



Analysis of iron composite flow in China

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Abstract

Iron is an important metal material that is crucial to social and national economic development. In order to understand iron's material flow, energy flow, and value flow in China, a composite flow framework is here established. Based on this framework, the concept of price is introduced, and China is taken as an example to study the composite flow of iron in 2018. The results showed the following. First, as iron moved down the industrial chain, its material flow decreased gradually, while the price continued to rise. Second, the annual loss of raw materials from iron processing was 150–200 million tons, and scrap iron had great potential for secondary utilization. Third, China had a trade deficit in terms of importing raw materials and exporting products, but it also had a trade surplus in trade volume. Finally, China imported iron-containing goods at high prices but exported iron-containing goods at low prices. This was due to the lack of high-end science and technology, which made China less competitive in the international market.

Keywords Iron · Material flow analysis · Value flow · Composite flow · Recycling economy · Energy flow

Introduction

Iron is an indispensable basic resource for social and economic development. It is also the most widely used and consumed metal in the world. In particular, it is an important resource during the industrialization of large countries. With the rapid development of the world economy, demand for iron has increased dramatically. Due to the uneven distribution of global iron resources, unbalanced industrial development, and varying levels of science and technology, iron resources in many countries cannot meet their own needs. Therefore, trade exchanges are common among countries for resource exchange. With the continuous development of global integration, international steel trade plays an important role in the economies of all countries.

When Covid-19 first spread around the world, the economic situation was complex and severe, the international background was turbulent, trade was blocked, and international trade was flagging. Many countries sought ways to reduce their dependence on international trade in resources to meet their own needs for economic development and stability. The iron and steel industry remains at the core of a sustainable modern society, and iron-containing commodities will become the cornerstone of economic recovery.

China is the world's largest producer, consumer, and trader of iron, and the world's second largest economy. Countries around the world have significantly increased their dependence on products made in China. In 2019, China imported 1.069 billion tons of iron ore from abroad, with an external dependence of more than 80%. From 2008 to 2018, the proportion of China's steel output in the world increased from 38.10 to 51.30%, and the consumption of crude steel increased from 36.30 to 48.80% year-on-year. Taking China as an example, we conducted a comprehensive study of the composite flow of iron and metal with a view to reducing China's external dependence on iron resources, maintaining internal development, and stimulating world economic recovery. Such goals are of great significance not only to China but also to other countries in the world.

Due to the importance of iron in economic and social development, research on iron flow has attracted the

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attention of many fields, such as the environment, economy, and trade. The flow of iron can be tracked and studied by using material flow analysis (MFA; Yan and Wang 2014). MFA examines the consumption, energy consumption, and output of a resource, and reveals the core control measures of a circular economy for sustainable development (Brunner and Rechberger 2004). Analysis and research on iron material flow is one of the core fields of material flow research. The time span for iron MFA and research in many countries around the world is as long as 100 years.

Fenton used the static logistics analysis method to analyze the iron recovery process in the American steel industry, and to provide the flow conditions of each part in the steel production process, from smelting to processing, manufacturing, discarding, and recycling after use. Based on a dynamic logistics analysis model, Igarashi et al. quantitatively analyzed the flow of each stage of steel production in Japan, and evaluated the potential savings in steel production (Igarashi, 2005). Park et al. systematically analyzed the logistics status of Korean steel products using the same dynamic logistics analysis method (Park et al. 2011a, b). The Yale Ecological Research Center divides waste into household waste and purchase waste according to its location, and Kavanagh further divides waste into immediate waste and long-term waste according to the generation time (Fischer-Kowalski and Hüttler 1999; Kavanagh 1998). However, because current MFA research rarely considers economic and social factors, such research can only be used as a decision-making guide and cannot be directly implemented in practice.

Compared with MFA, value flow analysis is a relatively new research field and a new approach to research on circular economies. Existing research is limited to the indirect value brought by the “reduction” at the input end or waste minimization, similar to end-of-life treatment. There is a lack of systematic research on the general laws of the value flow of circular economies and on the influencing factors at all stages of the life cycle of products or services (Xiao et al. 2009). In addition, there is no consensus on how to quantitatively analyze value flow at a macro-level.

In 2003, Mao and Zhongwu proposed selecting an element M in a product as the representative material to establish the price of element M, so as to obtain a diagram for value flow analysis under the material circulation flow of enterprises (Mao and Lu 2003). This concept has been widely used for value stream analysis (Sun et al. 2018; Chen et al. 2020). Using the material flow and value chain analysis method, Yan and Wang quantitatively analyzed the value flow of China’s iron ore resources. They established an iron resource value flow diagram corresponding to a material flow diagram according to the value chain and price theory of the M element, and quantitatively described the

circulation value of China’s iron resources in 2011 (Yan and Wang 2014).

In the process of iron flow, both material flow and value and energy flow have mutual effects on the environment. Taking matter as the carrier of value and energy, the circular flow of value and energy under the condition of iron can be obtained. The circulation of material, value, and energy has a far-reaching impact on the environment, economy, and society (Yu et al. 2018a). Research on the compound flow of these three aspects is of great significance. There is little research on iron flow in the literature. This field of research is growing, however, and with the promotion of sustainable development, the development of iron flow research is set to become a general trend in China and throughout the world.

Research method

Composite glow analysis framework

With MFA, data can be obtained regarding the circulation and value of substances in each link from the angle analysis of the life cycle of the substances. Then, we can analyze the value benefits and final social stock of different links, to improve resource utilization efficiency, reduce waste emissions, and ensure the sustainable development of the economy and resources (Wang and Liu 2018).

Calculating the material flow involves collecting the material quality data of iron-containing commodities and the input, output, consumption, and storage in various links in China, to analyze the material flow of iron in China. Since MFA follows the principle of material conservation, the iron material flow in this paper is calculated accordingly. The iron material output and input in each link of the whole life cycle and the whole national level should be equal.

Thus, ferrous metal flows can be classified by life cycle stages (Table 1). The artificial flow of iron metal within the boundary proceeds through the production stage, manufacturing stage, in-use stage, and scrap and regeneration stage. The links of iron flow in the life cycle are complex; there are many data statistics and calculations. Therefore, we adopt the fixed-point observation method (Lu 2006), taking the flow of China’s iron stocks in 2018 as the research object to observe the flow of iron over one year.

Considering that a certain amount of secondary iron metal resources are recycled every year, the secondary resources enter the iron and steel industry chain again, and ultimately become iron-containing products, which accumulate in the economy and society, forming the iron stock again. Therefore, to facilitate the statistical calculations, when analyzing the iron metal material flow in China, we regard the secondary iron resources

Table 1 Classification and iron content coefficient of iron-containing commodities in the life cycle

Life cycle	Category	Sub-category	Iron content coefficient		
Sintering and smelting	Iron ore	Sintered iron ore	0.62		
		Un-sintered iron ore	0.62		
Steel production	Ferroalloy	Pig iron	0.95		
		Iron alloy	0.9–0.95		
		Ordinary steel	0.99		
		Stainless steel	0.87		
		Long strip of steel	0.98–0.99		
	Ferrous material	Plate steel	0.98–0.99		
		Narrow strip steel	0.98–0.99		
		Tubular steel	0.98–0.99		
		Product manufacturing	Iron-containing end product	Iron wire	0.9
				Land vehicles	0.53
Marine transport	0.45				
Air traffic equipment	0.45				
Petrochemical supplies	0.93				
Building prefabricated materials	0.35–0.45				
Agricultural machinery	0.52				
Metal forgings	0.65				
Household appliances	0.58				
Engineering machinery	0.65				
Scraping and recycling	Ferriferous waste	Other iron products	0.45–0.9		
		Ferriferous waste	0.15–0.5		

recycled every year as part of the internal circulation of the research system. As such, we do not make statistical calculations for these resources.

The flow of iron in all links of the life cycle is based on human factors. The flow of iron can be tracked by using MFA (Yan and Wang 2014). To analyze China's iron metal composite flow and build an analytical framework based on this flow, we selected the Chinese mainland as the boundary and took the flow of iron as the research object. Then, we comprehensive studied the flow at national and global levels (Fig. 1).

Estimation method of composite flow

The components of various iron-containing commodities are complex. They contain not only iron but also many other elements. Therefore, to calculate the flow, we first divide all iron-containing commodities in the artificial flow into five categories and 21 sub-categories according to the sequence of the life cycle of iron (Table 1). Then, we can calculate them according to their actual iron content coefficient in combination with the flow data of each share.

Estimation of material flow

Iron and steel products account for a large proportion of iron-containing commodities that are produced, used, and traded in China every year. In order to improve the accuracy of the material flow analysis and the reliability of conclusions, all kinds of iron-containing commodities are considered. To quantitatively calculate the iron flow, iron-containing commodities are divided into five categories and 13 sub-categories, according to the order of the front-, middle-, and back-end of the industrial chain (Table 1), which basically includes all commodities containing iron metals. Upstream products of the industrial chain mainly refer to iron ore, which is divided into open-pit iron ore and underground iron ore. Products in the middle reaches of the industrial chain include pig iron, crude steel, and ferroalloy. The production process of pig iron is formed by processing iron ore, while crude steel and ferroalloy are formed by processing pig iron. The back-end products of the iron and steel industry chain are complex, with a wide range of products and complex types. After specific processing, they are applied to consumer industries, such as the construction industry, transportation industry, construction industry,

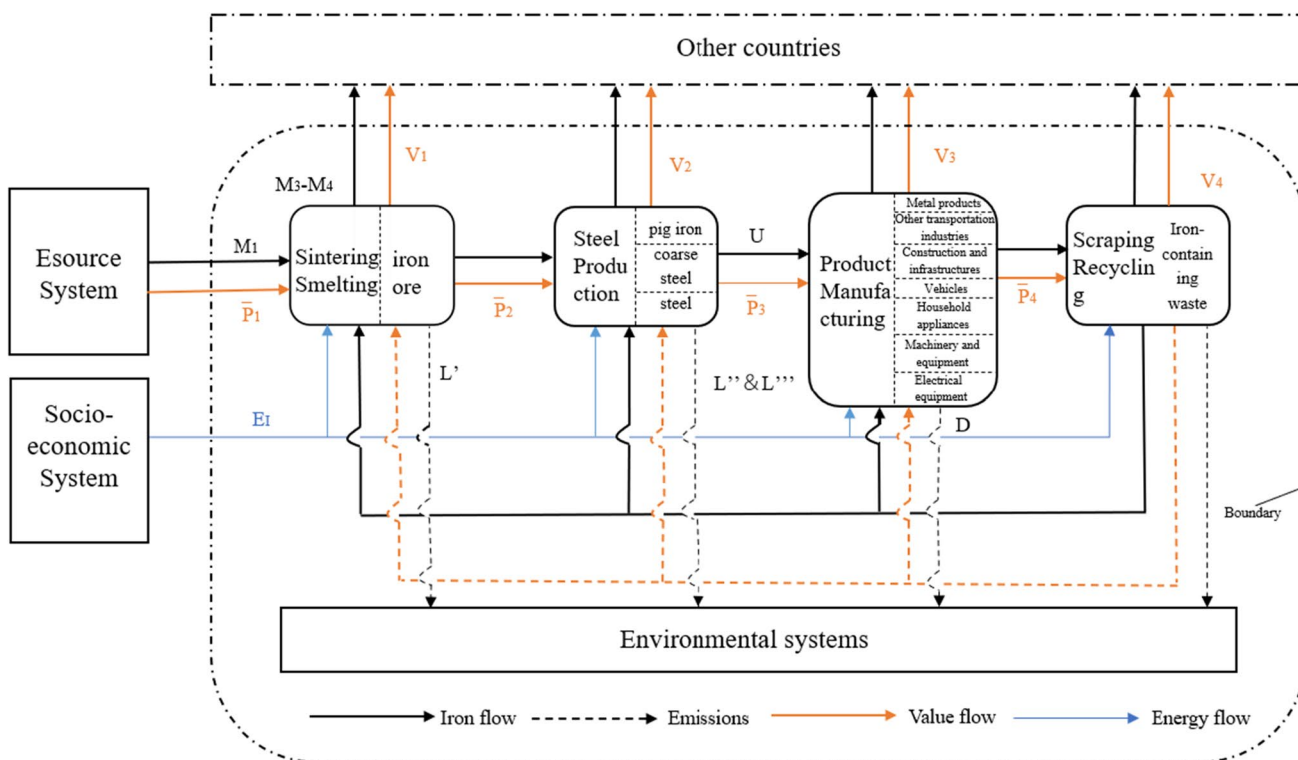


Fig. 1 Analysis framework of iron compound flow in China. The meaning of each physical quantity in the figure is shown in “Estimation method of composite flow”

transportation industry, and household appliances industry , In addition, some information is provided by CISIA (2015).

Table 1 was established by consulting the weight, material composition, and other parameters of samples of various sub-categories of iron-containing commodities, combined with the product parameters of relevant industries and the iron content coefficient of iron-containing commodities given by the China Nonferrous Metals Association and the China Iron and Steel Industry Association (CISA). In Table 1, because there are many kinds of iron-containing commodities in some sub-categories, their iron content coefficient is a range rather than an exact number. Consequently, we use a weighted average to obtain the iron content coefficient of each sub-category of iron-containing commodities. After determining the iron content coefficient of each small category of iron-containing commodities, the iron content coefficient of each large category of iron-containing commodities is determined using a weighted average method. Therefore, the material flow in this paper reflects the mass of pure iron. The data in this study are mainly processed by Excel and MATLAB.

(1) Iron production stage

The iron quality of domestic iron ore is calculated as follows:

$$M_1 = P_{ore} \theta \tag{1}$$

where M_1 represents the iron quality of domestic iron ore, according to the World Iron and Steel Industry Association; P_{ore} is the domestic iron ore output, and θ represents the average grade of iron ore in China. The average grade of raw iron ore produced in China was about 34.3% in 2018, according to the China Iron and Steel Industry Association.

As the raw ore grade of locally produced iron ore in China was only about 34.3% in 2018, it did not meet the requirements for iron smelting and needed to go through beneficiation process. Iron ore produces tailings during beneficiation. The loss in this process is calculated as follows:

$$L' = P \times (1 - \gamma_1) \tag{2}$$

where L' is the iron loss of domestic iron ore during beneficiation, P is the iron content of domestic iron ore, and γ_1 is the metal recovery rate in the beneficiation process of domestic iron ore, which is 74.01%, according to the data provided by China Iron and Steel Industry Association. The total iron

content of iron ore minus the iron content of exported iron ore and beneficiation loss is the material input in iron flow.

(2) Steel manufacturing stage

In addition to the iron loss of domestic iron ore in the beneficiation process, iron concentrate produces iron-containing by-products such as iron-making waste slag, steel-making slag, furnace dust, and sludge during ironmaking and steelmaking. Therefore, ore dressing and smelting loss is calculated as follows:

$$L = L' + L'' + L''' \tag{3}$$

where L'' is the iron material loss of iron ore in the ironmaking process and L''' is the iron material loss of pig iron in the steelmaking process, respectively, calculated as follows:

$$L'' = (P \times \gamma_1 + I^{ore}) \times (1 - \gamma_2) \tag{4}$$

$$L''' = (P \times \gamma_1 + I^{ore}) \times \gamma_2 \times (1 - \gamma_3) \tag{5}$$

where γ_2 is the metal recovery rate of iron ore during ironmaking and γ_3 is the metal recovery rate in the steelmaking process, set to 91.37%, and 96.65%, respectively, according to data from the China Iron and Steel Industry Association, and I^{ore} is the iron content of imported iron ore.

We replace Eqs. 2, 4, and 5 into Eq. 3 to obtain the total ore dressing and smelting loss, L , from three aspects:

$$L = P \times (1 - \gamma_1) + (P \times \gamma_1 + I^{ore}) \times (1 - \gamma_2) + (P \times \gamma_1 + I^{ore}) \times \gamma_2 \times (1 - \gamma_3) \tag{6}$$

(3) Steel product manufacturing stage

Usage of iron-containing commodities in 2018 is calculated as follows:

$$U = M_1 + M_3 - (M_4 + L + R) \tag{7}$$

where U represents the consumption of iron-containing terminal commodities, M_1 represents the iron content of domestic iron ore, M_3 represents the mass of imported iron, M_4 represents the quality of exported iron, L represents the beneficiation and smelting loss of iron ore, and R represents the inventory change of steel.

There will be a certain amount of loss and dissipation in the use of iron and steel products. The use-loss ratio of iron and steel products is also different according to the final use (Hatayama et al., 2010). Among them, the use-loss ratio of building steel is 0.06, that of mechanical steel is 0.14, that of transportation equipment is 0.19, and that of other steel is 0.05. Thus, the consumption of iron-containing terminal goods is calculated as follows:

$$D = \sum_{i=1}^7 D_i = UC^i \beta^i \tag{8}$$

where D represents the consumption of iron terminal commodities; D_i represents the use of various iron containing terminal commodities; $D_1, D_2, D_3, D_4, D_5, D_6,$ and D_7 represent the use of household appliances, electrical equipment, metal products, automobiles, other transportation industries, mechanical equipment, and construction and infrastructure equipment, respectively; U represents the use of iron containing terminal commodities, C^i represents the proportion of class I terminal commodities in the consumption structure (according to data provided by the World Iron and Steel Association); and β^i represents the consumption ratio of class I end commodities. In 2018, the consumption structure of steel used in household appliances, electrical equipment, other transportation industries, metal products, automobiles, mechanical equipment, and construction and infrastructure equipment in China was 2%, 3%, 5%, 10%, 12%, 16%, and 52%, respectively.

(4) Estimating iron material flow in international trade

It can be seen from Table 1 that iron-bearing terminal products contain the largest number of trade product categories, and the iron content coefficient of commodities is lower than that of commodities in other links. The commodity types of iron ore link are the least, and the iron content coefficient is set as 0.62 according to the iron ore grade of Australia, Brazil, and other countries with the most widely distributed iron ore resources. The number of iron-containing commodities in pig iron, crude steel, and steel is medium, and the iron content coefficient of commodity types is relatively high.

The calculation formula of trade flow is as follows:

$$W_s = Q_s \cdot R_s \tag{9}$$

$$W = \sum_{s=1}^n W_s \tag{10}$$

Consider the measurement of the material flow of imported steel as an example. In Eq. 9, the physical meaning of Q_s is the mass of a small class of imported steel s , in 10,000 tons. The data were obtained directly from the United Nations Commodity Trade Statistics Database (UN COMTRADE) and China Customs. The physical meaning of R_s is the iron content coefficient of s of this sub-type of steel. It is obtained by consulting the weight, material composition, and other parameters of various steels of the China Iron and Steel Industry Association (CISA) and combined with the data from the China Nonferrous Metals Industry Association. The specific values are shown in Table 1. W_s is calculated by Eq. 9. The physical meaning is the iron content of imported steel s , in 10,000 tons.

We add the mass of iron metal contained in each small class of iron-containing commodities under the general category obtained in Eq. 9 to obtain W , which physically means the iron content of imported steel, and the unit is 10,000 tons. The same is true for measuring the export iron flow.

Estimating energy flow

The driving force of the artificial flow of matter is energy. Iron is driven by the energy provided by the socio-economic system. It is refined and processed from iron ore or scrap iron, and then put into production and trade. This process not only changes the types of iron-containing commodities in which iron metals are located at different life-cycle stages, but also allows them to meet the different functional needs of society for iron (Mao et al., 2014; Liang and Mao, 2015). In order to intuitively analyze the energy flow at each stage of the life cycle, and to quantify the energy flow and provide targeted suggestions and a basis for the implementation of energy conservation and emission reduction, we obtain the flow e of each energy flow by multiplying the unit energy consumption in each stage by the output of iron-containing commodities E_i . The calculation formula is as follows:

$$E_i = e_i O_i \quad (11)$$

where the physical meaning of e_i is the unit energy consumption of class I iron-containing commodities in different processing procedures, with the unit of kg/ton. The physical

meaning of O_i is the output of class I iron-containing commodities, with the unit of 100 million tons. Data for both were obtained from the China Energy Statistical Yearbook 2019, as shown in Table 2.

Estimating value flow

Material is the carrier of value, carrying the flow of value. In the process of iron flow, since there is a material exchange of iron, there must be value exchange, that is, iron value flow. Based on material flow, value flow describes the value flow of material in the process of circulation from the perspective of the “resource value” of a circular economy (Yu et al., 2018b).

If the value of a product can be assigned to each of its constituent elements, each element of the product will become a carrier of value (Yan and Wang 2014). According to the concept of the “price of element M” (Mao and Lu 2003), in the process of iron flow, when leaving a certain stage of the life cycle, the value per unit mass of iron can be defined as the value level of the iron element in the iron flow at that stage, which is equal to the corresponding value flow divided by the mass of the iron element. In the analytical framework, the value flow of stocks at a certain link, or at the national level, is represented by value (Fig. 1).

In this paper, the weighted average unit price of each type of iron-containing commodity that is exported is taken as the value of the unit mass of iron metal in a commodity in

Table 2 Process energy consumption and related parameters of iron-containing commodities

Process		Process energy consumption	Unit	The source of the data
Mining	Open-air	14.64	10^3 kJ	2019 China Energy
	Ground floor	58.83	10^3 kJ	Statistics Yearbook
	Open-pit and underground iron ore production ratio in China is about 4:1			
Beneficiation		210.45	10^3 kJ	2019 China Energy Statistics Yearbook Yearbook
		The grade of concentrate iron ore after mineralization is about 62%		Department of Science and Technology Standards, State Environmental Protection Administration, 2006
Blast furnace ironmaking steel-making		114.19	10^5 kJ	2019 China Energy Statistics
	Converter	-416.22	10^3 kJ	Yearbook
	Electric	184.75	10^4 kJ	
	The proportion of crude steel output of converter Steelmaking and electric furnace			
Steel processing		179.66	10^4 kJ	2019 China Energy Statistics
Hot rolling		155.25	10^4 kJ	Yearbook
Cold rolling		188.85	10^4 kJ	
Plating		165.43	10^4 kJ	
Coating		166.58	10^4 kJ	

domestic circulation in the corresponding stage of the life cycle. The calculation formula is as follows:

$$\bar{P} = \sum_{s=1}^n P_s f_s \tag{12}$$

where the physical meaning of P_s is the unit price of a small class of iron-containing commodities, in US\$/ton. The physical meaning of f_s is the proportion of this small category of iron-containing commodities s in the imports of this large category of iron-containing commodities, and the average unit price \bar{P} of this large category of iron containing commodities is calculated. When leaving this life-cycle stage, the calculation formula of value flow per share is as follows:

$$V = \bar{P}W \tag{13}$$

where the physical meaning of V is the value flow of this large class of iron-containing commodities, in \$100 million US dollars. The physical meaning of W is the physical quality of this large class of iron-containing commodities in this flow, which is obtained from the 2019 China Iron and Steel Industry Yearbook and Eq. 10. In the calculation of international trade value flow, the flow of substances and the values of each major category of iron-containing commodities can be directly obtained by the United Nations Commodity Trade Statistics Database (UN COMTRADE) and China Customs. The unit value of iron-containing commodities in international trade is calculated as follows:

$$P_s = \frac{V_s}{W_s} \tag{14}$$

$$P = \sum_{s=1}^n P_s \tag{15}$$

Consider the measurement of the value flow of imported iron-containing commodities as an example. In Eq. 14, the physical meaning of V_s is the total trade volume of a small category of ferrous goods s imported, in \$10,000 US dollars. The data are obtained directly from the United Nations Commodity Trade Statistics Database (UN COMTRADE) and China Customs. However, in the calculation, only iron-containing commodities with high iron content and relatively high value dominated by iron metals are calculated, and products with low iron content but high value (such as computers, mobile phones, and other electronic products) are excluded. This is because the iron content of high-grade iron-containing commodities in the processing process is very low, and the value is dominated by the high added value brought by high-end technology and other precious metals, rather than ferrous metals (Chen et al., 2020). The physical meaning of W_s is the iron content of imported iron-containing commodities s in this category, in 10,000 tons, calculated by material flow. P_s is calculated by Eq. 14. The physical meaning is the unit price of this small class of

iron containing commodities s , with the unit of US\$/ton. In Eq. 15, we add the unit price of each small category of iron-containing commodities under the general category obtained in Eq. 15 to obtain P . The physical meaning is the unit price of imported iron-containing commodities, and the unit is US\$/ton. The same is true for measuring the value flow of exported iron-containing commodities.

Results and analysis of iron composite flow

Composite flow results of iron in China

Results of iron flow

In 2018, the original mineral content of iron ore in China was 783 million tons, and the iron content was 262 million tons. The net import of iron ore was 1.064 billion tons, and the iron content of imported iron ore was 660 million tons. Iron ore from Australia, Brazil, and other places was the main body of China’s iron metal import trade, accounting for more than 90% of total iron metal imports. This is because most of China’s iron ores are lean and deeply buried. The cost of mining and screening is too high and the quality is poor, so China can only import iron ore from other countries. In addition, with the improvement of China’s overall awareness of environmental protection, the recycling of iron containing waste has also become a part of iron import and export trade.

The domestic beneficiation loss was calculated at 68.05 million tons. The iron content in the solid waste generated in the two stages of ironmaking and steelmaking loss was 73.7 million tons and 27.6 million tons, respectively. The total iron loss in the three stages was 169 million tons. In 2018, the amount of scrap steel used for steelmaking accounted for about 85–90% of the total. This part of recycled secondary iron resources is regarded as the internal circulation of the research system. In China’s iron and steel industry, the amount of iron metal lost in the three stages of beneficiation, ironmaking, and steelmaking is considerable. This is partly due to the poor grade and low iron content of China’s self-produced iron ore. In addition, there are technical constraints and other reasons. The grade of iron ore originating from China is about 30%, and as such, it needs to go through beneficiation, sintering, and other processes. The grade of processed iron concentrate is about 62%. The above description can be showed as a detail composite flow of Iron as Fig. 2.

In 2018, China imported 19 million tons of iron terminal commodities, with an iron content of 11 million tons. Moreover, 140 million tons of iron terminal commodities were exported, and the iron content was 88 million tons. The net export volume of iron-bearing terminal commodities was 122 million tons, and the iron content was 77 million tons.

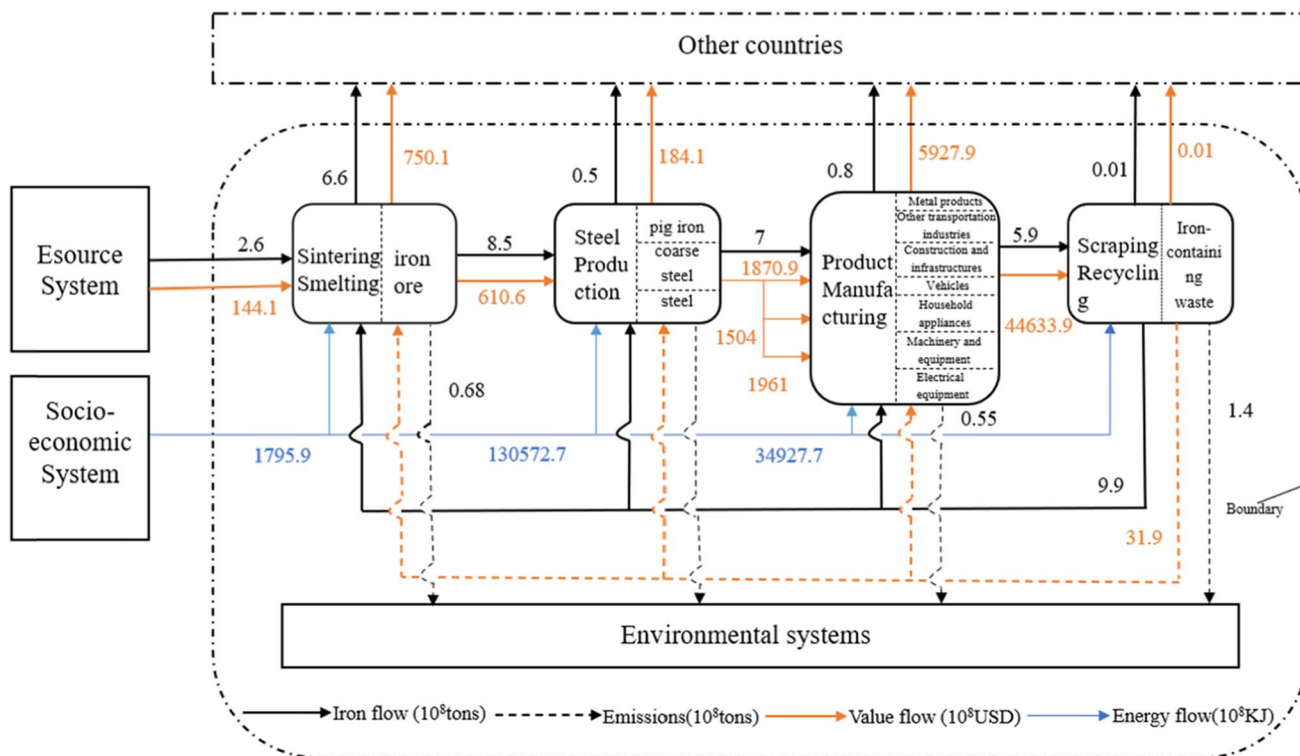


Fig. 2 Composite flow of iron of China in 2018

Iron-bearing terminal commodities are the main body of China’s iron-bearing commodity export trade. China imports a large number of raw materials and exports final products every year.

In 2018, China’s iron metal trade was in a state of net import. There was a huge trade deficit in the international trade volume of iron metal, and the dependence on foreign resources was high. In 2018, China imported 689 million tons of iron metal and exported 154 tons of iron metal, less than one-third of the import volume.

With rapid economic development, China has become a major exporter of ferrous materials and iron products in the world. In 2018, China imported 24 million tons of steel and iron terminal commodities, mainly from developed countries such as Japan, South Korea, the USA, and Germany. These iron-containing commodities have high requirements for science and technology. At present, China still needs to import from countries with a more developed manufacturing industry. China’s ferroalloys, ferrous materials, and iron products are the main exports, with a total of 152 million tons of steel and ferrous terminal commodities exported in the same year. However, these iron-containing commodities are low-end and low in technology. China is a big country in iron resources, but not a strong country in iron resources. It can only import high-end iron-containing goods from countries with a more developed manufacturing industry,

and it exports a large number of medium- and low-end iron-containing goods to more than 200 countries.

Results of iron energy flow

In 2016 and 2017, China respectively consumed 1995.06 million tons and 1973.5 million tons of standard oil (China Energy Statistical Yearbook, 2019), accounting for more than one-fifth of the total global end energy consumption. China’s demand for energy conservation is urgent.

The energy consumption of the iron and steel industry accounts for about 15% of China’s total energy consumption and about 23% of China’s total industrial energy consumption. In 2018, China’s iron flow consumed about 485.2 million tons of standard coal. The energy consumption in the mining process was 646,800 tons of standard coal, including 293,900 tons of standard coal for open-pit mining and 352,900 tons of standard coal for underground mining. Open-pit mining of iron ore has the advantages of large mining scale, short capital construction time, high degree of mechanization, and good operating conditions. In addition, the production efficiency of open-pit mining is very high, and the mining recovery rate can reach more than 90%. In 2018, China’s iron ore open-pit mining volume accounted for 77% of the total, and the open-pit mining recovery rate

reached 96.4%. Compared with underground mining, open-pit mining has low energy consumption and high energy utilization.

In 2018, China consumed 6.5 million tons of standard coal at the mining and beneficiation stages, including 5.4887 million tons of standard coal at the beneficiation stage alone, which is much higher than the energy consumed in mining. The iron ore produced locally in China is of poor quality and needs beneficiation. During this process, a large amount of energy is consumed and a large amount of pollutants are discharged, resulting in a large amount of scrap iron. The iron ore imported from Australia, Brazil, and other places is of high grade. Without beneficiation, it can reach the same iron content as local iron ore after beneficiation. Using high-grade imported iron ore not only reduces resource waste but also saves energy and reduces emissions.

In the process of ironmaking and steelmaking, energy consumption was 300.8 million tons and 58.9 million tons of standard coal, respectively. Blast furnace ironmaking consumes a lot of power and hydraulic resources, which is the most energy-consuming link in the iron and steel industry. Further, 119.3 million tons of standard coal were consumed in steel processing. Although the consumption is large, a large number of iron-containing final commodities with high added value are produced, and the energy utilization rate is high.

Results of iron value flow

The data in this section reflect the mass of pure iron. In 2018, the prices of iron ore, pig iron, crude steel, and steel-and iron-bearing terminal commodities in China were 71.5 US\$/ton, 1000 US\$/ton, 644 US\$/ton, 687.8 US\$/ton, and 7616.7 US\$/ton, respectively. The price of iron continued to rise from the front end to the back end of the industrial chain. In the international trade of iron containing commodities, China's iron ore imported from Oceania has the highest cost performance, with a unit price of 107.1 US\$/ton, but the price is still higher than the domestic circulation price. In 2018, China's iron-containing materials imported from Asia accounted for about 96.2% of the total iron-containing materials imported from the world. The import unit price was about 762.9 US\$/ton, and the export unit price was about 793.9 US\$/ton. The unit price of imported iron terminal commodities from countries around the world was about 27,536.2 US\$/ton, and the unit price of exported iron terminal commodities was about 7620 US\$/ton, which is a very big gap.

Contrary to the trade situation of iron ore and iron-containing waste, ferroalloys, iron-containing materials, and iron products are the main body of China's iron export trade. In 2018, China exported 153 million tons of pig iron, crude steel, and steel and iron terminal commodities, accounting

for more than 98% of iron exports. However, the total import volume of these commodities was only 29 million tons, accounting for only 19% of iron imports. The export trade volume of the above iron-containing commodities reached US \$1117.7 billion in 2018, accounting for 99.9% of the total export trade. The value of iron-containing commodities is mainly concentrated in iron-containing materials and iron products. Importing steel- and iron-containing final commodities from China has become the best choice for other countries in the world. In 2018, China's total iron import trade was 486.4 billion US dollars, and its total export trade was 1118.5 billion US dollars, with a trade surplus of nearly 632.1 billion US dollars. Although China's iron trade is in the state of net import, China is a surplus country of iron trade, and countries all over the world are more dependent on importing iron from China.

Discussion

- (1) Compared with underground mining, open-pit mining has a high energy utilization rate with considerable savings in energy. However, open-pit mining brings environmental impacts that cannot be ignored. First, excavation damage occupies a lot of land. Second, it causes dust and pollutes the land, atmosphere, and water. Third, it is easy to induce geological disasters, such as landslides, collapsed areas, soil erosion, and debris flow. It can cause ground deformation and endanger public safety. Furthermore, open-pit mining has a great impact on the disturbance and destruction of the ecological environment, which is difficult and expensive to repair and control. Underground mining of iron ore causes relatively little damage to the environment, but its energy utilization rate is very low. It thus wastes resources, and the pollutant emissions from energy consumption cannot be underestimated. At present, as long as the deposit occurrence conditions are met, China generally gives priority to open-pit mining.
- (2) In the process of iron flow, the loss occurs in the stages of ore dressing, smelting, ironmaking, and steelmaking. The amount of iron metal lost is 169 million tons, and an average of 1 ton of waste is generated for every 405 tons of iron produced. Among these, the loss during the ironmaking stage is the most, up to 73.7 million tons, mainly because China mainly uses blast furnace ironmaking, and the scrap output does not reach the scale of 200 million tons per year, which limits the recycling of iron and steel. Ore dressing and smelting loss is 68.1 million tons, mainly due to the low grade, poor quality, low beneficiation efficiency, and high energy consumption of China's local iron ore. Iron ore imported from abroad does not need beneficiation, because of

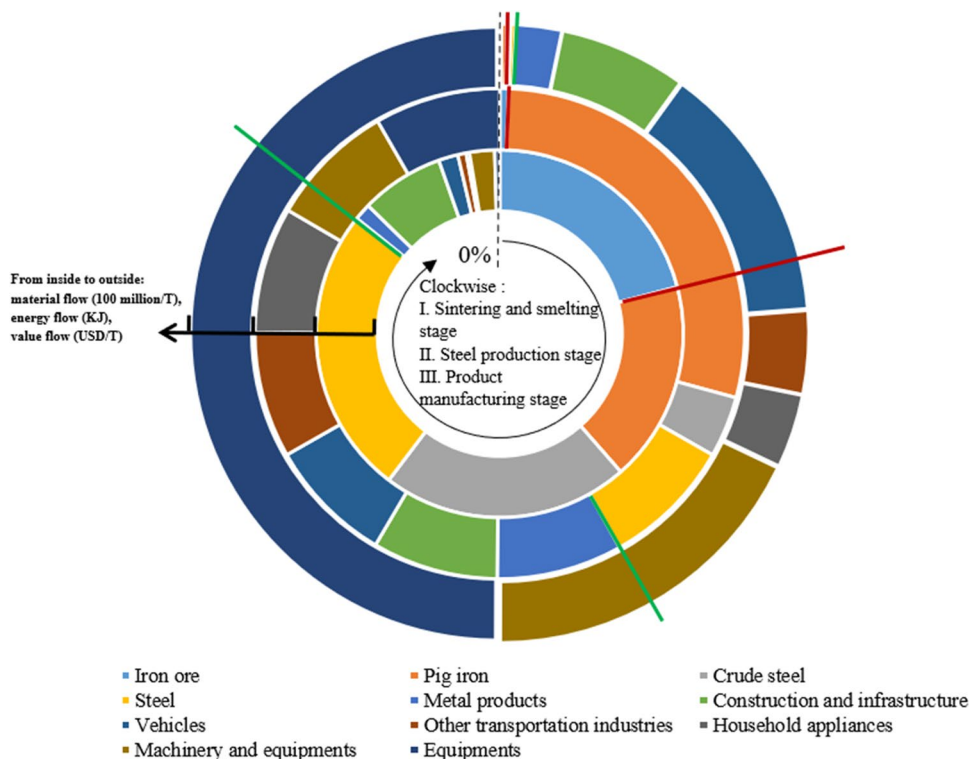
its high quality and low price, avoiding resource waste and pollution emissions. However, imports of iron ore by foreign countries cannot meet China’s production and living needs. The grade of self-produced iron ore is low and the output is small. Therefore, many front- and middle-end iron commodities must be imported to meet the demand for domestic production and consumption. Due to the complicated international situation, and in particular Covid-19, China’s iron ore imports are increasingly restricted. This will impede many industries, trade, and other fields, and this problem needs to be solved urgently.

(3) In China’s iron composite flow in 2018, 922 million tons of iron metal were put into production at the input end, and 684 million tons of iron were output at the output end, with an input–output ratio of about 1.35:1. Among them, the iron content of net exported iron-containing commodities was 127 million tons, most of which comprised iron-containing commodities in the middle and lower reaches of the industrial chain, such as steel- and iron-containing terminal commodities. As shown in Fig. 3, the price of iron-containing commodities downstream from the industrial chain is more than 100 times that of upstream commodities. This is caused by the added value brought by the higher industrial processing degree and science and technology. Although the price difference is huge, there is not much difference between the energy consumption of

iron-containing final commodities further down the industrial chain compared to upstream commodities. The production of pig iron and crude steel, the primary products in the upper reaches of the industrial chain, consumes a lot of energy and is environmentally harmful, with low transaction prices and low-cost performance. This has also led to the reluctance of all countries to import and export a large number of pig iron and crude steel. Although the production link of advanced products downstream from the industrial chain consumes little energy and the transaction price is high, China lacks high-end science and technology and innovation capacity. As such, it can only produce low-end ferrous terminal commodities, and the export price is lower than the import price.

(4) Currently, China imports iron-containing goods at high prices and exports them at low prices. The price of exported iron is even lower than the domestic circulation price. The reasons for this situation are as follows. First, China’s own innovation ability is insufficient. It lacks high-end technology, and the exported iron products do not have the added value brought by high-end technology. In addition, China needs to import high-end iron-containing materials and high-tech iron-containing commodities at high prices from Britain, the USA, Germany, and other countries with a more developed manufacturing industry and high-end technology. Second, large enterprises monopolize the

Fig. 3 Composite flow of iron throughout the life cycle



international market. Although the iron products made in China have a good reputation around the world, some large enterprises occupy the international market with similar goods at low prices and dominate the market share. Therefore, China can only lower the price to compete with them.

Conclusion

- (1) China's iron resources are scarce, in large part due to the lack of raw materials such as iron ore. China lacks high-quality iron ore resources and is dependent on imports of foreign raw materials. On this basis, a large number of iron-containing commodities are processed and manufactured in China, and many terminal commodities are ultimately exported. In this process, a large amount of energy is consumed to provide energy for iron and steel production, resulting in considerable emissions of CO₂, SO₂, and other pollutants. China thus remains a "world factory" and bears a heavy responsibility for environmental emissions and pollution for other countries in the world.
- (2) The processing loss of raw materials of iron resources in China is huge, with a total loss of about 150–210 million tons every year. The loss of beneficiation and iron-making of domestic iron ore accounts for more than 80% of the total loss. In 2018, China invested 922 million tons of iron ore at the iron and steel production stage, including 660 million tons of imported iron ore, and it lost 169 million tons of iron in the iron and steel production process. Iron loss mainly occurs in the iron production stage, and the resource utilization efficiency needs to be improved. Given the huge potential for the secondary utilization of scrap resources, on the one hand, the transformation process of electric furnaces in the iron and steel production stage should be accelerated to provide capacity guarantees for the secondary utilization of scrap resources. On the other hand, vigorously support for technological innovation is needed in order to improve the processing technology and processing means for iron and steel production such as mining, beneficiation, and metallurgy, and to reduce the loss of resources and the impact of scrap metal on the environment.
- (3) China is a large iron importer. In 2018, it imported 689 million tons of iron and exported 154 million tons of iron, less than one-third of the import volume. At the same time, there is a huge trade surplus in China's iron international trade, which reached nearly US \$632.1 billion in 2018. China's steel- and iron-bearing terminal products are the main commodity exports, whereas iron ore, pig iron, and crude steel are the main imports. In

2018, most of China's iron imports were raw materials. More than 98% of exported iron was in the form of iron-containing end-products and steel.

- (4) At present, China imports from abroad come with high prices, yet exports of iron-containing goods are sold at low prices. Technology needs to be introduced to allow for imports of high-end ferrous materials and high-tech ferrous commodities. In addition, China lacks market competitiveness in the international market and can only lower prices to compete for market resources.

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Author contribution All authors contributed to the study. The whole research was designed and guided by Jiansu Mao. Material preparation, data collection, and analysis were performed by Xinxin Chen and Guangjie Yu. The first draft of the manuscript was written by Xinxin Chen and Jiansu Mao, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability The datasets generated during and analyses during the current study are available in the United Nations Commodity Trade Statistics Database and China Customs.

Declarations

Ethical approval There is no research involving human participants or Animals in the study. The study was established according to the ethical guidelines of the Helsinki Declaration and was approved by the Human Ethics Committee of Beijing Normal University.

Consent to participate Informed consent was obtained from individual or guardian participants.

Consent for publication All the authors confirm that consent is obtained for all identifiable individuals should appear in the manuscript.

Competing interests The authors declare no competing interests.

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