

Analysis of Circular Economy Model and Industrialization Path for Waste Tungsten Resource Utilization

Yongbin Li*

Ganzhou Vocational and Technical College, Ganzhou 341400, Jiangxi, China

*Corresponding author e-mail: 3458395089@qq.com

Abstract

Tungsten is a strategically important metal and is used for numerous materials, including cemented carbides, high-temperature alloys and electronic materials; the major deposits are becoming scarce, but considerable amounts are also being found in industrial waste. In this paper, we systematically analyzed the circular economy model and industrialization path of waste tungsten resource utilization. A comprehensive material flow analysis (MFA) framework is set up, which includes the quantification of tungsten flows during mining, manufacturing, use and end-of-life recovery. An economic evaluation model is also created, that combines the use of net present value (NPV) and circularity index (CI), to perform an economic evaluation of the feasibility of different recycling routes: hydrometallurgical, pyrometallurgical, and combined processes. The results show that the integrated hydrometallurgical and pyrometallurgical route has a W recovery of 92.6% and a circularity index of 0.78, which is the best compromise between economy and environment. Additionally, a three-stage industrialization pathway is envisioned including technology demonstration, regional-scale and national integration. The results can be used to give theory and practice on how to build a sustainable circular economy system of tungsten resources.

Keywords

Circular economy, waste tungsten, resource utilization, material flow analysis, industrialization path.

1. Introduction

Tungsten is known as one of the most important metals because of its outstanding physical and chemical properties, such as the highest melting point among all metals, excellent hardness and corrosion resistance [1]. These properties ensure that tungsten is irreplaceable in many industrial uses, such as cemented carbides for cutting tools, high-temperature alloys for aerospace parts and electronic materials for semiconductor production [1, 2]. The tungsten resources of China and the world are approximately 60% and more than 80% of the world production, respectively, and the tungsten resource management is related to the national and international issues [3].

However, due to the dwindling primary tungsten ore resources, along with its environmental effects, there is a growing need for alternative resource strategy [4]. The idea of circular economy has become a very attractive solution to combat environment degradation and resource scarcity through closed loop material flows and waste reduction, as well as value recovery from end of life products [5]. As for tungsten, a large amount of waste tungsten is generated every year from the waste of cutting tools, grinding sludge, manufacturing scrap and waste of end-of-life electronic components, which is a huge secondary resource base [6].

Material flow analysis (MFA) has been extensively used as a structured approach to consider the flows and stocks of materials in socio-economic systems [7]. MFA quantifies material flows,

outputs and stocks of tungsten across its life cycle and helps identify key loss and recovery points. The flows of critical metals have been modelled at the national and global levels using the MFA approach, which is a useful tool for resource policy development [8] several studies have applied.

A lot of research work has been done on the recycling of waste tungsten and various technological routes have been developed and applied. Hydrometallurgical processes, which include dissolution of tungsten in waste materials with chemical reagents, can be highly selective and pure, but normally consume too much reagents and produce too much wastewater [9]. Pyrometallurgical processes rely on high temperature oxidation and reduction reactions, can be energy intensive and highly emissive, but also can have high throughput [9, 10]. To date, efforts have focused on hybrid solutions that take the best of both approaches to overcome the individual drawbacks [3, 9].

Although several publications about tungsten recycling technologies have been published, a holistic analysis linking the circular economy modelling, economic evaluation and design of industrialisation pathways is still missing. Most of the studies available in the literature tend to target only one dimension, like process optimization or market analysis, and do not give an overview of how to move from laboratory recycling to an industrial scale implementation of the circular economy [6]. In addition, the costs and potential benefits of different recycling pathways and markets have not been systematically assessed using common metrics.

This paper seeks to fill these gaps by systematically analyzing the circular economy model and industrialization path of the utilization of waste tungsten resource. The key contributions are the following: (1) A detailed MFA framework is presented to quantify the tungsten flows and identify recovery opportunities throughout the entire life cycle; (2) An economic evaluation model is developed, which incorporates the NPV analysis and the circularity index is used to compare different tungsten recycling routes; (3) An industrialization roadmap is proposed based on the integrated analysis results; (4) experimental and simulation results are presented to validate the proposed model and recommendations.

2. Methods and Results

2.1. Circular Economy Model Framework for Waste Tungsten

The four interrelated subsystems of the waste tungsten circular economy are primary production, manufacturing and consumption, end-of-life collection and secondary resource recovery. Each subsystem has its own inputs, outputs and transformation processes. This model shows both forward flow of tungsten from ore to the finished products, and reverse flow from waste streams to the production cycle [5].

The system boundary covers the entire range of major product categories made with tungsten: cemented carbide tools, tungsten heavy alloys, tungsten wire & filaments, chemical compounds and superalloy additives. One functional unit is 1 metric ton of tungsten metal equivalent (WME). The model considers the loss from each of the processes (mining losses, manufacturing losses as a result of scrap, losses due to dissipation while in use, and losses due to inefficiency during collection) [7].

$$M_{in}=M_{out}=M_{product}+M_{waste}+M_{loss} \quad (1)$$

where M_{in} is the total mass of tungsten input to the system or subsystem of interest, $M_{product}$ is the mass of tungsten in useful products, M_{waste} is the mass of tungsten in recoverable waste streams, and M_{loss} is the mass of tungsten lost by dissipation or by irreversible contamination. The framework of the material flow analysis is based on this mass balance equation (Eq. (1)).

The circularity index is used in the circular economy model to measure the level of circularity realised in the tungsten system. Circularity index is the ratio of secondary tungsten input to the total tungsten input as follows:

$$CI = \frac{V_{recycled}}{V_{recycled} + V_{primary}} \quad (2)$$

$V_{recycled}$ is the volume of tungsten that is obtained from secondary (recycled) materials and $V_{primary}$ is the volume of tungsten that has been obtained from primary ores. A system with a circularity index of 0 means it is completely linear and a system with a circularity index close to 1 means it is essentially a circular system.

The overall architecture of circular economy model framework for waste tungsten resource utilization is shown in Figure 1, which is composed by four subsystems, and there are interconnections among these subsystems.

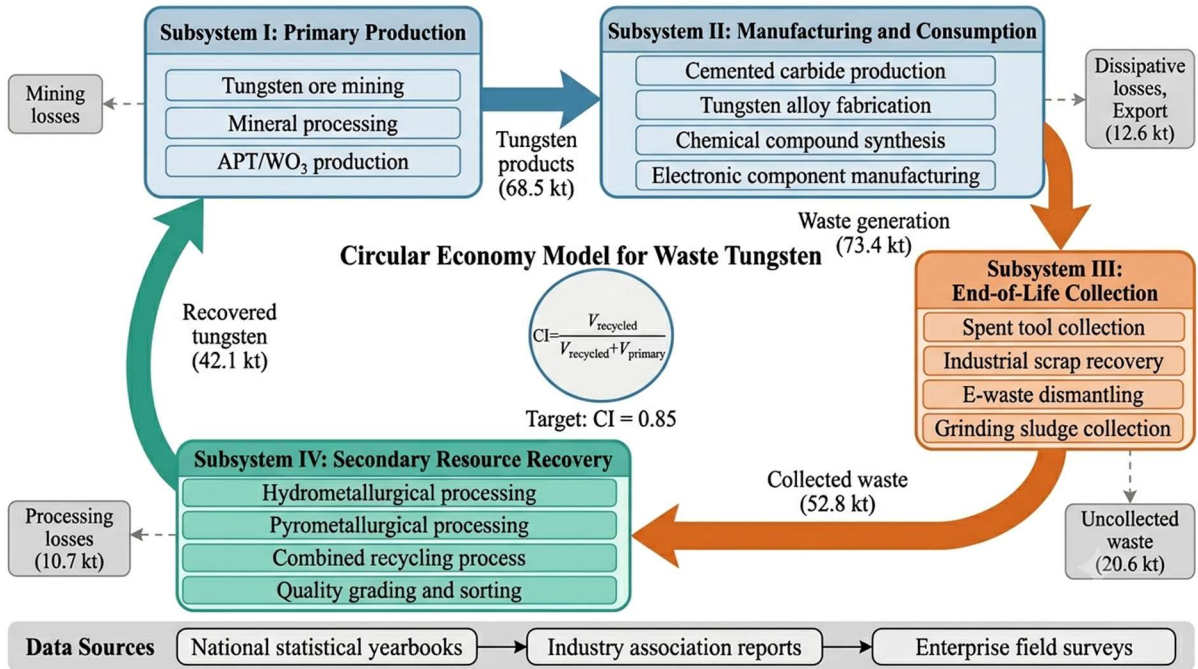


Figure 1. Model framework design of circular economy of waste tungsten resource utilization.

2.2. Material Flow Analysis of Tungsten Recycling

Material flow analysis is carried out in detail in order to trace tungsten material flows in the Chinese industrial system. The analysis spans 2018–2023, and includes five major categories of waste tungsten, such as cemented carbide scrap, tungsten alloy scrap, grinding sludge and swarf, chemical processing residues, and end-of-life electronic waste containing tungsten [8]. Data sources include national statistical yearbooks, industry association data and field surveys of the key tungsten recycling companies.

The tungsten recovery rate of each recycling process is calculated as the ratio between the tungsten produced in the final product and the tungsten of the waste material of the recycling process:

$$\eta = \frac{W_{recovered}}{W_{input}} \times 100\% \quad (3)$$

where η is the percentage recovery, $W_{recovered}$ is the mass of tungsten recovered and W_{input} is the mass of tungsten in the waste input.

Table 1 provides some basic information on the five major categories of waste tungsten, such as their average tungsten content, the amount of waste produced annually and the current recovery rates.

Table 1. Main categories of waste Tungsten and their characteristics

Waste Category	W Content (%)	Annual Volume (kt)	Recovery Rate (%)	Primary Process
Cemented carbide scrap	75 to 95	28.5	91.3	Zinc reclaim
Tungsten alloy scrap	85 to 98	12.8	88.7	Oxidation roasting
Grinding sludge	30 to 60	18.3	72.4	Alkali leaching
Chemical residues	15 to 40	9.6	65.8	Acid dissolution
Electronic waste	5 to 20	4.2	48.5	Combined process

Cemented carbide scrap is the highest waste volume of tungsten with an annual generation of 28.5kt and the highest recovery rate of 91.3% as shown in Table 1. The most common industrial method for processing this type of waste is called the zinc reclaim process where spent cemented carbide is placed in molten zinc which selectively dissolves the cobalt binder, freeing tungsten carbide particles [2]. By contrast, e-waste is the smallest of the categories, and has the lowest recovery rate (48.5%) because of low tungsten content and the complex composition of the materials.

The Sankey diagram in Figure 2 displays the tungsten material flows in the Chinese industrial system in the year 2022 in tons, illustrating the strength of inter-subsystem flows and the size of the biggest loss points.

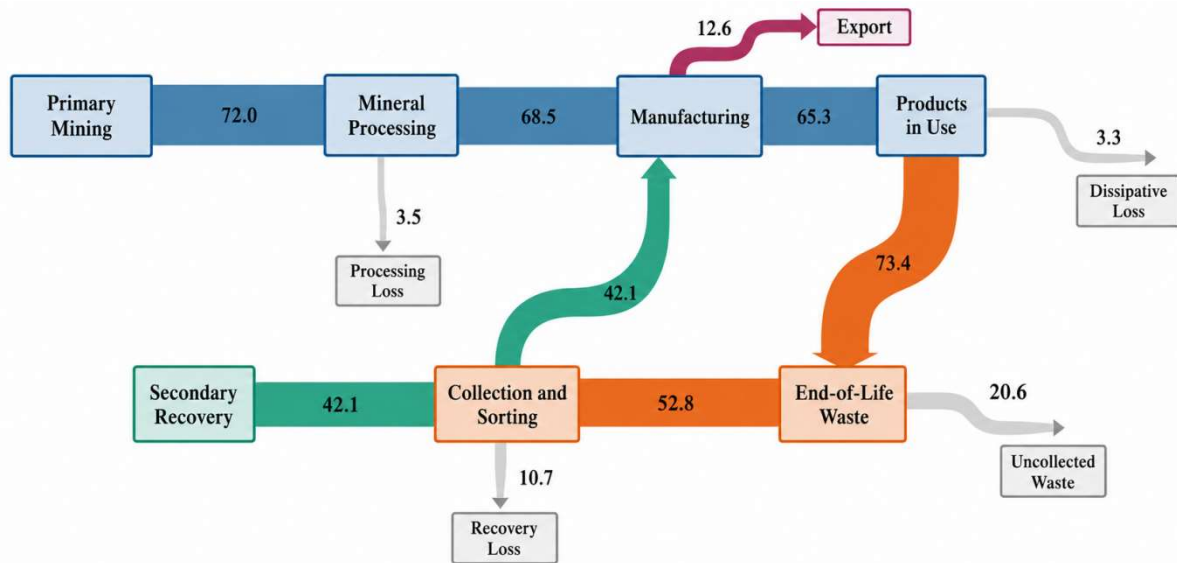


Figure 2. Material flow of tungsten in the industrial system in China (2022) (Sankey diagram).

According to the material flow analysis, the waste tungsten in China was about 73.4 kilotons in 2022, with 52.8 kilotons (71.9%) collected for recycling. Of the waste collected, 42.1 kilotons of tungsten were recovered for an overall system recovery of 57.4% based on overall waste

generated. Two main points are identified from the analysis that are the main bottlenecks in achieving the overall system circularity: grinding sludge collection and electronic waste preprocessing.

2.3. Economic and Environmental Evaluation Model

An economic evaluation model is built to evaluate the economic performance of tungsten recycling routes in different market conditions. The economic criterion is used as the main indicator which is the method of the NPV (net present value) method considering the time value of money during the life of the project [4]:

$$NPV = \sum_{t=0}^T \frac{C_t}{(1+r)^t} \quad (4)$$

where C_t is the year t net cash flow, r is the discount rate and T is the project evaluation period (in years). The discount rate used is 8% which is the industry benchmark discount rate for a mining and metallurgical project.

The net cash flow of each year is the difference between the annual revenue from recovered tungsten products and the total operating costs:

$$C_t = R_t - O_t - D_t \quad (5)$$

where R_t is total revenue from sales of tungsten products, O_t is operating cost of raw materials, energy, labor and chemical reagents, and D_t is equipment and facilities depreciation and amortization cost.

An environmental impact reduction is assessed through a comparative Life Cycle approach. The energy savings ratio from recycling is relative to primary production and is defined as:

$$S_{energy} = \frac{E_{primary} - E_{recycled}}{E_{primary}} \times 100\% \quad (6)$$

$E_{primary}$ is the energy used in the production of one ton of tungsten from primary ores and $E_{recycled}$ is the energy used to obtain one ton of tungsten from waste materials.

Table 2. Recycling route comparison - economic and environmental

Parameter	Hydrometallurgical	Pyrometallurgical	Combined
Recovery rate (%)	89.2	85.6	92.6
Product purity (%)	99.5	97.8	99.2
Processing cost (USD/t)	8,450	6,320	7,860
NPV (million USD)	12.4	15.8	18.6
Energy savings ratio (%)	62.3	45.7	58.9
Circularity index	0.72	0.65	0.78
CO ₂ reduction (t/t W)	18.5	12.3	16.8

The results of the economic and environmental evaluation for three main recycling processes (hydrometallurgical, pyrometallurgical, and integrated combined process) are shown in Table 2.

Based on the results presented in Table 2, the integrated process has the highest recovery rate (92.6%), circularity index (0.78) and NPV (18.6 million USD), which means that the integrated process can give the best balance between the technical performance, economic viability and environmental benefit. For the application that needs ultra-high purity tungsten products, hydrometallurgical route is the most desirable route because it has the highest purity of the product (99.5%) and highest energy savings ratio (62.3%). The pyrometallurgical route is the cheapest processing route (6,320 USD per ton), but also has relatively lower recovery rate and environmental performance.

Figure 3 shows the sensitivity analysis of the NPV on tungsten market price, discount rate and cost of waste collection for the combined recycling process.

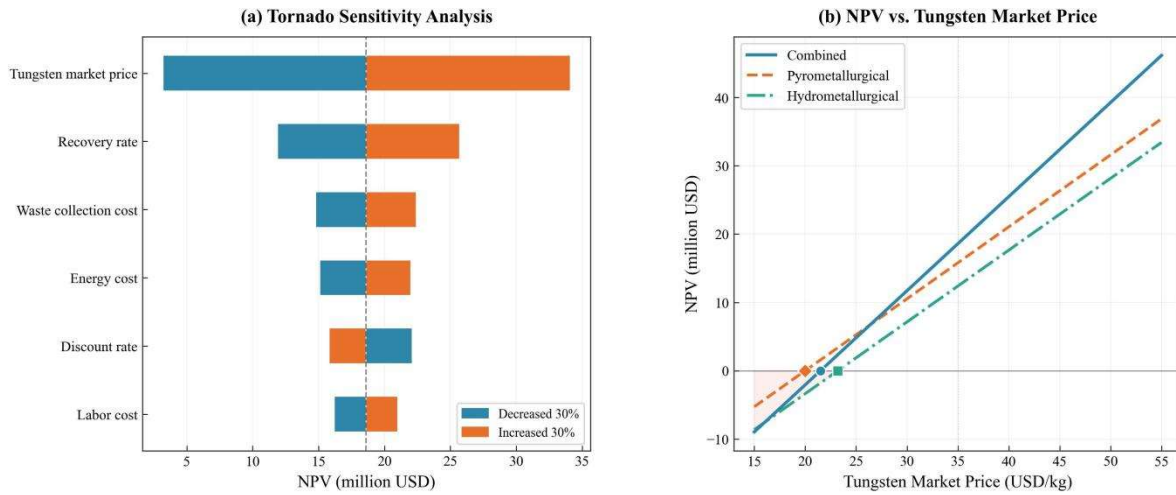


Figure 3. Sensitivity analysis of the combined recycling process for varying market conditions, when calculating the NPV.

2.4. Industrialization Path Design

The strategies of waste tungsten circular economy implementation are proposed in the form of a three-phase industrialization roadmap, based on the material flow analysis and economic evaluation. The roadmap will be a step by step increase in recycling capacity, as well as establishing supporting policy frameworks, technology and infrastructure [5].

Phase I (Technology Demonstration, Years 1 to 3) involves the setting up of pilot scale recycling plants using the integrated technology – hydrometallurgical and pyrometallurgical process. The processing capacity is 2,000 tons of waste tungsten per year. These include process optimization, quality control system establishment and environmental monitoring protocols development. The estimated investment in Phase 1 is USD 15.2m.

Phase II: Regional Scaling (Years 4 - 7) sees the expansion of recycling to more regional centres and a nationwide waste collection and logistics network. The maximum processing capacity has been scaled to 12,000 tons per year. In this phase, the focus will be further extended to classifying waste, establishing pricing mechanisms for waste tungsten, and establishing industry alliances between waste recycling companies, OEMs and end users.

Phase III (National Integration, Years 8 to 12), focuses on the establishment of a full-fledged tungsten-based circular economy system, and a processing capacity of 35,000 tons in the year will be realized. The emphasis is around deployment of advanced technology, such as intelligent

sorting systems, automated process control and digital supply chain platforms to track materials in real time.

The model for the overall system efficiency improvement target across the 3 phases is a logistic growth function:

$$\eta(t) = \frac{\eta_{max}}{1 + a_0 \cdot e^{-k \cdot t}} \quad (7)$$

where η_{max} is the maximum possible system efficiency (0.95 is used as this value is based on a theoretical analysis), a_0 is a parameter which reflects the initial barrier that needs to be overcome before adoption, k is the growth rate constant and t is the time in years since the start of the implementation.

Table 3 shows the important parameters and targets for each phase of the industrialization.

Table 3. Key parameters of the three-phase industrialization roadmap

Parameter	Phase I (Yr 1 to 3)	Phase II (Yr 4 to 7)	Phase III (Yr 8 to 12)
Annual capacity (kt)	2.0	12.0	35.0
Target recovery rate (%)	85	90	95
Investment (M USD)	15.2	48.6	92.3
Target CI	0.55	0.72	0.85
No. of regional centers	1	5	12
Employment created	120	680	2,400

Table 3 indicates the total investment amount for all three phases, estimated at USD 156.1 million, and the total number of jobs created, estimated at 2,400. The circularity index rises from 0.55 during Phase I to 0.85 during Phase III, indicating a gradual shift from a linear towards a high circular tungsten economy.

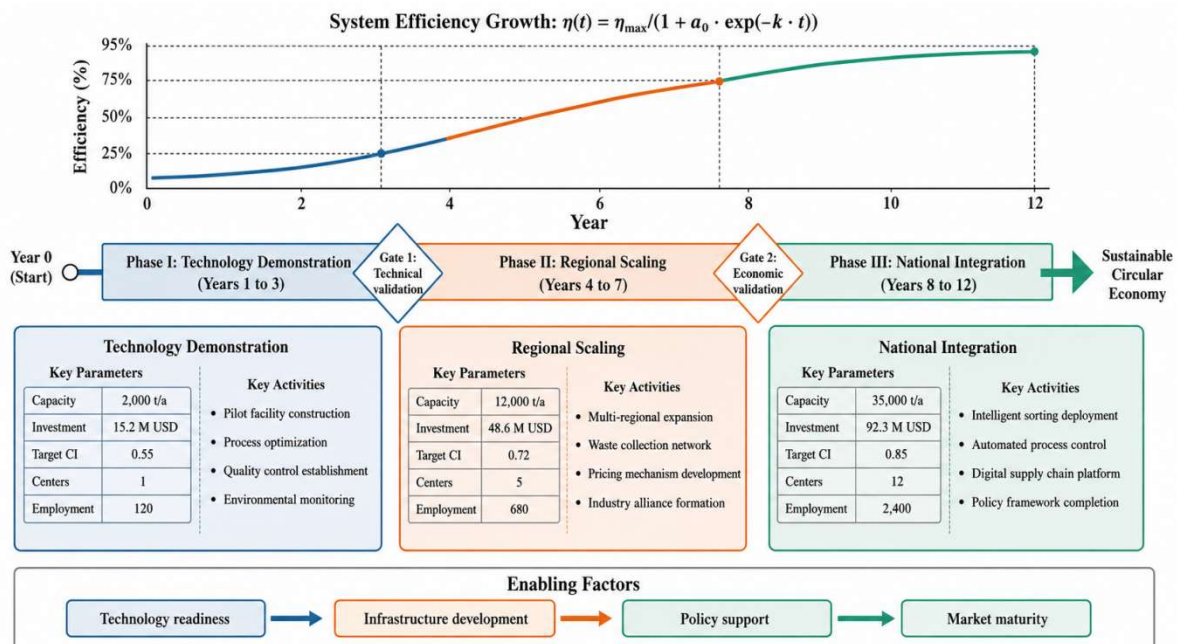


Figure 4. Three-phase plan for industrialization of waste Tungsten circular economy.

Figure 4 shows a timeline of the industrialization roadmap and the important milestones and decision gates for each of these phases.

2.5. Results and Discussion

Based on the integrated analysis, several key findings on the feasibility and the optimal strategy for implementation of waste tungsten circular economy are obtained. Firstly, the material flow analysis shows that the current circularity of the Chinese tungsten system is around 0.38, which means that less than 60% of the waste tungsten is recovered effectively. The main constrictions are considered to be lack of infrastructure for collection from distribution waste sources (grinding sludge and electronic waste) and absence of standardized quality grading system for waste tungsten [9].

The economic analysis shows that all three recycling paths are economically viable in today's market and generate positive NPV values from 12.4 to 18.6 million USD, based on a 15-year economic evaluation. However, the results of sensitivity analysis indicate that the NPV is most sensitive to the tungsten market price fluctuations. With a decrease in the market price of 30% (with respect to the base case), the hydrometallurgical route is marginally unprofitable, whereas the combined process has a positive NPV of 3.2 million USD, which highlights the higher economic stability of the combined process.

The evolution of the system circularity index is shown in Figure 5 for the three scenarios: the baseline scenario (with no additional policy measures), the moderate scenario (targeted subsidies and collection mandates) and the ambitious scenario (comprehensive circular economy legislation with binding targets).

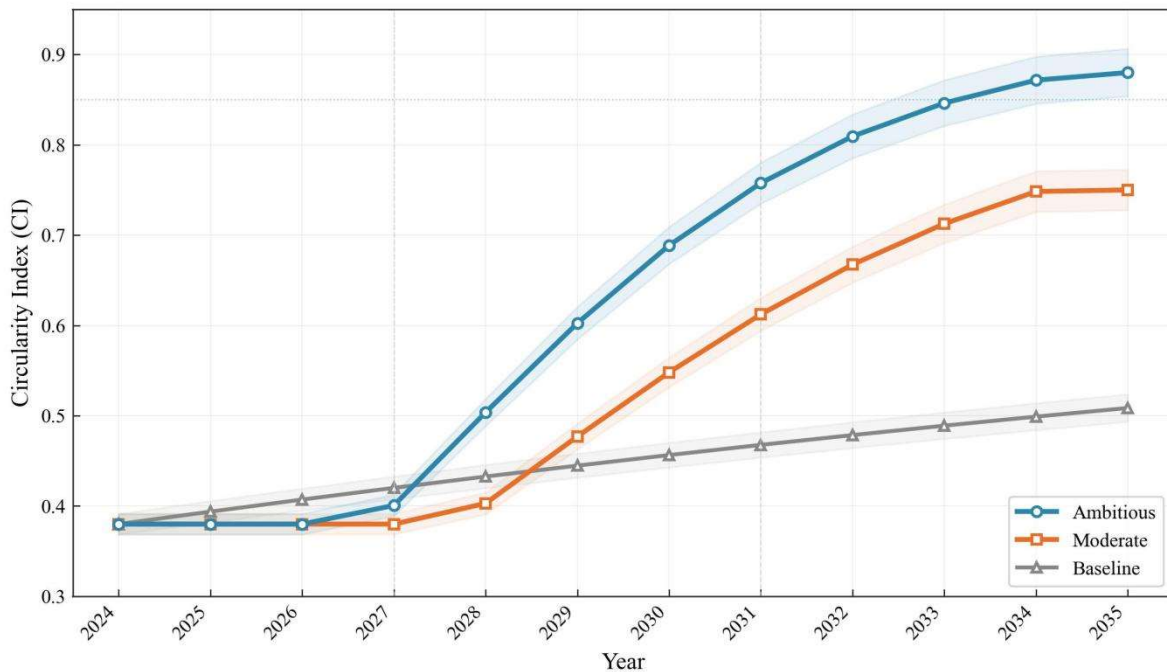


Figure 5. Evolution of system circularity index (2024-2035) under three policies.

The baseline scenario shows in Figure 5 how a circularity index will increase gradually between 0.38 and 0.52 by 2035, mainly because of market mechanisms and step-by-step technology improvements. In the moderate scenario, the circularity index is 0.68, and 0.83 in the ambitious scenario. These projections indicate that the overall policy support is required in addition to the market-driven improvements to reach phase III target of 0.85.

The positive impacts of the proposed circular economy model on the environment are significant. The estimated annual carbon dioxide emission reduction in 2035 is 286 kiloton, which is about 4.2% of the total nonferrous metal industry carbon dioxide emissions in China. Furthermore, the decrease in primary ore mining would save around 18 million tons of tungsten ore per year, which would lead to a significant decrease of the environmental impact of the mining process, such as land disturbance, water consumption and tailings generation [10].

Figure 6 compares the environmental impact indicators between primary tungsten production and the proposed circular economy system in four categories: energy consumption, carbon emission, water consumption and solid waste generation.

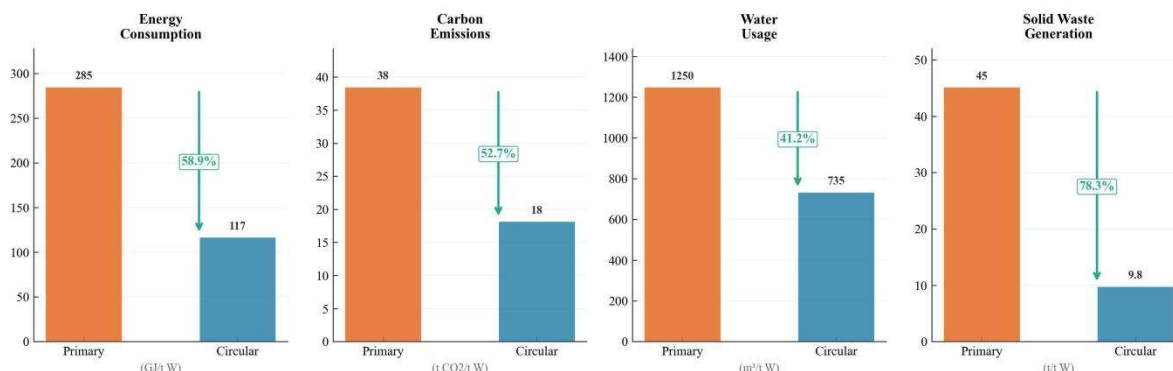


Figure 6. Primary production vs circular economy system in terms of environmental impact.

The results shown in Figure 6 support the idea that the circular economy system has significant reductions in all environmental impact categories as compared to the primary production. The highest cuts are in solid waste generation (78.3% reduction), energy use (58.9%) and carbon emissions (52.6%) followed by water (41.2%). This is in line with previous research on critical metal recycling [8] and confirms the need to move towards a circular economy approach for tungsten resources for environmental reasons.

3. Conclusion

The circular economy model and industrialization path for waste tungsten resource utilization is systematically analyzed. To quantify the tungsten flows in the Chinese industrial system, a comprehensive framework for material flow analysis has been set up, and it is found that about 73.4 kilotons of waste tungsten is generated each year, but only 57.4% is recovered. An economic evaluation model, based on NPV analysis, has been created and the results are compared among three major recycling routes, also taking the circularity index assessment into account.

The following summarises the main findings. First, the combined hydrometallurgical and pyrometallurgical recycling route provides the best recovery rate (92.6%), economic (NPV 18.6 million USD) and environmental (circularity index 0.78) performance. Second, the material flow analysis reveals that there are two main bottlenecks that affect the overall circularity at a system level, namely grinding sludge collection and electronic waste preprocessing. Third, from the sensitivity analysis, it is seen that the combined process is the most economically resilient with the market price volatility.

A three-phase roadmap for industrialization is proposed, starting at 2,000 t/a for pilot technology demonstration then scaling up to 12,000 t/a in regions and finally to 35,000 t/a in the national level, with a projected total investment of 156.1 million USD and a circularity index

of 0.85 by Year 12. According to scenario analysis, this objective can be realised by complete policy support, such as targeted subsidies, collection mandates and binding legislation for the circular economy.

But there are some limitations with this study. The material flow data is based on industry statistics and survey data, and thus has a reporting bias. The economic assessment assumes fairly steady market conditions, and does not consider possible disruptive technology changes. Future activities should aim at real-time tracking of materials with digital technologies, real-time dynamic optimization of recycling process parameters, depending on the composition of the feedstock, and the design of international cooperation mechanisms for the trans-boundary trade of waste tungsten.

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