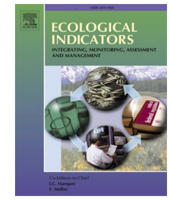
Ecological Indicators 161 (2024) 112006

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind



Original Articles

Emergy-based environmental accounting of China's nickel production

Chang Su [a], Yong Geng [b,*], Gengyuan Liu [c], Aiduan Borrion [d], Jingjing Liang [a]

[a] School of Environmental Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[b] School of International and Public Affairs, Shanghai Jiao Tong University, Shanghai 200030, China
[c] State Key Joint Laboratory of Environmental Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, China
[d] Department of Civil, Environmental and Geomatic Engineering, University College London, London WC1E 6DE, UK

ARTICLE INFO

Keywords:
Nickel
Emergy analysis
Sustainability
Recycling
Circular economy
China

ABSTRACT

Nickel is deemed as one of the critical metals because it is currently essential in making both stainless steel and lithium-ion batteries. It is therefore critical to evaluate such impacts so that appropriate mitigation measures can be taken. Emergy is an effective evaluation method, which is widely used for environmental accounting. This study applies such an emergy-based method to evaluate nickel production in China so that the holistic environmental performance of nickel production can be examined. Typical products are chosen for different processes by considering both quantity and the development potential. Results show that nickel production is unsustainable and the associated environmental costs are not fully covered in the nickel prices. In addition, we find that environmental loading from nickel recycling is less than that from primary nickel production. Several policy recommendations are then raised based upon these results to facilitate sustainable nickel management in China.

1. Introduction

Nickel, one of the iron series elements, is a silvery-white lustrous metal. It is an essential ingredient in various products that modern society relies on, such as stainless steels and other alloys (Giuliodori and Rodriguez, 2015). Besides, nickel plays a significant role in the development of clean energy due to its use in the production of lithium-ion batteries, as well as its application in several green power generation technologies (Sun et al., 2021; Tian et al., 2021; Xiao et al., 2022; Cai et al., 2023; Miao et al., 2023). Driven by the target of "carbon neutrality", electric vehicle is expected to occupy the majority of the passenger vehicle markets in the mid-21th century (Crabtree, 2019; Mallapaty, 2020). Additionally, green power is widely regarded as one effective way to cope with energy issues in the forthcoming decades (Lei et al., 2023; Zhao et al., 2023). Both initiatives will result in a soaring demand for nickel in the forthcoming decades. Consequently, nickel has been considered one of the essential strategic metals in the USA, Japan, Canada, European Union and China (Graedel et al., 2022).

Currently, China consumes over 50 % of the global nickel resource. Roughly 60 % of the global stainless steel and 70 % of the global lithium-ion batteries are produced in China, implying China's dominance in nickel production and consumption (UN Comtrade, 2023). However, nickel production is associated with serious environmental impacts, such as air pollution, water and soil contamination, due to its high energy consumption and intensive emissions (Bai et al., 2022; Fukuzawa, 2012). Besides, China's total nickel reserve (2.8 million tons) only accounts for 3 % of the global total, indicating a high risk of stable nickel supply (USGS, 2023). Hence, it is crucial to encourage nickel recycling in China. By considering these realities, it is necessary to measure the environmental impacts of both primary nickel production and secondary nickel production so that valuable insights can be obtained to all the stakeholders. Moreover, it is important to identify the key environmental issues of nickel production so that appropriate mitigation measures can be taken.

Material flow analysis is a widely accepted method on tracing one element along its life cycle and has been applied to evaluate nickel production at global and regional scales so that the features of nickel flows can be uncovered across various temporal and spatial scales (Huang et al., 2014; Nakajima et al., 2018; Reck et al., 2008; Su et al., 2023; Zeng et al., 2018). Also, several studies utilized different models to estimate future nickel demand and supply (Eckelman, 2010; Yuan et al., 2019). Moreover, life cycle assessment (LCA) also is effective to evaluate environmental impacts of nickel production. In this regard, several studies measure such impacts by focusing on one or two nickel

* Corresponding author.
E-mail address: ygeng@sjtu.edu.cn (Y. Geng).

https://doi.org/10.1016/j.ecolind.2024.112006
Received 4 March 2024; Received in revised form 2 April 2024; Accepted 4 April 2024
Available online 8 April 2024

products (Bai et al., 2022; Deng and Gong, 2018; Liu et al., 2016; Ma et al., 2019; Wei et al., 2020; Yu, 2006). However, they do not cover nickel recycling perspectives. Similarly, environmental impacts of specific nickel-containing products (such as lithium ion batteries and stainless steel) are measured between the use of primary nickel and secondary nickel, but they do not fully characterize recycling efforts and neglect the holistic perspectives of virgin nickel production, such as the ecologic benefits and feedback features of recycling nickel (Johnson et al., 2008; Majeau-Bettez et al., 2011; Costanza et al., 2017; Sun et al., 2020).

Emergy analysis is one method that can address this problem. Derived from ecology, thermodynamics, and general systems theory, it quantifies the value of natural capital and ecosystem services (Geng et al., 2013; Odum, 1996). Emergy helps to assign the correct value to ecological and economic products and services, and compares flows with various quality by transforming them into a common energy metric (usually solar energy) (Rugani and Benetto, 2012). Currently, emergy analysis has become a prominent approach for sustainability assessment (Geng et al., 2019). In fact, this method has experienced rapid development and is widely applied across various domains, such as agriculture and agroforest production systems (de Oliveira et al., 2018; Tsai and Lee, 2024; Zhuang et al., 2021), economic systems (Liu et al., 2022; Ohnishi et al., 2017; Tilley and Swank, 2003), international trade (Tian et al., 2017; Zhong et al., 2017), and industrial processes (Brown et al., 2012; Liu et al., 2021; Pan et al., 2016). This method has also been used to investigate the production of different minerals. For example, Xue et al. (2018) conducted an emergy analysis along the entire life cycle of aluminum in China so that the effects of changes in domestic production and import policies on aluminum outputs can be measured. By applying emergy analysis, Buranakarn (1998) concentrated on the recycling and reuse of building materials, including aluminum, so that the costs and benefits of recycling can be accounted. Ingwersen (2011) assessed the overall sustainability of gold production by conducting an emergy analysis. Similarly, Chen et al. (2019) assessed the overall environmental performance of gold ingot production by utilizing this emergy analysis method, in which the UEVs of production-related flows were explicitly stated. Cano Londoño et al. (2019) compared the overall environmental performances of two gold production methods (open-pit and alluvial gold mining) by integrating emergy analysis with life cycle assessment and found that the alluvial gold mining approach is more environmentally friendly than the opne-pit aproach. Yang et al. (2017) employed emergy analysis to determine the UEVs of both natural graphite and spherical graphite and accounted ecological losses and public health impacts associated with two graphite production systems. Rui et al. (2022) further compared the impacts of both natural graphite production and synthetic graphite production through the application of emergy analysis and identified the environmental potential of synthetic graphite production to replace natural graphite production. However, this emergy analysis method has not been used to evaluate nickel production.

In view of these challenges, this study aims to conduct an emergy analysis-based environmental accounting for the nickel industrial chain in China. Several typical nickel products are selected to represent different life cycle stages of nickel production. In this regard, nickel ore is selected as a mining product; nickel metal, ferronickel and nickel sulphate are selected as the typical products at the smelting and refining stage; stainless steel and lithium-ion battery are selected as the typical products at the fabrication stage. We expect that research results from this study can facilitate sustainable nickel resource management. The whole paper is organized as below. After this introduction part, section 2 describes our research methods and data sources; section 3 presents our research results; section 4 discusses these results and proposes policy recommendations; finally, section 5 draws research conclusions.

2. Methods and data

2.1. Emergy accounting

Emergy is defined as a method to evaluate the total amount of available energy needed directly and indirectly in a certain product or service (Odum, 1996). In this study, emergy accounting is conducted for nickel production in China based on an emergy system diagram, containing flows, storages, components, and products related with nickel production. The total emergy (U) used for one product can be calculated by using Eq. (1):

$$U = \sum_{i=1}^{n} U_i = \sum_{i=1}^{n} f_i \times UEV_i \tag{1}$$

Where i represents an individual flow i associated with the investigated system; U_i represents the emergy of the i^{th} flow; f_i represents the amount of the i^{th} flow in the unit of mass, energy or money; UEV_i represents the unit emergy value of the i^{th} flow.

All the flows supporting the investigated system can be classified into three types: (1) local renewable resources (R), (2) local non-renewable resources (N), (3) purchased resources (F) (Ulgiati and Brown, 2013). A set of emergy-based indicators, including Environmental Loading Ratio (ELR), Emergy Yield Ratio (EYR), and Emergy Sustainability Index (ESI), are applied in this study to evaluate environmental impacts and the overall sustainability of nickel production in China. They can be calculated based on the quantitative results of all the flows (see Eqs. (2)–(4)).

$$ELR = \frac{N + F}{R} \tag{2}$$

$$EYR = \frac{R + N + F}{F} \tag{3}$$

$$ESI = \frac{EYR}{ELR} \tag{4}$$

Furthermore, the emergy values of primary nickel production in China are transformed to monetary equivalents (emergy currency, EMC) so that the economic values of nickel products can be accounted from a natural contribution perspective (Campbell and Brown, 2012). EMC can be calculated by using Eq. (5).

$$EMC = \frac{U}{EMR} \tag{5}$$

Where U represents the total emergy used for one product; EMR represents emergy monetary ratio. The details of EMR accounting are provided in the supporting information (Fig. S1).

2.2. Emergy flows of nickel production

In this study, emergy accounting is conducted for China's nickel production along its life cycle. The whole nickel production includes six life cycle stages: (1) mining, (2) smelting and refining, (3) fabrication, (4) manufacturing, (5) use, and (6) waste management and recycling (Su et al., 2023). Nickel metal, ferronickel and nickel sulfate are selected as the typical products at the smelting and refining stage because nickel metal or ferronickel are major nickel products at this stage, while nickel sulfate plays an increasingly important role with the development of lithium-ion battery (Nickel Institute, 2023). Stainless steel and lithium-ion battery (containing nickel) are selected as the representative products in the fabrication phase. In particular, stainless steel dominates nickel consumption, while lithium-ion battery is expected to grow significantly due to the rapid deployment of new energy vehicles. Other products in the fabrication stage occupy smaller shares, indicating their marginal roles. Both the manufacture and use stages are not included in this study since the majority of nickel exists in the form of semi-finished goods and there is almost no nickel dissipation at the use stage. Nickel recycling mainly refers to produce stainless steel from stainless steel scraps. Moreover, since lithium-ion battery becomes more important for new energy vehicles, nickel recycling from such battery is also considered in this study. There are several recycling routes for such battery, including direct recycling, pyrometallurgy, hydrometallurgy, or a combination of different methods (Baum et al., 2022). Considering data availability, the spatial boundary of this study is the geographical border of China's mainland, while the temporal boundary is the year of 2019.

Fig. 1 illustrates the emergy system diagram of China's nickel production, which is based upon a cradle-to-gate approach. The direct renewable sources include sun, rain, wind, and geothermal heat, entering this system from the left side of this diagram.Industrial wastes from different stages of nickel production exit at the bottom, and nickel scraps exit at the right side. Purchased sources include different nickel materials, water, energy, chemicals, transport, and labor and services (L&S), which are shown as the inflows on the top.

2.3. Data sources

Data used in this study were obtained from multiple sources. Data of the amounts of different nickel products were taken from Su and her colleagues (2023). Material and energy flows associated with China's nickel production were obtained from official statistics (CNIA, 2020), international organizations (ISSF, 2023; Nickel Institute, 2023), several academic papers (Deng and Gong, 2018; Ma et al., 2019; Wei et al., 2020; Yu, 2006), market reports and interviews with experts in several investigated companies. Most of UEVs adopted in this study were taken from international publications, while the UEV values of nickel ores and nickel concentrates were calculated and listed in the supporting information. Based on the updated global emergy baseline with a value of 12.00E + 24 sej/yr (Brown et al., 2016; Brown and Ulgiati, 2016), we calculated all the emergy flows, in which all the UEVs based on other baselines were recalculated.

2.4. Sensitivity analysis

Since the total emergy input of each nickel product can be affected by different input parameters, it is necessary to conduct a sensitivity analysis. Impacts of different inputs on the total emergy of all the investigated products are measured. Each result is expressed as the relative total emergy change when an input parameter is reduced by 1 %.

3. Results

3.1. Emergy accounting results of nickel production in China

Fig. 2 illustrates emergy inputs at different stages of nickel production in China, showing that the total emergy has extensively increased along the nickel production chain. This can be explained by the fact that extra input is required at each life stage, especially for nickel raw materials. Specifically, the domestic nickel mining cannot meet with the domestic demand for nickel. Therefore, China has to import a large amount of primary nickel. In addition, it is crucial to pay attention on other resource inputs. For instance, the total nickel contained in nickel sulphate is more than that in the lithium-ion batteries although the total emergy of the former is less than the latter. In contrast to other phases of nickel production, the total emergy of recycling is marginal. The main reason is that the amount of nickel recycling is much smaller than the total nickel production. The emergy inputs of different renewable sources are also too less than those of non-renewable and purchased sources at all stages of nickel production. These detailed emergy accounting inventories for nickel production in China are presented in the supporting information (from Table S1 to Table S4).

Fig. 3 illustrates the contributions of different flows to the total emergy at different stages of nickel production in China.

Mining Stage Nickel mining has been limited in China during the recent years, with an amount of only 0.12 million tons in 2019. Local non-renewable resource (>99 %) is the main input to nickel mining, while the contributions of purchased resources and renewable sources are very marginal. The UEV of nickel ore is 1.60E + 17 sej/ t Ni in China.

Smelting & Refining Stage Three major nickel products are produced at this stage. Nickel metal is mainly produced from local ores (local non-renewable resource) and imported sulphide ores (one of purchased resources), accounting for 16.8 % and 46.2 % of the total emergy input. Other main emergy inputs include transport (33.1 %) and energy (2.8 %). Nickel sulphate are assumed to be produced from local ores and imported MHPs in this study. The purchased resources dominate the emergy input, in which imported MHPs account for 68.6 % and chemicals account for 16.1 % of the total emergy input. The emergy input of local ores is also significant, accounting for 14.0 % of the total emergy input. It is assumed that all the ferronickel is produced from imported nickel laterite in China, meaning that there is no local non-renewable input since all the raw materials are purchased. Imported nickel laterite (84.4 %) and energy (11.8 %) are the main emergy inputs. The UEV of nickel metal, nickel sulphate and ferronickel is 3.23E + 17 sej/ t Ni, 3.86E + 17 sej/ t Ni and 2.78E + 17 sej/ t Ni in China, respectively.

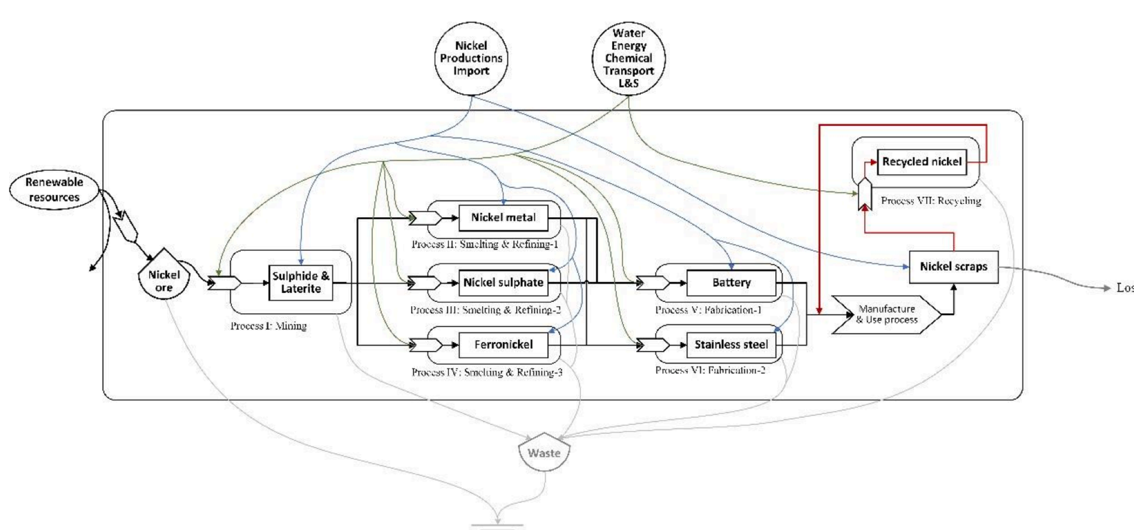


Fig. 1. Emergy system diagram of China's nickel production.

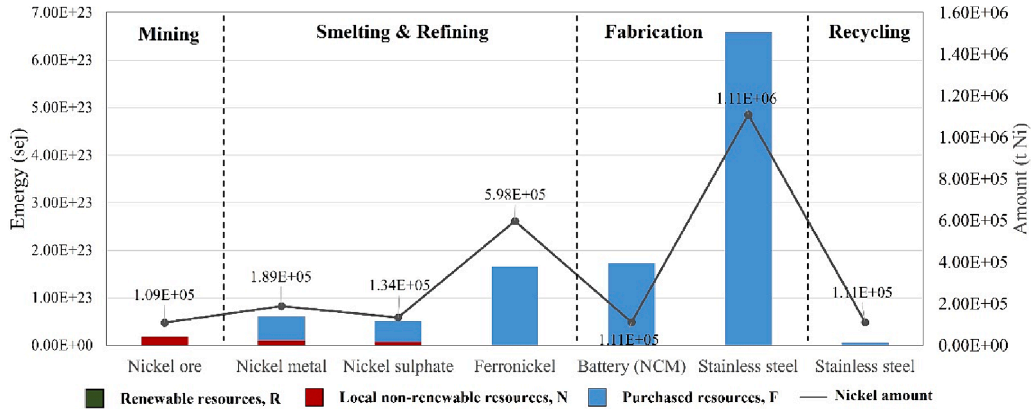


Fig. 2. Emergy inputs at different stages of nickel production in China.

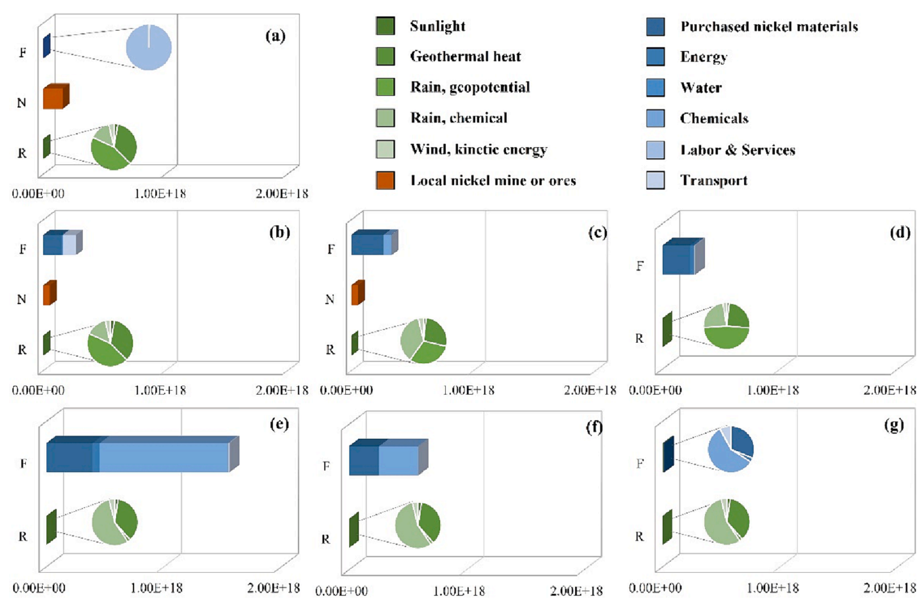


Fig. 3. Detailed components of the total emergy of (a) nickel ore (mining), (b) nickel metal (S&R-1), (c) nickel sulphate (S&R-2), (d) ferronickel (S&R-3), (e) battery NCM622 (Fabrication-1), (f) stainless steel 304L (Fabrication-2) and (g) stainless steel 304L (Recycling). All the results are shown with products containing one ton nickel.

Fabrication Stage Since most nickel materials are fabricated in other places, it is assumed there is no local non-renewable input at this stage. Two nickel-contained products are selected as the representative products, namely the NCM622 (nickel- cobalt and manganese) battery and the 304L stainless steel. Our results show that chemicals accounted for 70.0 % of the total emergy of NCM622 battery, followed by imported nickel materials (25.2 %) and energy (3.8 %), while chemicals and imported nickel materials accounted for 56.4 % and 43.3 % of the total emergy of 304L stainless steel. The UEV of nickel battery (NCM622) and stainless steel (304L) and ferronickel is 1.55E + 18 sej/ t Ni and 5.91E + 17 sej/ t Ni in China, respectively.

Recycling Only stainless steel scraps are considered at this stage since

Table 1
Emergy-based performance indicators of China's nickel production.

Emergy indicators	Unit	Mining	Smelting & Refining			Fabrication-		Recycling
		Nickel ore	Nickel metal	Nickel sulphate	Ferronickel	Battery (NCM)	Stainless steel	Stainless steel
Local renewable resources, R	sej	1.36E + 18	6.98E + 17	4.56E + 17	2.35E + 18	1.94E + 17	5.86E + 17	5.87E + 16
Local non-renewable resources, N	sej	1.74E + 22	1.02E + 22	7.23E + 21	0	0	0	0
Purchased resources, F	sej	3.71E + 19	5.06E + 22	4.44E + 22	1.66E + 23	1.73E + 23	6.54E + 23	1.64E + 21
Total emergy input	sej	1.74E + 22	6.08E + 22	5.16E + 22	1.66E + 23	1.73E + 23	6.54E + 23	1.64E + 21
Output	t Ni	1.09E + 05	1.89E + 05	1.34E + 05	5.98E + 05	1.11E + 05	1.11E + 06	1.11E + 05
Unit emergy value, UEV	sej/t Ni	1.60E + 17	3.23E + 17	3.86E + 17	2.78E + 17	1.55E + 18	5.91E + 17	1.48E + 16
Environmental loading ratio, ELR		>100	>100	>100	>100	>100	>100	>100
Emergy yield ratio, EYR		470.09	1.20	1.16	1.00	1.00	1.00	1.00
Emergy sustainability index, ESI		0.03	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
EMC (in 2019)	em$/ t Ni	5.25E + 04	1.06E + 05	1.27E + 05	9.11E + 04	5.09E + 05	1.94E + 05	4.85E + 03
Sell price (in 2019)	$/t Ni	3.00E + 03	1.50E + 04	1.98E + 04	4.78E + 03	1.16E + 05	2.50E + 04	2.50E + 04

it accounts for over 80 % of nickel recycling. In addition, the whole recycling amount is very small, with a secondary input ratio of only about 10 %. Chemicals accounted for 58.0 % of the total emergy, followed by imported ferronickel (31.1 %), and transport (7.8 %). The UEV of recycled stainless steel (304L) is 1.48E + 16 sej/t Ni in China.

3.2. Emergy-based performance indicators

Table 1 lists the results of emergy-based indicators at different stages of nickel production in China. The values of ELR and ESI show that nickel production is nonrenewable resources-based along its entire life cycle, leading to serious environmental impacts on the local ecosystem. EYR is used to evaluate the efficiency of purchased resources, reflecting that nickel mining had a high productivity from the perspective of resource efficiency due to its local non-renewable inputs. In other words, the use of local non– renewable resources is more efficient than the use of purchased resources.

Emergy Money Ratio (EMR) is 3.05E + 12 sej/$ in China in 2019 (supporting information). Combined with UEVs of nickel products at all the life stages, the Emcurrency (EMC) results show that EMCs for most nickel products are higher than their corresponding sale prices in 2019 (see Table 1). It means that the associated environmental costs at different life cycle stages of nickel production are not fully reflected in the Chinese markets. However, EMC of recycled stainless steel is 4.85E + 03 em$/t Ni, much lower than the corresponding sale price (2.50E + 04 $/t Ni) in 2019. This is because the unit emergy of recycled stainless steel is low when assuming that the UEV of nickel scraps is zero.

3.3. Recycling perspectives

Different from bulk metals such as aluminum and copper, nickel is mostly recycled in the form of semi-finished products, rather than nickel metal (Henckens and Worrell, 2020). Current recycling technology from stainless steel scraps is relatively mature. In fact, many Chinese stainless steel enterprises began to recycle such nickel-containing stainless steel in 2006 (Reck et al., 2010). In addition, it is possible to recycle nickel from lithium-ion batteries (Islam et al., 2022). In particular, with the rapid development of new energy vehicles, the total amount of lithium-ion batteries will increase quickly, indicating a great recycling potential from such sources (UNEP, 2024).

Fig. 4 shows the UEVs and detailed components of stainless steel (304L) and nickel battery (NCM622) produced from current raw materials as well as from stainless steel scraps and retired batteries. More details are presented in the supporting information (Table S5). Results indicate that it is a more sustainable option to produce nickel from scraps and retired batteries. For example, nickel recycling from retired batteries can reduce 78.1 % of the emergy input, while nickel recycling from end-of-life stainless steel can reduce 97.5 % of the total emergy. We assume that the emergy inputs of nickel materials in both recycling routes are zero, which can reduce corresponding UEVs. Additionally, emergy inputs of chemicals in both recycling routes can be greatly reduced.

3.4. Sensitivity analysis results

The results of sensitivity analysis are shown in Fig. 5. At the mining stage, 10 % decrease of local nonrenewable resources lead to 9.98 % reduction of the total emergy of nickel ores, indicating the dominance of local nonrenewable resources in nickel extraction. At the smelting & refining stage, the characteristics of three nickel products are different. For nickel metal, 10 % reduction of purchased nickel materials, transport and locally non-renewable inputs lead to 4.61 %, 3.30 % and 1.67 % reduction of the total emergy, respectively. In terms of nickel sulphate, 10 % decrease of purchased nickel materials, chemicals and locally non-renewable inputs can result in 6.84 %, 1.60 % and 1.40 % reduction of the total emergy, respectively. In terms of ferronickel, 10 % reduction of purchased nickel materials and energy can lead to 8.42 % and 1.18 % reduction of the total emergy, respectively. At the fabrication stage, the inputs of chemicals and purchased nickel materials dominate the production of both stainless steel and lithium-ion battery. To be specific, 10 % reduction of chemicals and purchased nickel materials can lead to 7.02 % and 2.52 % reduction of the total emergy of battery respectively, while such reduction can cause 5.62 % and 4.31 % decrease of the total emergy of stainless steel. At the recycling stage, chemicals play the most significant role. To be specific, 10 % reduction of chemicals can lead to 5.79 % and 8.52 % reduction of the total emergy in stainless steel and battery production, respectively. In summary, the changes of major dominators for typical products at different stages lead to decreases of the total emergy.

4. Discussions

4.1. Contributions of individual flows

With regard to nickel production in China, nickel materials (including local non-renewable resources and purchased nickel

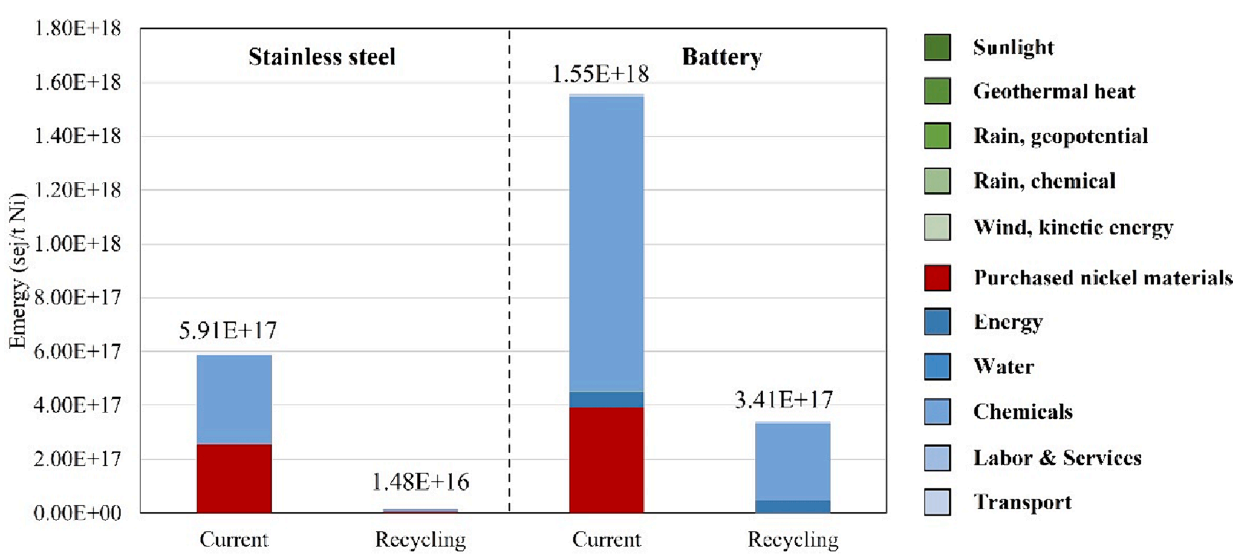


Fig. 4. UEVs of stainless steel (304L) and lithium-ion battery (NCM622) between primary nickel source and secondary nickel source.

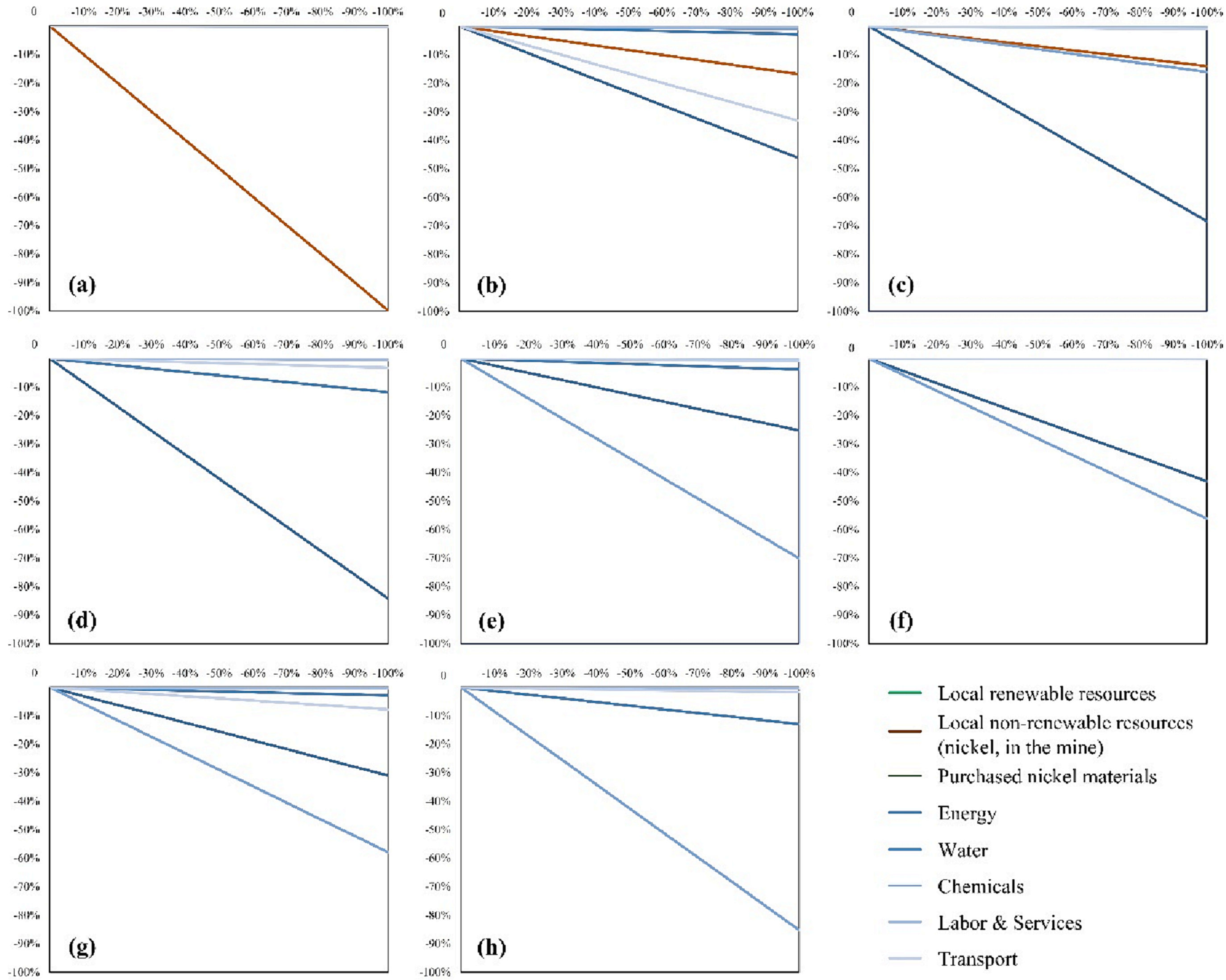


Fig. 5. Sensitivity analysis results of emergy inputs of (a) nickel ore (mining), (b) nickel metal (S&R-1), (c) nickel sulphate (S&R-2), (d) ferronickel (S&R-3), (e) battery NCM622 (Fabrication-1), (f) stainless steel 304L (Fabrication-2), (g) stainless steel 304L (Recycling) and (h) battery NCM622 (Recycling).

materials) account for the majority of the total emergy at the mining stage (97.8 %) and the S&R stage (63.0 %, 82.6 % and 84.4 % for three different products respectively), while chemicals are the main contributors at both fabrication and recycling stages. Nickel is the most important output from both mining and S&R stages. More components are added to increase nickel contents during both mining and S&R stages. For example, nickel concentration in most nickel ores ranges from 0.2 % to 2.0 % (Wollschlaeger, 2017). During fabrication and recycling stages, more elements are added to the two typical products. For instance, a large amount of ferrochrome is added to the stainless steel so that the chromium content can reach a certain level in the final product. Similarly, many chemicals are added to the lithium-ion battery to ensure the quality of such batteries. Both rely on increased emergy input of chemicals.

The contribution of transport is significant in nickel metal production because the production site locates in Gansu province, which is in the western part of China. China's major nickel reserves are concentrated in this province, leading to that it is convenient to set up such factories near the nickel mining site. However, domestic ores cannot meet with the increasing demand for nickel metal production. Therefore, China has to import nickel ores from Australia, Indonesia and Philippine, which means that it is necessary to deliver such ores with long-distance transport. As such, more nickel processing factories operate their businesses in coastal regions so that they can easily get such imported ores.

An unexpected result is that emergy input of energy accounts for a relatively small part in all the production stages, ranging from 0.1 % to 11.8 %. This indicates that the contribution of energy is less. However, it does not mean that energy consumption is not important in nickel production. Actually, nickel industry is energy intensive. But our study emphasizes the importance of other inputs from an emergy perspective. It reflects a more comprehensive picture since other inputs, especially those non-renewable resources, are embodied with large ecosystem contributions in which energy consumption is also associated. The same is true for the emergy input of L&S. In terms of renewable resources, their contributions to the total emergy are negligible in all the production stages (less than 0.01 %), meaning that nickel production mainly relies on non-renewable inputs and L&S inputs.

4.2. The selection of nickel raw materials and their prices

The complete nickel industrial chain is based upon various nickel raw materials. Among them, ferronickel is a key component for stainless steel fabrication, while nickel sulphate is important for lithium-ion battery production. In addition, nickel metal can be used in all the application fields, and nickel wastes and scraps can be collected and recycled at the fabrication stage. Normally, the selection of such raw materials is based upon prices and accessibility. For example, ferronickel is always used to make stainless steel since it is cheap and can be easily obtained. Stainless steel scraps are sometimes more expensive due to the costs of classification, collection and delivery although it is more environmentally friendly. With regard to lithium-ion battery production, the emerging and rapid development of electric vehicles increased the demand for nickel-containing batteries. But due to their relatively longer life spans, most nickel-containing batteries are still being used, meaning that the production for such batteries relies on primary nickel products, namely nickel sulphate. In order to meet with such soaring demand, even nickel metal is used to produce nickel sulfate, leading to rapidly increasing price of nickel sulfate. Details about nickel price are shown in the supporting information (Fig. S2). Actually, nickel price is relatively low due to its abundant reserves. But its price fluctuated during the past three years, with a peak price occurred in 2022 induced by the rapid development of nickel-containing batteries. Interestingly, such high price encouraged the utilization of nickel wastes and scraps, making secondary nickel production more acceptable globally. But there are concerns on future market demands, which may restrict further development of nickel recycling.

4.3. Policy recommendations

Nickel is an important metal in both traditional (stainless steel) and emerging areas (electric vehicle batteries, various power generations and hydrogen production), therefore nickel industry will continue to boom in China (UNEP, 2024b). Under such a circumference, associated environmental impacts should be measured. Based on the key findings in this study, we propose several policy recommendations to facilitate sustainable nickel resource management in China.

Firstly, it is essential to have a national plan on nickel industrial development. Currently, most nickel enterprises are located in coastal regions due to the geographical advantages of accessing imported primary nickel resources. However, the best nickel metal (electrolytic nickel with over 99.99 % nickel content) is produced in a nickel firm in Gansu, a landlocked province in Northwest China (Liu and Xu, 2023). In fact, this firm is the largest nickel producer in China due to local rich nickel reserves (Liu, 1991). But local extraction cannot meet with its production demand since it has been extracted for many years. Thus, this nickel firm has to import nickel ores from other countries, meaning that such ores have to be delivered through long-distance transport. Also, this firm is state-owned, its relocation to new sites need to be approved by the state council. Therefore, we suggest that the Chinese government should prepare a national nickel industrial development plan so that reasonable distribution of nickel industries can be achieved. In particular, although China dominates nickel production in the world, most low value-added nickel products can be easily produced in other nickel-rich countries, such as Philippines and Indonesia (Kurniawan et al., 2020; Nakajima et al., 2017). This means that the Chinese government should upgrade the entire nickel industrial chain so that more value-added products can be manufactured in China.

Secondly, it is critical to improve the overall nickel resource efficiency along its industrial chain. The emergy input of chemicals plays an important role in nickel production. More efficient nickel mining, smelting & refining, fabrication and recycling technologies can greatly reduce nickel losses and chemical inputs at each stage of nickel production. But these measures rely on more advanced technologies and management. Therefore, we suggest more university-industrial co-operations so that more innovative nickel production technologies can be developed and applied. A round table should be created so that different stakeholders can regularly meet and discuss the common research needs, share information, data and technologies, and organize capacity building activities to make sure such technologies and advanced management practices can be promoted.

Thirdly, it is necessary to address associated environmental costs. The EMC values of nickel products produced from primary nickel are all higher than their sale prices, indicating that it is necessary to incorporate environmental costs into pricing. Actually, most downstream firms are not willing to afford such environmental externalities. But with further development of domestic mining, local ecosystem functions may be lost, which will influence sustainable development of these mining sites. In fact, numerous studies have proved that mining activities cause serious environmental disturbances, including environmental pollution and ecological degradation (Lei et al., 2016; Li et al., 2024; Ran et al., 2022). Therefore, an ecological compensation mechanism should be created so that necessary funds can be collected for recovering damaged ecosystem functions. Our emergy analysis results can provide valuable references to determine ecological compensation level through appropriate pricing of such ores.

Lastly, it is crucial to encourage nickel recycling. Our results indicate that secondary nickel production is more sustainable than primary nickel production. There are two different recycling routes, namely open-loop recycling and close-loop recycling. The first refers to recycling nickel from end-of-life nickel-containing batteries, while the latter refers to recycling nickel-containing stainless steel scrapes directly so that secondary stainless steel can be resold. Current close-loop recycling technologies are relatively mature and have been widely applied. But it is difficult to collect adequate nickel-containing stainless steel scraps when considering the delivery costs of such stainless steel scraps. In addition, inconsistent production requirements may lead to unknown nickel concentrations, which technically hinders nickel recycling (Su et al., 2023). Therefore, it is necessary to build a transparent and open scraps collection system. Another issue is that such scraps are not enough to meet with the domestic demand. Therefore, we suggest importing such scraps from other countries, especially from those developing countries without mature nickel recycling facilities. For nickel-containing batteries, the challenge is that recycling efforts for such batteries often focus on cobalt and lithium due to their higher economic values, rather than nickel. Thus, it is crucial to initiate more research efforts to extend the life spans of such batteries or co-recycle nickel from such wastes. As such, since most lithium-ion batteries are still in their service and will retire in several years, the Chinese government may plan the establishment of national end-of-life batteries collection platform. At the same time, it is critical to set up national standards on collecting such retired batteries so that key information, such as the concentrations of nickel and other alloy metals, the amounts of such batteries and associated clients, key producers and recyclers, are available to all the stakeholders.

5. Conclusions

China is the largest nickel producer in the world and has to pay attention on associated environmental challenges. This study performs an environmental accounting for nickel production in China by employing an emergy analysis approach.

Our results show that the total emergy input has extensively increased since additional inputs are added at each life cycle stage of nickel production. The UEVs of typical nickel products also increased from mining stage to fabrication stage. At the stage of mining and S&R, the total emergy inputs of all the selected products are dominated by nickel raw materials, including both local nonrenewable resources and purchased nickel materials. But the contributions of chemicals become the majority at the fabrication stage. Also, transport plays a significant role in the total emergy input since a large amount of such resources are purchased from other countries and have to be delivered through long distance transport. At the recycling stage, the emergy input of nickel scraps are defined as zero, leading to both decreased total emergy and UEV. Chemicals are the most important input in the total emergy at this stage. Moreover, emergy-based performance indicators indicate that nickel industry is unsustainable with a low value of ESI since its production mainly depends on nonrenewable resources. From an overall sustainability point of view, recycling nickel from both stainless steel scraps and end-of-life batteries are more sustainable. However, nickel scraps are limited, which restricts secondary nickel production. Moreover, the EMC of nickel products from primary nickel indicates additional environmental costs although such costs are not fully reflected in nickel prices.

These research results provide valuable insights for preparing appropriate nickel resource management policies, such as national plan on nickel industrial chain, the improvement of the overall nickel resource efficiency, the consideration of associated environmental costs, and the wide application of nickel recycling.

Several research limitations exist in this study. The first one is that we only selected several nickel-related products in this study, which cannot represent the situations of other nickel industries in China. The second one is that UEVs used in this study were obtained from different sources, which may result in uncertainties. The third one is that transformities for different input items are not always available for the investigated firm. We have to rely on those most relevant literatures to get more relevant transformities, which may lead to biased results. However, this issue does exist for all the emergy-related studies. In general, the application of emergy analysis method can help understand the nickel production cycle from a donor side so that a more complete picture of nickel production can be presented.

CRediT authorship contribution statement

Chang Su: Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Yong Geng:** Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Gengyuan Liu:** Writing – original draft, Methodology, Investigation, Conceptualization. **Aiduan Borrion:** Writing – original draft, Methodology, Formal analysis. **Jingjing Liang:** Writing – original draft, Investigation, Formal analysis.

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.

Data availability

Data will be made available on request.

Acknowledgements

This study is financially supported by the National Key R&D Program of China (2019YFC1908501) and National Natural Science Foundation of China (Grant No. 72088101; 72004125)

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2024.112006.

References

Bai, Y., Zhang, T., Zhai, Y., Jia, Y., Ren, K., Hong, J., 2022. Strategies for improving the environmental performance of nickel production in China: Insight into a life cycle assessment. J. Environ. Manage. 312, 114949 https://doi.org/10.1016/j.jenvman.2022.114949.

Baum, Z.J., Bird, R.E., Yu, X., Ma, J., 2022. Lithium-ion battery recycling — Overview of techniques and trends. ACS Energy Lett. 7, 712–719. https://doi.org/10.1021/acsenergylett.1c02602.

Brown, M.T., Raugei, M., Ulgiati, S., 2012. On boundaries and "investments" in Emergy Synthesis and LCA: A case study on thermal vs. photovoltaic electricity. Ecol. Indic. 15, 227–235. https://doi.org/10.1016/j.ecolind.2011.09.021.

Brown, M.T., Campbell, D.E., De Vilbiss, C., Ulgiati, S., 2016. The geobiosphere emergy baseline: A synthesis. Ecol. Modell. 339, 92–95. https://doi.org/10.1016/j.ecolmodel.2016.03.018.

Brown, M.T., Ulgiati, S., 2016. Assessing the global environmental sources driving the geobiosphere: A revised emergy baseline. Ecol. Modell. 339, 126–132. https://doi.org/10.1016/j.ecolmodel.2016.03.017.

Buranakarn, V., 1998. Evaluation of recycling and reuse of building materials using the emergy analysis method. University of Florida.

Cai, W., Geng, Y., Li, M., Gao, Z., Wei, W., 2023. Mapping the global flows of steel scraps: An alloy elements recovery perspective. Environ. Res. Lett. 18 (9), 094048 https://doi.org/10.1088/1748-9326/acf2ad.

Campbell, E.T., Brown, M.T., 2012. Environmental accounting of natural capital and ecosystem services for the US National Forest System. Environ. Dev. Sustain. 14, 691–724. https://doi.org/10.1007/s10668-012-9348-6.

Cano Londoño, N.A., Velásquez, H.I., McIntyre, N., 2019. Comparing the environmental sustainability of two gold production methods using integrated emergy and life cycle assessment. Ecol. Indic. 107, 105600 https://doi.org/10.1016/j.ecolind.2019.105600.

Chen, W., Geng, Y., Tian, X., Zhong, S., Gao, C., You, W., Li, S., 2019. Emergy-based environmental accounting of gold ingot production in China. Resour. Conserv. Recycl. 143, 60–67. https://doi.org/10.1016/j.resconrec.2018.12.021.

Cnia, 2020. The yearbook of nonferrous metals industry of China. China Nonferrous Metals Association, Beijing.

UN Comtrade, 2023. International Trade Statistics Database. https://comtrade.un.org/ (accessed 10.20.23).

Costanza, R., de Groot, R., Braat, L., Kubiszewski, I., Fioramonti, L., Sutton, P., Farber, S., Grasso, M., 2017. Twenty years of ecosystem services: How far have we come and how far do we still need to go? Ecosyst. Serv. 28, 1–16. https://doi.org/10.1016/j.ecoser.2017.09.008.

Crabtree, G., 2019. The coming electric vehicle transformation. Science. 366, 422–424. https://doi.org/10.1126/science.aax0704.

de Oliveira, R.K., Higa, A.R., Silva, L.D., Silva, I.C., da Penha Moreira Gonçalves, M., 2018. Emergy-based sustainability assessment of a loblolly pine (Pinus taeda) production system in southern Brazil. Ecol. Indic. 93, 481–489. doi: 10.1016/j.ecolind.2018.05.027.

Deng, S.Y., Gong, X.Z., 2018. Life Cycle Assessment of Nickel Production in China, in: Materials Science Forum. Trans Tech Publ, 1004–1010.

Eckelman, M.J., 2010. Facility-level energy and greenhouse gas life-cycle assessment of the global nickel industry. Resour. Conserv. Recycl. 54, 256–266. https://doi.org/10.1016/j.resconrec.2009.08.008.

Fukuzawa, R., 2012. Climate change policy to foster pollution prevention and sustainable industrial practices - A case study of the global nickel industry. Miner. Eng. 39, 196–205. https://doi.org/10.1016/j.mineng.2012.07.011.

Geng, Y., Sarkis, J., Ulgiati, S., Zhang, P., 2013. Measuring China's circular economy. Science 339, 1526–1527. https://doi.org/10.1126/science.1227059.

Geng, Y., Sarkis, J., Bleischwitz, R., 2019. Globalize the circular economy. Nature 565, 153–155. https://doi.org/10.1038/d41586-019-00017-z.

U.S. Geological Survey, 2023. Mineral commodity summaries, 2023, U.S Geological Survey. doi: 10.3133/mcs2021.

Giuliodori, D., Rodriguez, A., 2015. Analysis of the stainless steel market in the EU, China and US using co-integration and VECM. Resour. Policy 44, 12–24. https://doi.org/10.1016/j.resourpol.2014.11.006.

Graedel, T.E., Reck, B.K., Miatto, A., 2022. Alloy information helps prioritize material criticality lists. Nat. Commun. 13, 1–8. https://doi.org/10.1038/s41467-021-27829-w.

Henckens, M.L.C.M., Worrell, E., 2020. Reviewing the availability of copper and nickel for future generations. The balance between production growth, sustainability and recycling rates. J. Clean. Prod. 264, 121460 https://doi.org/10.1016/j.jclepro.2020.121460.

Huang, C.L., Vause, J., Ma, H.W., Li, Y., Yu, C.P., 2014. Substance flow analysis for nickel in mainland China in 2009. J. Clean. Prod. 84, 450–458. https://doi.org/10.1016/j.jclepro.2013.12.079.

Ingwersen, W.W., 2011. Emergy as a Life Cycle Impact Assessment Indicator: A Gold Mining Case Study. J. Ind. Ecol. 15, 550–567. https://doi.org/10.1111/j.1530-9290.2011.00333.x.

Nickel Institute, 2023. https://nickelinstitute.org/ (accessed 10.16.23).

Islam, M.T., Huda, N., Baumber, A., Hossain, R., Sahajwalla, V., 2022. Waste battery disposal and recycling behavior: a study on the Australian perspective. Environ. Sci. Pollut. Res. 29, 58980–59001. https://doi.org/10.1007/s11356-022-19681-2.

ISSF, 2023. International Stainless Steel Forum. https://www.worldstainless.org/ (accessed 10.20.23).

Johnson, J., Reck, B.K., Wang, T., Graedel, T.E., 2008. The energy benefit of stainless steel recycling. Energy Policy 36, 181–192. https://doi.org/10.1016/j.enpol.2007.08.028.

Kurniawan, A.R., Murayama, T., Nishikizawa, S., 2020. A qualitative content analysis of environmental impact assessment in Indonesia: A case study of nickel smelter processing. Impact Assess. Proj. Apprais. 38, 194–204. https://doi.org/10.1080/14615517.2019.1672452.

Lei, K., Pan, H., Lin, C., 2016. A landscape approach towards ecological restoration and sustainable development of mining areas. Ecol. Eng. 90, 320–325. https://doi.org/10.1016/j.ecoleng.2016.01.080.

Lei, Y., Wang, Z., Wang, D., Zhang, X., Che, H., Yue, X., Tian, C., Zhong, J., Guo, L., Li, L., Zhou, H., Liu, L., Xu, Y., 2023. Co-benefits of carbon neutrality in enhancing and stabilizing solar and wind energy. Nat. Clim. Chang. 13, 693–700. https://doi.org/10.1038/s41558-023-01692-7.

Li, N., Guo, Y., Wang, L., Wang, Q., Yan, D., Zhao, S., 2024. Evaluation and quantitative characterization for the ecological environment impact of open pit mining on vegetation destruction from landsat time series : A case study of Wulishan limestone mine. Ecol. Indic. 158, 111371 https://doi.org/10.1016/j.ecolind.2023.111371.

Liu, Q., 1991. Development of nickel smelting at Jinchuan nickel smelter, China. EMC'91 Non-Ferrous Metall. Futur. 165–174 https://doi.org/10.1007/978-94-011-3684-6_17.

Liu, Z., Xu, K., 2023. Nickel Metallurgy, in: The ECPH Encyclopedia of Mining and Metallurgy. Springer, 1–8. doi: 10.1007/978-981-19-0740-1_840-1.

Liu, Y., Zhang, J., Xiao, Q., Huang, D., Wang, Z., Xing, X., 2016. Improvement and optimization of nickel alloy smelting process I. Ferro-Alloys 47, 1–7.

Liu, Y., Li, H., An, H., Santagata, R., Liu, X., Ulgiati, S., 2021. Environmental and economic sustainability of key sectors in China's steel industry chain: An application of the Emergy Accounting approach. Ecol. Indic. 129, 108011 https://doi.org/10.1016/j.ecolind.2021.108011.

Liu, Y., Qu, Y., Cang, Y., Ding, X., 2022. Ecological security assessment for megacities in the Yangtze River basin: Applying improved emergy-ecological footprint and DEA-SBM model. Ecol. Indic. 134, 108481 https://doi.org/10.1016/j.ecolind.2021.108481.

Ma, X., Yang, D., Zhai, Y., Shen, X., Zhang, R., Hong, J., 2019. Cost-combined life cycle assessment of ferronickel production. Int. J. Life Cycle Assess. 24, 1840–1850. https://doi.org/10.1007/s11367-019-01600-2.

Majeau-Bettez, G., Hawkins, T.R., Strømman, A.H., 2011. Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles. Environ. Sci. Technol. 45, 4548–4554. https://doi.org/10.1021/es103607c.

Mallapaty, S., 2020. How China could be carbon neutral by mid-century. Nature 586, 482–483. doi: A639031249/HRCA?u=anon~68112183.

Nakajima, K., Nansai, K., Matsubae, K., Tomita, M., Takayanagi, W., Nagasaka, T., 2017. Global land-use change hidden behind nickel consumption. Sci. Total Environ. 586, 730–737. https://doi.org/10.1016/j.scitotenv.2017.02.049.

Nakajima, K., Daigo, I., Nansai, K., Matsubae, K., Takayanagi, W., Tomita, M., Matsuno, Y., 2018. Global distribution of material consumption: Nickel, copper, and iron. Resour. Conserv. Recycl. 133, 369–374. https://doi.org/10.1016/j.resconrec.2017.08.029.

Odum, H.T., 1996. Enviromental accounting: emergy and enviromental decision making. Wiley, New York, US.

Ohnishi, S., Dong, H., Geng, Y., Fujii, M., Fujita, T., 2017. A comprehensive evaluation on industrial & urban symbiosis by combining MFA, carbon footprint and emergy methods—Case of Kawasaki, Japan. Ecol. Indic. 73, 315–324. https://doi.org/10.1016/j.ecolind.2016.10.016.

Pan, H., Zhang, X., Wang, Y., Qi, Y., Wu, J., Lin, L., Peng, H., Qi, H., Yu, X., Zhang, Y., 2016. Emergy evaluation of an industrial park in Sichuan Province, China: A modified emergy approach and its application. J. Clean. Prod. 135, 105–118. https://doi.org/10.1016/j.jclepro.2016.06.102.

Ran, M., Wang, W., Wang, X., Liu, C., Zhu, P., 2022. Analysis of eco-environmental quality change in Jinchuan nickel mine based on remote sensing ecological index. Ind. Miner. Process. 51, 16–21. doi: Analysis of eco-environmental quality change in Jinchuan nickel mine based10.16283/j.cnki.hgkwyjg.2022.08.004.

Reck, B.K., Müller, D.B., Rostkowski, K., Graedel, T.E., 2008. Anthropogenic nickel cycle: insights into use, trade, and recycling. Environ. Sci. Technol. 42, 3394–3400. https://doi.org/10.1021/es072108l.

Reck, B.K., Chambon, M., Hashimoto, S., Graedel, T.E., 2010. Global stainless steel cycle exemplifies China's rise to metal dominance. Environ. Sci. Technol. 44, 3940–3946. https://doi.org/10.1021/es903584q.

Rugani, B., Benetto, E., 2012. Improvements to emergy evaluations by using life cycle assessment. Environ. Sci. Technol. 46, 4701–4712. https://doi.org/10.1021/es203440n.

Rui, X., Geng, Y., Zhuang, M., Xiao, S., Sun, X., 2022. Emergy-based environmental accounting of graphite anode material production. J. Clean. Prod. 339, 130705 https://doi.org/10.1016/j.jclepro.2022.130705.

Su, C., Geng, Y., Zeng, X., Gao, Z., Song, X., 2023. Uncovering the features of nickel flows in China. Resour. Conserv. Recycl. 188, 106702 https://doi.org/10.1016/j.resconrec.2022.106702.

Sun, X., Luo, X., Zhang, Z., Meng, F., Yang, J., 2020. Life cycle assessment of lithium nickel cobalt manganese oxide (NCM) batteries for electric passenger vehicles. J. Clean. Prod. 273, 123006 https://doi.org/10.1016/j.jclepro.2020.123006.

Sun, X., Liu, Z., Zhao, F., Hao, H., 2021. Global Competition in the Lithium-Ion Battery Supply Chain: A Novel Perspective for Criticality Analysis. Environ. Sci. Technol. 55, 12180–12190. https://doi.org/10.1021/acs.est.1c03376.

Tian, X., Geng, Y., Viglia, S., Bleischwitz, R., Buonocore, E., Ulgiati, S., 2017. Regional disparities in the Chinese economy. An emergy evaluation of provincial international trade. Resour. Conserv. Recycl. 126, 1–11. https://doi.org/10.1016/j.resconrec.2017.07.017.

Tian, X., Geng, Y., Sarkis, J., Gao, C., Sun, X., Micic, T., Hao, H., Wang, X., 2021. Features of critical resource trade networks of lithium-ion batteries. Resour. Policy 73, 102177. https://doi.org/10.1016/j.resourpol.2021.102177.

Tilley, D.R., Swank, W.T., 2003. EMERGY-based environmental systems assessment of a multi-purpose temperate mixed-forest watershed of the southern Appalachian Mountains. USA. J. Environ. Manage. 69, 213–227. https://doi.org/10.1016/j.jenvman.2003.08.002.

Tsai, H., Lee, Y., 2024. Will changing land use and cropping practices affect resource use efficiency and environmental sustainability of agricultural systems ? A hierarchical emergy assessment approach. Ecol. Indic. 160, 111933 https://doi.org/10.1016/j.ecolind.2024.111933.

Ulgiati, S., Brown, M.T., 2013. Labor and services, in: Proceedings of the 7th Biennial Emergy. 557–562.

UNEP, 2024a. Global Resources Outlook 2024: Bend the Trend – Pathways to a liveable planet as resource use spikes. Nairobi. doi: wedocs.unep.org/20.500.11822/44901.

UNEP, 2024b. Global Waste Management Outlook 2024: Beyond an age of waste - Turning rubbish into a resource. doi: 10.59117/20.500.11822/44939.

Wei, W., Samuelsson, P.B., Tilliander, A., Gyllenram, R., Jönsson, P.G., 2020. Energy consumption and greenhouse gas emissions of nickel products. Energies 13, 5664. https://doi.org/10.3390/en13215664.

Wollschlaeger, S., 2017. Enhanced methods for nickel recovery from low-grade ores and bleed streams. Retrieved July 21, 2021.

Xiao, S., Geng, Y., Pan, H., Gao, Z., Yao, T., 2022. Uncovering the key features of dysprosium flows and stocks in China. Environ. Sci. Technol. 56, 8682–8690. https://doi.org/10.1021/acs.est.1c07724.

Xue, J., Liu, G., Brown, M.T., Casazza, M., 2018. Trash or treasure? Prospects for full aluminum chain in China based on the recycling options. J. Clean. Prod. 193, 217–227. https://doi.org/10.1016/j.jclepro.2018.05.075.

Yang, Q., Geng, Y., Sun, L., Liu, Z., Dong, H., Yu, X., Lyu, X., 2017. Emergy accounting on natural graphite and spherical graphite. Chinese J. Ecol. 36, 2592–2604. https://doi.org/10.13292/j.1000-4890.201709.031.

Yu, H., 2006. Study on life cycle assessment for electronlysed-nickel production. Kunming University of Science and Technology.

Yuan, Y., Yellishetty, M., Muñoz, M.A., Northey, S.A., 2019. Toward a dynamic evaluation of mineral criticality: Introducing the framework of criticality systems. J. Ind. Ecol. 23, 1264–1277. https://doi.org/10.1111/jiec.12920.

Zeng, X., Zheng, H., Gong, R., Eheliyagoda, D., Zeng, X., 2018. Uncovering the evolution of substance flow analysis of nickel in China. Resour. Conserv. Recycl. 135, 210–215. https://doi.org/10.1016/j.resconrec.2017.10.014.

Zhao, L.T., Li, F.R., Wang, D.S., 2023. How to achieve the common developments of green finance and clean energy in China? Evidence from coupling coordination evaluation. Ecol. Indic. 155, 111011 https://doi.org/10.1016/j.ecolind.2023.111011.

Zhong, W., An, H., Shen, L., Fang, W., Gao, X., Dong, D., 2017. The roles of countries in the international fossil fuel trade: An emergy and network analysis. Energy Policy 100, 365–376. https://doi.org/10.1016/j.enpol.2016.07.025.

Zhuang, M., Geng, Y., Pan, H., Wu, F., Wu, D., 2021. Ecological and socioeconomic impacts of payments for ecosystem services – A Chinese garlic farm case. J. Clean. Prod. 285, 124866 https://doi.org/10.1016/j.jclepro.2020.124866.