechanism for evaluating how different recovery options contribute to long-term material efficiency. By ranking landfill as a failure and recovery as a lower-priority option, the RTSF reinforces the need for proactive recovery planning and improved integration between product design and end-of-use decision-making (Kirchherr et al., 2017).

3.4.3 System-Level Insights

The analysis highlights that many sustainability challenges in metal recovery are systemic rather than technological. Even mature technologies such as recycling underperform when decision-making prioritises throughput over value retention. The RTSF addresses this gap by introducing multiple evaluation criteria that guide strategic recovery selection.

3.5 Section Summary

This section presented and discussed the results obtained from applying the Recycling Technology Selection Framework (RTSF) to evaluate metal recovery options within a circular economy context. Using a qualitative, literature-based assessment across four evaluation pillars technical feasibility, environmental sustainability, innovation and technological advancement, and system efficiency the framework enabled systematic comparison of reuse, recycling, recovery, and landfill as alternative recovery pathways.

The results reveal a clear and consistent hierarchy of performance among the recovery options. Reuse demonstrates the strongest overall performance due to its ability to preserve product form, functionality, and embedded energy with minimal environmental impact. Recycling, while technically mature and widely practiced, exhibits inherent limitations arising from energy-intensive processing, material losses, and downcycling effects, resulting in moderate sustainability performance. Recovery pathways contribute only limited value retention and are suitable mainly as transitional options when higher-value strategies are infeasible. Landfill performs poorest across all evaluation pillars and is identified as a system failure due to complete loss of material and functional value.

The findings confirm that sustainability challenges in metal recovery are largely systemic rather than purely technological. Even well-established recovery technologies underperform when decision-making prioritises throughput over value preservation. The RTSF effectively addresses this limitation by embedding circular economy principles directly into recovery selection, shifting focus from end-of-life recycling to life-cycle-based value retention. Overall, this chapter demonstrates that the RTSF provides a robust, transparent, and practical framework for guiding recovery decisions in metal resource management. The results support a strategic transition away from recycling-dominant systems toward recovery pathways that maximise value retention, energy efficiency, and long-term sustainability, thereby reinforcing the relevance of the RTSF as a decision-support tool for circular economy implementation.

4 CONCLUSIONS

This section has analysed and synthesised the findings obtained from the application of the Recycling Technology Selection Framework (RTSF) to metal recovery systems, with the aim of evaluating recovery options from a value-retention and circular economy perspective. The analysis confirms that conventional metal recovery practices remain largely recycling-dominant, with recovery decisions typically concentrated at the end-of-life stage and guided primarily by material throughput rather than sustainability performance.

The results demonstrate that recovery options exhibit substantially different sustainability outcomes when evaluated across multiple dimensions. Reuse consistently offers the highest level of value retention and environmental benefit by preserving product form, functionality, and embedded energy. This finding is consistent with earlier studies which emphasise that retaining product integrity delivers greater energy and emission savings than material recycling alone (Allwood et al., 2011; Bocken et al., 2016). In contrast, recycling, while essential for severely degraded materials, is constrained by high energy demand, material losses, and downcycling effects that reduce long-term material quality (Reck & Graedel, 2012; Cullen & Allwood, 2013).

Lower-value pathways categorised as recovery provide limited contribution to circular material flows, as they fail to preserve either product functionality or material quality over successive cycles. These pathways may serve a transitional role but do not support long-term circularity objectives. Landfill, as confirmed by the RTSF evaluation, represents a system failure that results in complete loss of material value and embedded energy, directly contradicting circular economy principles (Kirchherr et al., 2017).

A key outcome of this chapter is the identification that many limitations in current metal recovery systems are systemic rather than technological. Even technically mature recovery processes underperform when decision-making frameworks lack structured prioritisation of value retention and life-cycle integration. This finding aligns with prior literature highlighting the absence of effective decision-support mechanisms linking design, use, and end-of-use stages in metal recovery systems (Reuter, 2012; Allwood et al., 2011).

Overall, the analysis confirms that the RTSF provides a coherent and robust framework for improving recovery decision-making by embedding circular economy principles directly into technology selection. From an industrial perspective, the RTSF offers a structured decision-support tool that can assist manufacturers, recyclers, and policymakers in prioritising recovery strategies beyond conventional recycling. By integrating value-retention logic into recovery planning, the framework may support improved resource efficiency and long-term cost optimisation in metal-intensive industries. By explicitly prioritising reuse, critically evaluating recycling, and identifying recovery and landfill as progressively less desirable options, the RTSF offers a clear pathway for transitioning from recycling-centric systems toward value-oriented and resource-efficient metal recovery strategies.

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