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Improving aluminium resource efficiency in China: Based upon material flow analysis and entropy analysis

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A B S T R A C T

Aluminium is one widely used metal that plays an important role in China's industrial and economic development. The life cycles of aluminium products involve high energy inputs, intensive material consumption and heavy environmental emissions. China has released its ambitious climate change targets, namely reaching carbon peak in 2030 and achieving carbon neutrality in 2060. It is therefore urgent to take appropriate actions to reduce the overall greenhouse gas emissions from aluminium production and increase resource efficiency along the entire aluminium life cycle. Under such circumstances, this study aims to explore China's aluminium recycling potential through dynamic material flow analysis for the period of 2000–2019, covering its whole life cycle and including relevant international trade activities. An entropy analysis method is also applied to identify optimal pathways to improve aluminum resource efficiency and circularity. Results indicate that China has experienced fast growth of aluminum production and consumption during the last two decades, with its output of primary aluminium increasing from 4.18 Mt in 2000 to 35.11 Mt in 2019 and its aluminium consumption increasing from 2.99 Mt in 2000 to 32.5 Mt in 2019. Such rapid growth has resulted in significant environmental impacts. For instance, environmental loss of aluminium at the production stage accounted for 46% of the total loss throughout its entire life cycle in 2000, while such a rate increased to 69% in 2019. As such, entropy analysis results reflect that at the stage of waste management, the relative entropy of aluminium is rising, which indicates that any pollutants discharged into the environment will cause significant damage. Scenarios analysis results further help to identify the optimal pathway of aluminium metabolism system. Finally, several policy recommendations are proposed to improve the overall aluminium resource efficiency.

1. Introduction

Aluminium is one indispensable raw material for sectors such as electrical appliances, aircraft manufacturing, construction, machinery and civil appliances (Cullen et al., 2013). Sectors of construction, transportation and packaging consume more than 60% of the global aluminium consumption (Bertram et al., 2017). China is the largest primary aluminium production country, and over 50% of the global bauxite has been imported to China to meet with its soaring demand (Gulley et al., 2018). China is the fourth largest alumina producer in the world. Due to the low grade of bauxite, more red mud was generated, but the comprehensive utilization rate of red mud is only 4% (Owens, 2013). Therefore, it is urgent to effectively manage such waste so that resource efficiency of virgin material for making aluminum can be improved.

Aluminium is renewable and has the highest recycling rate among all the metal elements, contributing to both energy saving and emissions reduction. The production of one tonne aluminium

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through recycling secondary aluminium resource consumes only 2800 kWh of electricity and generates only 600 kg of carbon dioxide, leading to 95% electrical energy consumption and greenhouse gas emissions reduction (Hao et al., 2016). Based on the bottom-up life cycle assessment method, the environmental effects of bauxite, aluminium oxide and electrolytic aluminium were calculated in China, accounting for approximately 1.4%, 8% and 90.6% of the overall environmental burden, respectively (Zhang et al., 2021). Furthermore, besides energy savings and emissions reductions, aluminium recycling can create new employment opportunities, generate more economic revenues, reduce the overall solid wastes to the local landfills and promote sectoral cooperation (Bleischwitz, Nechifor, et al., 2018; Li et al., 2020).

Currently, the COVID-19 pandemic has seriously influenced industrial supply chains, but at the same time creates a new opportunity for countries to prepare their own recovery plans toward sustainable production and consumption. Also, many countries have prepared their carbon neutrality targets to respond climate change. For instance, China is committed to reach carbon peak in 2030 and achieve carbon neutrality in 2060. Under such a circumstance, improving resource efficiency is conducive to decoupling economic growth from greenhouse gas emissions (Geng et al., 2016; Zeng & Li, 2021). It is therefore essential to promote aluminium recycling, improve aluminium resource efficiency and mitigate corresponding emissions from aluminium production. This study aims to fill these research gaps in the following three aspects. First, China's aluminium recycling potential is evaluated using dynamic material flow analysis, in which the corresponding flows, aluminium resource efficiency and sectoral yields are measured by different indicators. Second, the entropy analysis method—an extension of material flow analysis method in resource efficiency —is used to evaluate aluminium recycling efficiency and identify key life cycle stages with high energy inputs, low resource efficiency and heavy pollution emissions. Third, valuable policy insights are proposed to prepare appropriate policies to support sustainable aluminium industrial development. The rest of the paper is organized as follows: After this introduction section, Section 2 details research methods and data sources, Section 3 presents research results, Section 4 discusses policy recommendations, and Section 5 draws research conclusions.

2. Methods and data

2.1. Material flow analysis

Material flow analysis (MFA) is a systematic assessment method for studying industrial metabolism of different materials by identifying their stocks and flows within a defined system (Graedel et al., 2015). It establishes a link between sources, pathways, intermediate and final sinks of different materials. According to the law of matter conservation, the results of MFA are controlled by material balances so that all inputs, stocks, and outputs of one process can be compared. MFA has become a decision support tool for resource and environmental management. The stocks and flows analysis framework (STAF) identifies the stocks and flows from the whole life cycle of one material so that the opportunities of improving material efficiency can be identified (Chen et al., 2018). In particular, the dissipative flows to the environment can be evaluated through the application of STAF so that valuable insights can be obtained for preparing appropriate resource and environmental policies.

According to the law of conservation of matter and energy, the total energy flowing into the system must be equal to the total energy flowing out of the system plus the change of internal energy of the system (Geng et al., 2021; Wiedenhofer et al., 2019). The following principle is used for each aluminium flow in the STAF model. This means that each aluminium material flow equals its material flow multiplying corresponding aluminium material content. The life cycle of aluminium in the social and economic system is divided into four stages: production, fabrication & manufacturing, use and waste management (see Fig. 1). Aluminium production is composed of bauxite mining, alumina refining, aluminium electrolysis and other production links. Such material flows mainly include: (1) the flows between each link and its application fields, and (2) the flows between production, waste recycling and the natural environment. Production and consumption stocks, as well as substances discharged into the environment, are considered losses (Munoz et al., 2020). Specific aluminium products are processed at each stage and its sub-stages of the aluminium life cycle. In the production and fabrication & manufacturing stages, aluminium is continuously processed and refined, with the aluminium content in each particular material constantly increasing. However, in the use and waste management stages, the aluminium content in each product is gradually reduced. The recycling potential of aluminium is evaluated by investigating the stocks and flows in the entire aluminium life cycle so that aluminium recycling opportunities can be identified.

2.2. Entropy analysis

In this study, the entropy analysis method refers to the application of entropy theory in material flow analysis. This method calculates the relative entropy at a certain node according to material flows and evaluates the degree of material concentration and dissipation based on relative entropy (Parchomenko et al., 2020; Yue et al., 2009). The results of entropy analysis can help prepare policies for improving aluminium efficiency. The following formulae are used for entropy analysis :

$$X_i = M_i c_i \tag{1}$$

$$m_i = \frac{M_i}{\sum_{i=1}^{k} X_i} \tag{2}$$

$$H(c_i, m_i) = -\sum_{i=1}^{k} m_i c_i ld(c_i) \geq 0 \tag{3}$$

where M_i is the weight of the ith aluminium flow, with a unit of megaton (Mt), c_i is the aluminium concentration of the ith aluminium flow, X_i is the aluminium weight of the ith aluminium flow, with a unit of megaton (Mt), m_i is the ratio of the aluminium weight of the ith aluminium flow to the concentrated aluminium weight of all the aluminium flows (totally there are k aluminium flows), H represents the entropy of the investigated system and ld is the logarithm to the base 2. When the material content in a regional system is the same as that in the natural environment, its entropy reaches an extreme value. C_{EC} is the aluminium concentration rate in the natural environment. Aluminium is the most abundant metallic element in the Earth's crust (8.23% by weight) (Orians & Bruland, 1985). The formula for calculating this entropy is

$$H_{\max} = ld\left(\frac{1}{C_{EC}}\right) \tag{4}$$

Relative entropy is the ratio of the entropy calculated by the system to the maximum entropy (Rechberger & Brunner, 2002; Rechberger & Graedel, 2002). This value can be calculated by using Eq. (5):

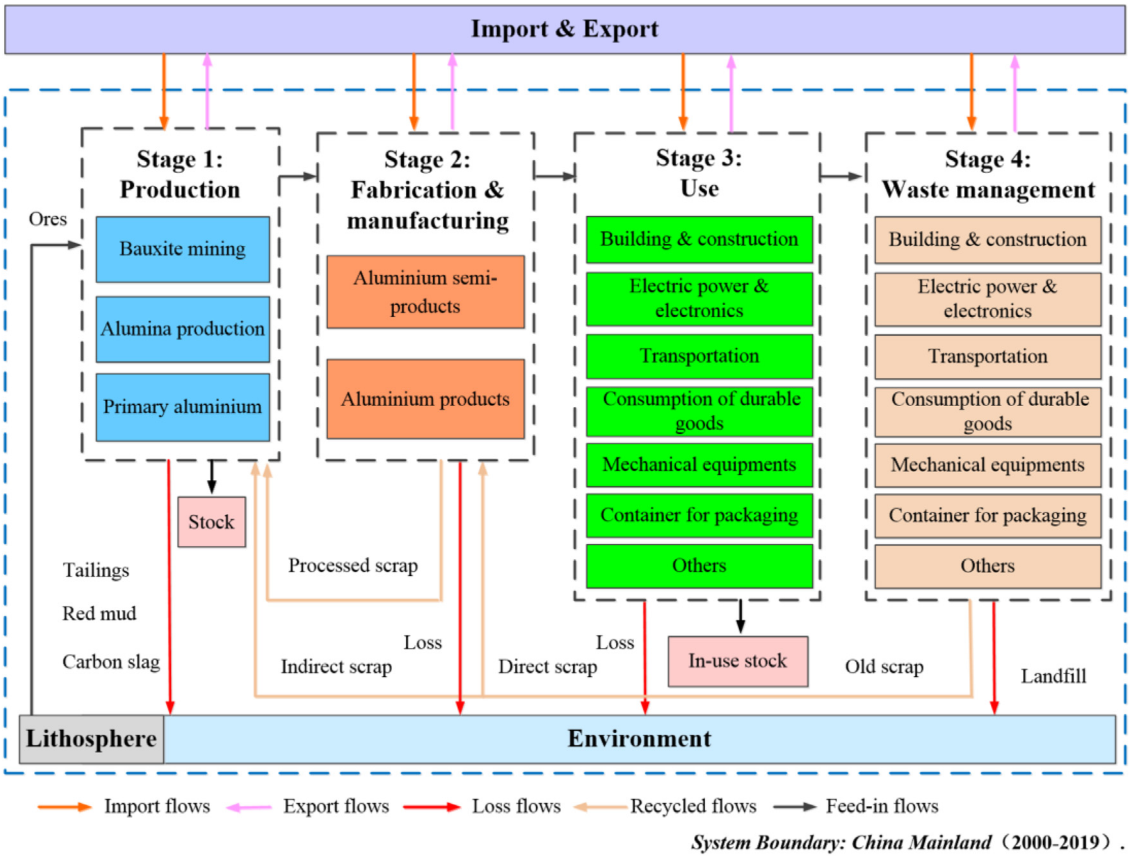

Fig. 1. STAF framework applied to the aluminium life cycle.

$$RE = \frac{H}{H_{\max}} \tag{5}$$

where RE represents relative entropy at each node and H represents information entropy. When H takes the maximum value, it is represented as $H_{\max}$, indicating that the chaotic degree of this system is the highest. When H takes the minimum value of 0, it indicates that the degree of system chaos is the lowest. In other cases, the value of H ranges between 0 and $H_{\max}$.

In this study, when this relative entropy reaches the minimum value of 0, it means that the aluminium resources are presented at the maximum concentration, namely pure aluminium. When the relative entropy is equal to 1, it means that the entropy of this system reaches its peak, indicating that the distribution of aluminium concentration in this system is the same as that in the crust. Based on the relative entropy change, the concentration and dissipation degree of aluminium can be quantitatively evaluated. Because it adds an assessment dimension which has been missed in the traditional MFA studies, it helps further evaluate the overall resource efficiency related to materials and their industrial systems.

According to the characteristics of China's aluminium cycle and the entropy analysis method, a life cycle-based entropy analysis method is proposed. Fig. 2(a) shows the aluminium life cycle. This life cycle is divided into four stages: P_1, P_2, P_3 and P_4, referring to raw material production, fabrication & manufacturing, use and waste management stages, respectively. There are nine aluminium flows in these four stages, which are represented by F_1, $F_2 \cdots F_9$. Fig. 2(b) illustrates a life cycle-based entropy analysis model. Fig. 2(c) illustrates a line chart of relative entropy, in which five nodes refer to aluminium material losses generated from different life cycle stages, namely node 1 to node 5. Then, the entropy value at each node is calculated. A higher relative entropy value means that more aluminium is dissipated at this node; while a smaller value means more aluminium is concentrated at this node. Changes in aluminium concentration and dissipation in different life cycle stages are then further analysed.

It is critical to investigate future material cycles and assess their environmental impacts so that sustainable resource management can be achieved (Ali et al., 2017; Bleischwitz, Spataru, et al., 2018). This study employs a life cycle-based entropy analysis method to investigate the characteristics of aluminium flows. A specific aluminium entropy analysis chart is prepared and illustrated in Fig. 3. The four aluminium life cycle stages are divided into five nodes for entropy analysis. There are five flows at node 1: domestic recycled aluminium, imported aluminium scrap, imported bauxite, domestic bauxite and imported primary aluminium. There are four flows at node 2: tailings, consumption of primary aluminium, red mud and carbon slag. There are five flows at node 3: tailings, loss, domestic aluminium products, red mud and carbon slag. There are five flows at node 4: tailings, loss, domestic aluminium scrap, red mud and carbon slag. Finally, there are five flows at node 5: tailings, loss, red mud, carbon slag and aluminium dissipation in the recycling process. The entropy values at five nodes are then calculated.

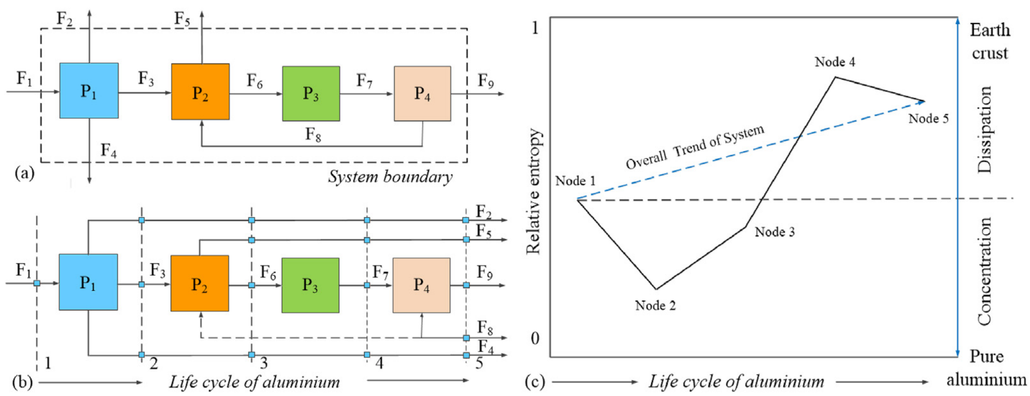

Fig. 2. Life cycle-based entropy analysis for aluminium resource in China.

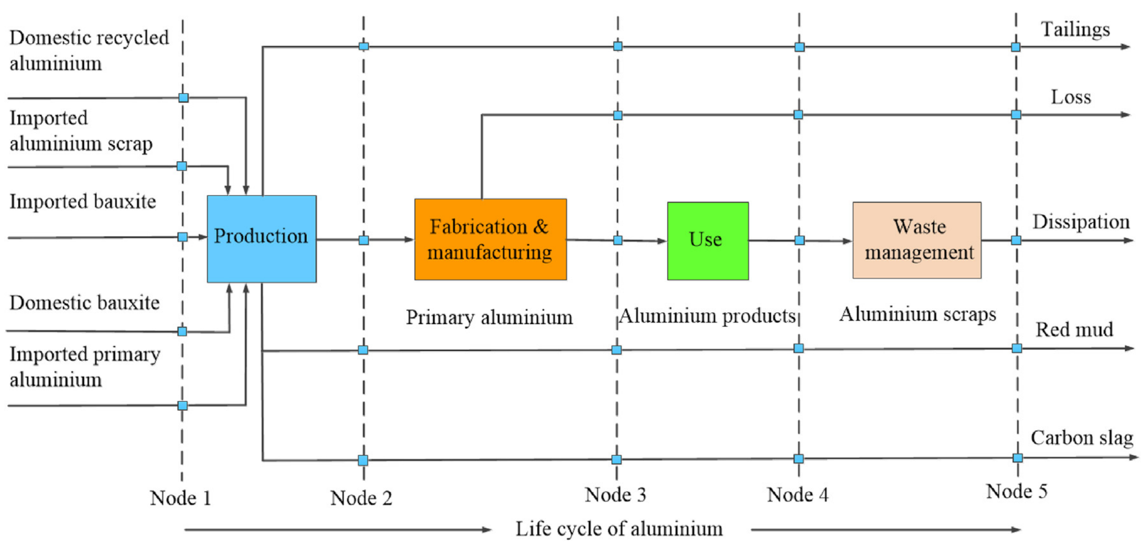

Fig. 3. Life cycle-based entropy analysis diagram for China's aluminium resources.

2.3. Scenarios development

Scenarios analysis is a prediction method that forecasts the possibilities related to future development of one system. This method helps assess different development results of the system led by different events so that the best decision can be made by considering all the situations (Li et al., 2019; Meng et al., 2017). Scenarios analysis is an important research tool for policy making and has been successfully applied in various disciplines, including management, medicine, engineering, finance and economics.

Since aluminium has a great recycling potential, the implementation of circular economy is one effective approach since circular economy encourages the full application of reduction, reuse and recycling and can extend the life cycle of aluminium. Aluminium production includes mining and refinery processes, and both are energy and emissions intensive (Hoornweg et al., 2013; Reck & Graedel, 2012). Also, aluminium mining generates a large amount of tailings, indicating potential environmental risks to the local ecosystem. In order to reduce such impacts and improve the overall resource efficiency, more energy efficient efforts should be made at aluminium mining stage, as well as fabrication & manufacturing stage. In particular, aluminium recycling is more effective due to its significant energy saving and emissions reduction benefits (Chen & Graedel, 2012; Eheliyagoda et al., 2022). Such an approach can help reduce the total entropy of aluminium life cycle. Therefore, considering the aluminium life cycle and circular economy principles, two scenarios are developed for future aluminium resource management:

Scenario I: The environmental loss of aluminium in tailings, red mud and carbon slag is reduced by 40% at the production stage, and the recycling aluminium scrap is increased by 60% at the waste management stage.

Scenario II: The environmental loss of aluminium in tailings, red mud and carbon slag is reduced by 60% at the production stage, and the recycling aluminium scrap is increased by 80% at the waste management stage.

2.4. Data sources

The application of MFA requires tracking the entire aluminium life cycle. The spatial boundary of such a system covers China's 31 provincial administrative regions, excluding Hong Kong, Macao and Taiwan of China due to a lack of relevant data. The study period is from 2000 to 2019, which can reflect the dynamic changes of China's aluminium production and consumption. Aluminium import and export data were obtained from China Customs Statistical Yearbooks and China Statistical Yearbooks. Aluminium product consumption and aluminium loss data were obtained from the Yearbooks of Nonferrous Metals Industry of China, Economic Network Statistical Database of China and relevant literature (Chen et al., 2010; Li et al., 2021; Nakajima et al., 2010). Data of aluminium mining, fabrication & manufacturing were obtained from the Yearbooks of Nonferrous Metals Industry of China, China Customs Statistical Yearbooks and China Statistical Yearbook. Finally, China's aluminium import and export data were obtained from the online database of the United Nations and the Chatham House, a think tank in the United Kingdom.

For the scrapped products, the research team of this study interviewed those experts working in the aluminium industry. These experts provided data of net aluminium imports. Output data of bauxite, primary aluminium products and intermediate aluminium products were obtained from the Yearbooks of Nonferrous Metals Industry of China.

The final outputs of aluminium products, aluminium scraps and aluminium recycling products were calculated based upon material balances. The aluminium concentration data in these products were obtained based on relevant standards of aluminium products, expert interviews and relevant literature. Waste recycling activities exist in the production and fabrication & manufacturing stages, in which corresponding recycled aluminium was considered as temporary stock.

3. Results

3.1. Life cycle-based aluminium flows

Fig. 4 illustrates life cycle-based aluminium flows in China for years 2000, 2005, 2010, 2015 and 2019, covering production, fabrication & manufacture, use and waste management stages. In 2000, China's domestic bauxite production reached 2.54 Mt, while 0.11 Mt bauxite were imported, indicating that the external dependence rate was 4%. In 2019, China's domestic bauxite production reached 22.88 Mt, while 26.70 Mt bauxite were imported, indicating that the external dependence rate increased to 56%. Guinea, Australia and Indonesia were major bauxite exporting countries to China, accounting for about 96% of the total bauxite import in 2019 (Yuan et al., 2019). In 2000 Mt alumina were imported, 0.01 Mt alumina were exported, and the domestic alumina production reached 2.29 Mt. In 2019, 0.87 Mt alumina were imported, 0.15 Mt alumina were exported and the domestic alumina production reached 38.56 Mt. Such great changes reflect that China has experienced dynamic trade structure adjustments on both bauxite and alumina. In terms of alumina production, energy consumption is the main factor to increase its production cost (Lin & Xu, 2015), which means that alumina import can contribute to

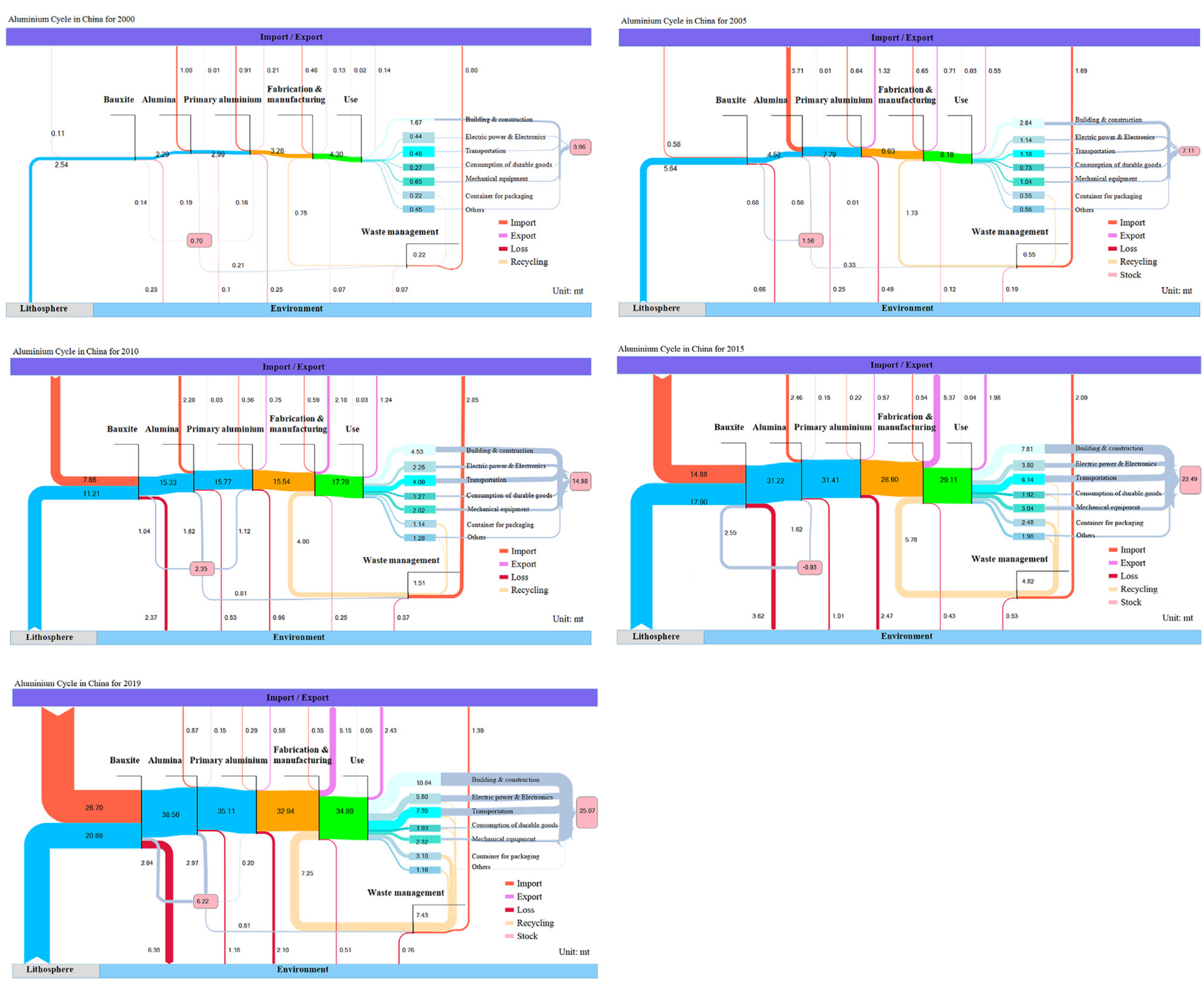

Fig. 4. Life cycle-based aluminium flows in China for 2000, 2005, 2010, 2015 and 2019.

the reduction of domestic energy input and bauxite consumption. In 2019, China's primary aluminium production reached 35.11 Mt, accounting for approximately half of the global total output, mainly supplying domestic consumption and international export markets. In 2000, the amount of tailings, red mud and carbon slag generated from China's aluminium production was only 0.33 Mt. Such a figure jumped to 7.56 Mt in 2019, implying a 21 times increase. This finding also indicates that serious environmental emissions occurred, leading to great challenges to local ecosystem and public health(Geng et al., 2013). The environmental loss of aluminium production accounted for 46% of the total loss throughout its entire life cycle in 2000, while such a figure increased to 69% in 2019. Consequently, it is necessary to improve the comprehensive utilization rate of tailings, red mud and carbon slag so that the environmental risks can be reduced.

In 2000, the total aluminium consumption reached 4.18 Mt, mainly in sectors of building & construction (1.67 Mt), electric power and electronics (0.44 Mt), transportation (0.48 Mt), durable goods (0.27 Mt), equipment manufacturing (0.65 Mt), containers (0.22 Mt) and others (0.45 Mt). In 2019, the total aluminium consumption reached 32.51 Mt, mainly in sectors of building & construction (10.84 Mt), electric power and electronics (5.80 Mt), transportation (7.35 Mt), durable goods (1.93 Mt), equipment manufacturing (2.32 Mt), containers (3.10 Mt) and others (1.16 Mt). The top three aluminium consumption sectors include building & construction (33% of the total consumption), transportation (23%) and electric power and electronics (18%), accounting for 74% of the total consumption. Another fact is that many aluminium-containing products will enter the ends of their life cycles (Milford et al., 2011). In 2019, domestic aluminium scraps reached 7.43 Mt and imported aluminium scraps reached 1.39 Mt, leading to that the self-sufficiency rate of aluminium scrap reached 84%. Technological development contributed to aluminium recycling efficiency, with clear energy and aluminium resource savings.

3.2. Entropy analysis for the aluminium life cycle

Based on five years intervals, Fig. 5 illustrates relative entropy values at five nodes in China's aluminium life cycle for years of 2000, 2005, 2010, 2015 and 2019, reflecting the aluminium

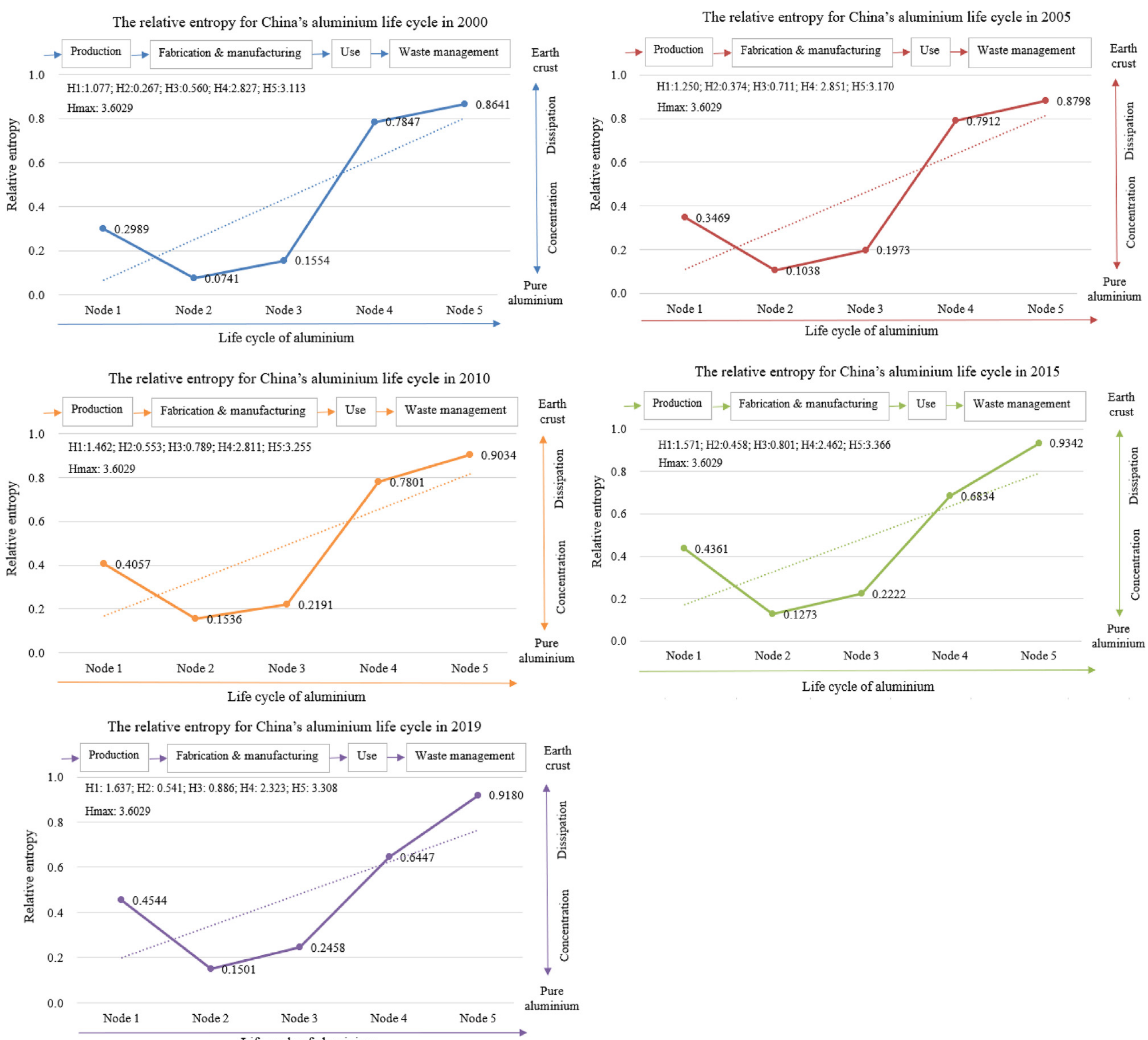

Fig. 5. Relative entropy values for aluminium life cycle in China for 2000, 2005, 2010, 2015 and 2019.

concentration and dissipation changes in different stages of its life cycle. According to the entropy analysis method, the four stages of aluminium life cycle are divided into five nodes, and there are several flows at each node. As the aluminium concentration (CEC) in the crust is 8.23% by weight (Orians & Bruland, 1985), the maximum entropy (H_{max}) is calculated to be 3.6029, and the statistical entropy (H) of each flow and the relative entropy (RE) of each node are calculated based on the mass and aluminium content of each flow.

There are 5 flows at node 1, including imported bauxite, imported primary aluminium, imported aluminium scrap, domestic bauxite and domestic recycled aluminium. The relative entropy of aluminium at node 1 was 0.4544 in 2019, while such a value was 0.2989 in 2000, 0.3469 in 2005, 0.4057 in 2010 and 0.4361 in 2015, respectively. Such a figure reached its highest value in 2019, mainly due to the import dependence on bauxite from the production stage. The bauxite import dependence in China increased from 4% in 2000 to 56% in 2019, with an increase rate of 51%.

Nodes 2 and 3 represent the fabrication & manufacturing stages of aluminium products. At node 2, there are 4 flows, namely tailings, red mud, carbon slag and domestic primary aluminium. The entropy of node 2 in each year is lower than that of node 1. When the entropy of this node approaches 0, it means that aluminium in the stage is close to the state of pure aluminium (Milovanoff et al., 2021). The relative aluminium entropy at node 2 was 0.1501 in 2019, while such a value was 0.0741 in 2000, 0.1038 in 2005, 0.1536 in 2010 and 0.1273 in 2015, respectively. As the production of primary aluminium increased from 2.99 Mt in 2000 to 35.11 Mt in 2019, environmental damages such as tailings, red mud and carbon slag also increased significantly from 0.33 Mt in 2000 to 7.56 Mt in 2019. There are 5 flows at node 3, including tailings, red mud, carbon slag, processing loss and domestic aluminium products. The relative aluminium entropy at node 3 was 0.2458 in 2019, significantly higher than that in 2000 (0.1554). This value at node 3 increased continuously from 2000 to 2019. With the increase of aluminium output, the processing loss also increased from 0.25 Mt in 2000 to 2.1 Mt in 2019, with an increase of 7.4 times. There are 5 flows at node 4, including tailings, red mud, carbon slag, processing loss and domestic recycled aluminium. The relative aluminium entropy at node 4 was 0.6447 in 2019, while such a value was 0.7847 in 2000. The decrease of relative entropy at node 4 is mainly due to the increase of domestic recycled aluminium. Such a figure increased from 0.75 Mt in 2000 to 7.25 Mt in 2019, contributing to the increased aluminium concentration along its life cycle. There are 5 flows at node 5, including tailings, red mud, slag, processing loss, dissipation. The relative entropy at node 5 significantly increased from 0.8641 in 2000 to 0.9180 in 2019, indicating that there is still significant environmental damage along the whole aluminium life cycle. The accumulated environmental pollutants mainly include tailings, red mud, slag, processing loss, dissipation (Mahinroosta & Allahverdi, 2018). Therefore, it is necessary to find an effective pathway to reduce the relative entropy along the aluminium life cycle and promote the aluminium concentration in its life cycle so that the utilization efficiency of aluminium resources in China can be improved.

3.3. Scenarios analysis results

Two improved scenarios are designed by adjusting the environmental loss rates of aluminium in tailings, red mud and carbon slag and the recycling rates of aluminium scrap. These adjustments decreased the entropy of each node along the aluminium life cycle, which are shown in Fig. 6. According to scenario I, when the aluminium loss in the production stage decreases by 3.0 Mt and the amount of recycled waste aluminium increases by 4.3 Mt, the entropy values of aluminium life cycle at five nodes decreases, which are 0.4326, 0.1204, 0.1895, 0.5721 and 0.8934, respectively. Compared with 2019, the entropy at node 1 decreased from 0.4544 to 0.4326, and the entropy at node 5 decreased from 0.9180 to 0.8934. This means that scenario I can help improve aluminium efficiency.

Under scenario II, when the loss of aluminium in tailings, red mud and carbon slag in the production stage decreases by 4.5 Mt and the amount of recycled waste aluminium increases by 5.8 Mt, the entropy of aluminium life cycle at five nodes decreased significantly compared with 2019, which are 0.4260, 0.0790, 0.1581, 0.5227 and 0.8724, respectively, indicating that aluminium resource is more concentrated under scenario II than that under scenario I, indicating that the efficiency of aluminium resources can be further improved. Such results imply that the implementation of circular

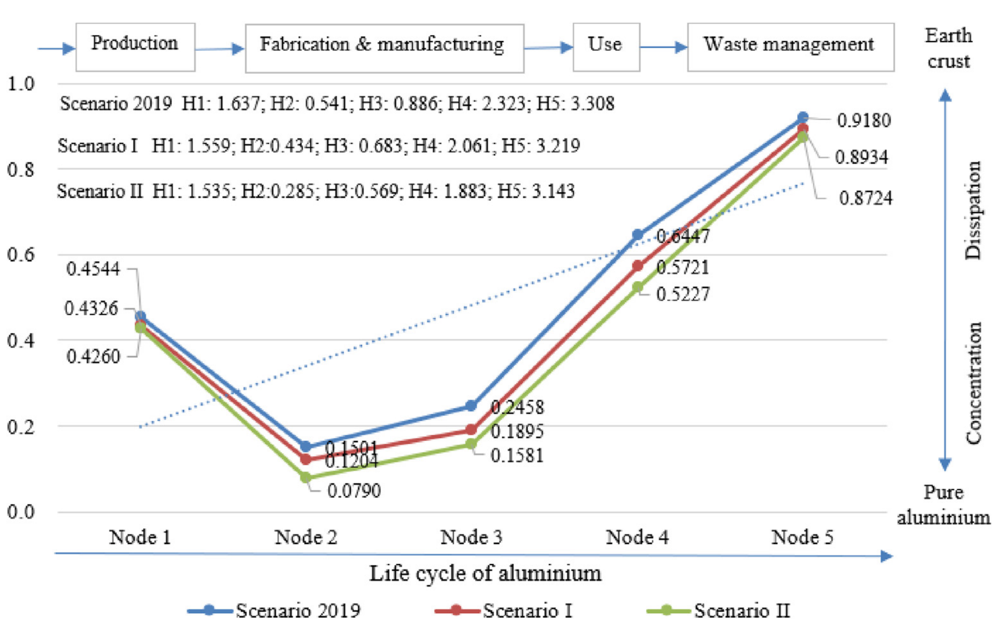

Fig. 6. Relative aluminium entropy values under two scenarios.

economy can mitigate environmental damage from aluminium production and promote the overall metabolic efficiency of the whole aluminium production system (Erdmann & Hilty, 2010; Yue et al., 2021). It can not only reduce the bauxite import dependence in China, but also reduce corresponding energy and resource consumption from the production of alumina and electrolytic aluminium (Hao et al., 2016).

4. Policy recommendations

4.1. Energy structure adjustment for China's aluminium industry

China's carbon peak and carbon neutrality targets led to both opportunities and challenges to aluminium supply and demand. The dynamic material flow analysis results in this study show that the output of China's primary aluminium was 35.11 Mt in 2019, experiencing an increase of 11 times over that in 2000. Similarly, aluminium consumption reached 32.5 Mt in 2019, experiencing an increase of 8 times over that in 2000. In particular, sectors of building & construction, electric power & electronics and transportation consumed 23.99 Mt in 2019, with an increase of 21.4 Mt compared with 2000. As one typical energy and emission intensive sector, aluminium industry is facing a great pressure to reduce its overall energy consumption and corresponding emissions (Hao et al., 2016). Consequently, it is urgent for China's aluminium industry to shift from fossil fuels-based energy structure to renewable and clean energy structure. This means that aluminium industry should actively apply renewable and clean energy. For instance, hydropower-based aluminium production can help reduce 86% of carbon emission intensity, comparing with coal power-based aluminium production (Liu et al., 2013). Thus, it is reasonable for such firms to relocate their aluminium production facilities in those provinces with rich hydro-power, such as Yunnan and Guangxi in south China.

4.2. Aluminium resource efficiency improvement along its whole life cycle

The aluminium entropy reduction along its life cycle can lead to both energy/resource conservation and emissions reduction. The evaluation of such entropy value can measure the dissipation or concentration degree of aluminium resources along its whole life cycle so that the key nodes can be identified. Our results show that the aluminium relative entropy value increased from 0.2989 in 2000 to 0.4544 in 2019 in the stage of production. Similarly, such a value increased from 0.8641 in 2000 to 0.9180 in 2019 in the stage of waste management. Both imply that large amounts of various pollutants had been released to the surrounding environment. Therefore, it is necessary to improve the aluminium resource efficiency along its whole life cycle. Various measures should be taken to improve the overall aluminium resource efficiency, such as green mining and fabrication (Sovacool et al., 2020), energy and water cascading, process synthesis and responsible waste management (Lin & Xu, 2015). Also, eco-design and cleaner production should be promoted in all the relevant enterprises as such efforts can help avoid/reduce the overall wastes and energy consumption and enhance the lifetime of products.

4.3. Aluminium recycling and re-use efforts

Aluminium is one of the most recyclable metals. Aluminium is widely used in many fields. The global aluminium production reached 65.27 Mt in 2020, ranking the second among all the metals, just followed iron and steel (Jha et al., 2018). From the perspective of carbon emissions, secondary aluminium generates only 5%–8% carbon emission comparing with traditional aluminium production (Blomberg & Söderholm, 2009). It is therefore necessary to initiate innovative waste management practices at every stage along both production and consumption perspectives so that the whole aluminium metabolism system can move toward a sustainable and circular system (Geng et al., 2019; Song et al., 2022). In this regard, our scenarios analysis results present significant aluminium resource efficiency improvements, indicating that the implementation of circular economy is necessary for all the aluminium stakeholders. Useful measures include extended producer responsibilities, the establishment of regional secondary aluminium markets, effective aluminium scraps collection and separation system, financial subsides to those aluminium recycling and re-use firms, research & development support, and preferable tax rates for aluminium recycling and re-use firms. In addition, capacity-building efforts are also crucial so that all the stakeholders can realize the significance of aluminium recycling and re-use fully engage in such efforts.

5. Conclusions

Aluminium is one indispensable metal to support economic development and has been widely used in various fields. However, aluminium industry is a typical energy and emissions intensive sector and has become a key barrier to achieve carbon neutrality target. Consequently, it is crucial to improve the utilization efficiency of aluminium resources along entire value chains and reduce corresponding emissions. In this study, material flow analysis was used to identify the key features of aluminium flows in China along its entire life cycle. The entropy analysis method is applied to calculate the entropy values of different nodes along the aluminium life cycle. Scenarios analysis is conducted to identify the effective pathways to improve the efficiency of aluminium resources and mitigate corresponding environmental emissions. Several policy recommendations are proposed for improving the overall aluminium efficiency, such as energy structure adjustment for China's aluminium industry, aluminium resource efficiency improvement along its whole life cycle and aluminium recycling and re-use efforts.

Several research limitations exist in this study. The first limitation is data availability. It is impossible to obtain the accurate aluminium loss data caused by corrosion in the stage of aluminium use. In terms of recycling aluminium scraps, official statistical data of aluminium scraps are lacking. We have to get such data through site surveys and expert interviews as well as better outlooks on future demand. Finally, although aluminium recycling can greatly reduce virgin material inputs and energy consumption, it is necessary to further evaluate the overall impacts of such circular metals and decarbonisation activities, especially from an economic perspective, so that better policies can be made.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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