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How Can China's Indium Resources Have a Sustainable Future? Research Based on the Industry Chain Perspective

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Abstract: Global competition and storage for indium resources are increasing. This paper uses substance flow analysis to quantify the flow of indium in China from 2000 to 2019 and discusses the problems facing China's indium industry chain. Over the past 20 years, China has mined more than 21,000 tons of indium from the lithosphere, and the accumulated indium content in imported ore is about 3600 tons. In the upper reaches of the industrial chain, the loss of indium exceeded 19,000 tons; in the middle reaches, due to technical barriers, China exported a large amount of indium at low prices and imported a large amount of *ITO* targets at high prices. The amount of indium in the imported targets exceeded 2100 tons; in the downstream, approximately 60% of the final products were exported abroad. China's cumulative output of recycled indium was about 630 tons, primary indium output was 5912 tons, and the cumulative inventory of indium reached 3200 tons. Therefore, increasing the recovery rate in the primary production stage, overcoming the technical barriers in the middle of the industry chain, and establishing an efficient recovery system are necessary measures to promote the sustainable development of indium resources and its industry chain.

Keywords: indium; substance flow analysis; industry chain; sustainable development

1. Introduction

Strategic emerging industries are based on major technological breakthroughs and major development needs, and they have an important leading role in the overall economic and social development and long-term development. Therefore, metal raw materials that meet the sustainable development of China's strategic emerging industries can be understood as critical mineral resources. It is the material foundation supporting the rapid and stable development of strategic emerging industries, and a safe and reliable supply is directly related to the healthy development of the national economy. In 2017, the United States president signed the "Federal Strategy to Ensure the Safety and Reliable Supply of Critical Minerals". The purpose was to ensure that the United States makes full use of domestic mineral resources to lead the global clean energy manufacturing and high-tech industries [1]. In addition to the United States, the European Union, Japan, the United Kingdom, South Korea, Australia and other countries have listed indium as a critical mineral since 2005 [2]. With the rise of new industries in the world, especially the rapid development of the information technology industry and new energy industry, indium resources will become the subject of fierce competition among countries [3].

The definition of China's superior mineral resources is mainly based on the classification of upstream resource endowments and exploration and mining capabilities. However, mineral resources do not exist in isolation. They are ultimately used to support and serve social and economic development through the processing and transformation of various

links in the industry chain. China is currently the world's largest producer of primary indium, accounting for more than 44% of the world's output [4]. However, China faces a series of problems, such as the disordered production of resources, the waste of resources, a lack of voice, the low-price outflow of primary products, low levels of domestic industrial technology, and low competitiveness [5]. Optimal management of advantageous mineral resources not only requires the improvement of the discourse power of upstream mineral resources, but more importantly, it solves the problems of each node in the industry chain and promotes the sustainable development of the industry.

Integrating the resource characteristics of indium and creating a valuable strategic mineral resource industry chain is of great practical significance for improving the security of strategic mineral resources and achieving national security. Substance Flow Analysis (SFA) provides a theoretical and methodological basis for the lifecycle research of the industry chain [6]. To solve the many problems facing China's indium resource industry, the fundamental way out lies in the construction of the industry chain. Thus, this paper uses the SFA method to analyze each link of China's indium industry chain, puts forward the problems, and proposes corresponding policies and suggestions to promote the sustainable development of China's indium resources.

2. Materials and Methods

The indium industry chain in this study refers to the entire industry chain, from the smelting and processing of indium raw materials to the final product, including four links: primary industry, deep processing industry, terminal application, and recycling industry. These correspond to the four stages of studying indium flow.

2.1. Scope and System Boundaries

The geographical boundary of the substance flow of indium analyzed in this study is mainland China. In terms of time, data from 2000 to 2019 were collected. As shown in Figure 1, this study focuses on the substance flow of indium based on four stages: primary production, manufacturing and fabrication, use, and waste management and recycling.

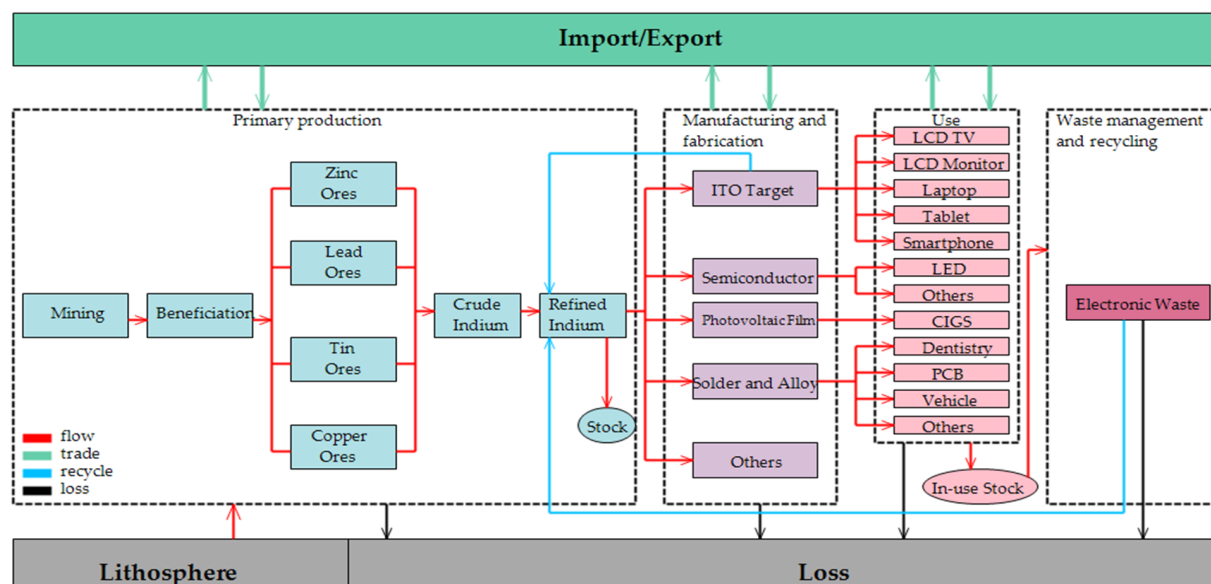**Figure 1.** Framework of indium flow in China mainland.

Indium is an associated mineral. The slag, dust, and ash produced during the smelting of zinc, lead, tin, and copper ores contain indium [7]. In the primary production stage, after the mining and beneficiation process, the indium present in ores is converted into refined indium. Some refined indium flows into the manufacturing and fabrication stage

for targets, semiconductors, photovoltaic film, solder and alloy, and others, while the unconsumed indium flows into "stock". The indium-tin-oxide (ITO) target is used in various electronic display products, including liquid crystal display (LCD) TVs, LCD monitors, laptops, tablets, and smartphones [8,9]. Indium is also used in the fields of semiconductors, photovoltaic (PV) films, solders and alloys, and others. In addition, indium is used in light-emitting diodes (LEDs), copper indium gallium selenide (CIGS), dentistry, vehicles, and printed circuit boards (PCBs) at the use stage [10,11]. This paper studies several representative indium-containing final products.

2.2. The SFA of Indium

This study focuses on the flow of indium in four stages. Depending on the content of indium in the ore, the content of indium in different fields and products and the quantity of products, the flow, trade, loss, and recycling can be calculated.

2.2.1. Primary Production

The initial input of indium for this study comes from the beneficiation of indium-bearing ores in the lithosphere, followed by mining. The recovery rates of indium in these two steps are 60% and 42% [12], respectively. Copper ores are often mixed with other ores, so the import and export volume of copper ores should be multiplied by 25% [13]. Since there is no data from lithosphere mining, it can be estimated based on the output and recovery rate of the four ores.

The input of indium in different ores can be calculated by the following equation:

$$I_p = \left(I_{import} - I_{export} + I_{output}\right) \times C_p, p = 1, 2, 3, 4 \tag{1}$$

where I_p is the amount of indium from different ores input into the system; I_{import} is the amount of ore imported into China; I_{export} is the amount of ore exported from China; I_{output} is the amount of ore output into China; C_p is the indium content in the four ores.

The approximate content of indium in different ores is shown in Table 1.

Table 1. The content of indium in different ores.

Concentrates	C_p	References
Zinc (p = 1)	0.005%	[14]
Lead (p = 2)	0.005%	[15]
Tin (p = 3)	0.004%	[16]
Copper (p = 4)	0.001%	[7]

The purification method most often used for crude indium is electrolysis, to remove the Cd and Tl; almost no loss of indium is involved. The purity of refined indium after purification is almost 100% [17]. Thus, this paper assumes that there is no loss of indium from crude indium to refined indium. China's annual output of indium comes from primary indium extracted from ore and recycled indium recovered from waste *ITO* target and electronic waste (e-waste). There are three output directions for refined indium: export, flowing into the next stage, and stock. The following equation shows the balance of refined indium:

$$I_{refined\ indium}^{production} + I_{refined\ indium}^{recycled} + I_{refined\ indium}^{net\ import} = I_{refined\ indium}^{consumption} + I_{refined\ indium}^{loss} + I_{refined\ indium}^{stock} \tag{2}$$

where $I_{refined\ indium}^{production}$ is the production of refined indium; $I_{refined\ indium}^{recycled}$ is the production of recycled indium; $I_{refined\ indium}^{net\ import}$ is the net imports of refined indium; $I_{refined\ indium}^{consumption}$ is the consumption of refined indium; $I_{refined\ indium}^{loss}$ is the loss of refined indium when manufacturing indium-containing materials; $I_{refined\ indium}^{stock}$ is the amount of refined indium flowing into the stock.

In the primary production stage, the efficiency of recovering indium from slag, dust, and wastewater is not high. Therefore, indium-producing enterprises produce a large amount of In-containing waste slag during the smelting process. The traditional solvent extraction process is mainly used. New technologies and new processes need to be further explored [18]. To meet the ever-increasing demand, in addition to the recovery of indium from high-grade materials, attention must also be paid to the recovery of indium from complex and difficult-to-handle indium-poor materials. The current annual output of zinc smelting in China exceeds 5 million tons. The zinc smelting slag alone contains a considerable amount of indium resources. Therefore, the recovery of indium from smelting slag is extremely conducive to expanding the limited indium resources [19].

2.2.2. Manufacturing and Fabrication

Refined indium is mainly used in the field of *ITO* targets, semiconductors, PV film, and solder and alloys. It is also used for scientific research and as an industrial additive.

LCDs need transparent and conductive electrodes, which are made from ITO. Indium is made into *ITO* films using a spattering process. Part of the scrap generated during this process is collected and recycled for secondary metal production [20]. In the sputtering process, the actual sputtering of the *ITO* film formed on the substrate accounts for only 30% of the total target materials. The remaining waste targets can be recycled and reused [21]. The total recovery rate of *ITO* waste target material reaches 93% [22]. At present, China's target demand is relatively great. However, the targets made in China are still unable to meet the requirements of the flat panel display industry, and the targets need to be imported from Japan and South Korea. With high technical added value and high profit margins, the ultra-thin, high-transparent, low-resistance, large-area high-end products used in LCD TVs, mobile phones, and laptops are monopolized by Japanese and Korean companies. The amount of indium manufactured in China for *ITO* targets is far less than the demand for *ITO* targets [23]. By 2018, domestic target companies gradually evolved into large-scale indium targets, and 4–5 companies use more than 10 tons of indium per year. At present, domestic targets are mainly small and medium-size targets. The output of large-size targets suitable for panels above the 6th generation line has begun to increase, and domestic target companies have begun mass production of large-size targets [24].

Various customs platforms do not classify *ITO* targets individually and thus do not record the annual import and export volume of *ITO* targets in China. Therefore, the net import of indium in the *ITO* target can be calculated by the following equation:

$$I_{ITO}^{net\ import} = I_{ITO}^{consumption} - I_{ITO}^{input} - I_{ITO}^{loss} \tag{3}$$

where $I_{ITO}^{net\ import}$ is the net import of indium in the *ITO* target; $I_{ITO}^{consumption}$ is the amount of indium in the *ITO* target consumed in the final product; I_{ITO}^{input} is the amount of refined indium applied to the *ITO* target; I_{ITO}^{loss} is the loss of indium in the *ITO* target when manufacturing end products.

Another important use of indium is in semiconductor materials for LEDs and laser diodes. InP, InAs, and InTe can be used as substrates for indium-based semiconductors.

Because of the increasing cost of fossil fuels, on the other hand, and to avoid the increased production greenhouse gases, clean energy currently receives considerable attention. As a new type of thin-film solar cell, CIGS is widely regarded by the market for its excellent conversion rate and low production cost. It is believed that it will become a major development route for photovoltaics in the future. With the development of thin-film solar energy included in the national strategy since 2015, many state-owned enterprises have invested in thin-film solar cells, and the production capacity of GIGS has increased on a large scale. In the future, with the advancement of clean energy advantages, photovoltaic film may become another important field that drives the consumption of indium after *ITO* targets [24].

Adding a small amount of indium to solder gives it better abrasion resistance and corrosion resistance. When indium is alloyed with metals such as bismuth, cadmium, lead, and tin, it lowers melting points. These alloys can be applied to different fields, such as the manufacture of glasses and turbine blades. Because these alloys have a low melting point, they can also be used in some safety equipment, such as indoor sprinkler systems. Therefore, indium is indispensable in the field of alloys and solders, but the amount of indium is relatively small in this field.

2.2.3. Use

Indium oxide has strong conductivity, heat reflection, and transparency. Indium oxide combined with 10% tin oxide can improve the performance of heat reflection and electrical conduction, but there is little improvement of the transparency of the oxide. Because of these special properties of indium tin oxide, *ITO* thin films have become ideal materials for converting electrical data into optical data in flat-panel displays and liquid-crystal displays. *ITO* film is made by the sputtering process of *ITO* target material in a vacuum environment. It is used in LCD TVs, LCD monitors, laptops, tablets, and smartphones.

The global implementation of energy saving and environmental protection promotes the gradual popularization of LEDs in the field of general lighting. The LED chip is made of group III-V compounds, such as Gallium arsenide (GaAs), Indium Gallium (InGaAs), and other semiconductors [25]. The content of indium in the LED is 0.021 mg/g [26]. For CIGS batteries, an average of 23.2 kg of indium is consumed for each additional 1 MW [27].

Indium is used as an additive in various final products of solders and alloys. The amount of indium used in PCBs and dentistry accounts for about 8.4% of solders and alloys (Licht et al. 2015) Vehicles also need indium for electronic components [28].

There is a certain loss in the process of manufacturing electronic products. In the manufacturing of display products and LEDs, the recovery rate of indium is 97% [29].

2.2.4. Waste Management and Recycling

The recovery of indium in electronic display products, on the premise of meeting the annual demand for indium, can effectively reduce the mining of primary ore and protect the environment.

Waste target is produced by sputtering of the target material, and scrap, cutting, and waste is produced during the target material forming process; thus, the use of waste target material to recover metal indium has become a main source of regenerated indium [30].

Recycling e-waste is another source of recycled indium. The e-waste recycling industry chain involves multiple stakeholders. At present, there are basically no third-party organizations or other industry associations participating in the e-waste recycling industry chain in China. However, informal recycling channels have become the main channels for e-waste recycling and processing [31,32]. The source of the recycling system is consumers, and consumers' attitudes and behaviors toward recycling affect the effectiveness of recycling directly. Consumer behavior also affects the amount of e-waste recycling. In addition to formal and informal channels, some consumers choose to leave scrap products idle at home [33].

This study focuses on e-waste containing *ITO* films from 2000 to 2019, including LCD TVs, LCD monitors, laptops, tablets, smartphones, and vehicles. This study considers the use of indium present in other fields as unrecyclable, given that it is used in very small quantities and is difficult to recycle. For example, the recycling of PCB is mainly focused on recycling the gold, silver, copper, and palladium, while other critical metals like indium are not being recycled [34]. Although waste LEDs contain a variety of metals with potential resource value, the content is low. It is difficult and costly to recycle them directly. Moreover, China's e-waste policies and regulations do not provide clear recycling and management regulations for waste LEDs [35].

According to the law of conservation of matter, the flow and stock of matter influence each other, and the increase in stock means that the inflow in the overall system exceeds the outflow [36,37]. This paper builds a StockBased model to calculate the resource potential of waste products in different times and spaces. The relationship is as follows:

$$S_t = P_t - P_{t-1} + O_t \tag{4}$$

$$O_t = \sum_{t=1}^{t} S_i \times g(i) \tag{5}$$

where S_t is the sales of the product (the inflow volume of the system) in year t; P_t is the stock of products in year t; O_t is the amount of product scrap (outflow); $g(i)$ is the life of the product.

The Weibull distribution can reliably describe the product life density distribution [38] and has the advantage of reasonable modeling, good data fitting, and convenient expression processing. The probability density function of the Weibull distribution is as follows:

$$f(t; u, v) = \frac{u}{v} \left(\frac{t - t_0}{v} \right)^{v-1} \exp\left[-\left(\frac{t - t_0}{v} \right)^u \right], \ t \geq t_0 \tag{6}$$

where t_0 is the initial year, u is the scale parameter, and v is the shape parameter.

Thus, u and v can be used to calculate the proportion of products scrapped in i years from the beginning of sales, that is, the life distribution $g(i)$. This study assumes that the lifecycle of LCD monitors and tablets is the same as that of LCD TVs and laptops. Therefore, their parameters are also the same. Table 2 shows the average lifespan and parameters of each type of product.

Table 2. Lifespans and parameters of different products.

Product	Average Lifetime	Scale Parameter	Shape Parameter	Distribution Type	Source
LCD TV	8.5	9.41	5.01	Weibull	[33]
LCD Monitor	8.5	9.41	5.01	Weibull	
Laptop	4.5	5.72	4.78	Weibull	[33]
Tablet	4.5	5.72	4.78	Weibull	
Smartphone	2.5	4	2.7	Weibull	[39]
Vehicle	12	9.8	3.6	Weibull	[40]

According to the changing law of products' number, its per capita holdings are comprehensively manifested in three states: growth, inflection point, and saturation, that is, maintaining an "S"-shaped growth trend and infinitely approaching a fixed maximum value (K value) in the long term, obeying the Logistic distribution [41]. This study introduces the distribution into the StockBased model to measure the data of the product's prospective holdings and scrap. The differential equation of Logistic distribution is as follows:

$$\frac{d_p}{d_t} = r \times p \times \left(1 - \frac{p}{k} \right) \tag{7}$$

where p represents the per capita holding of the product, r is the intrinsic growth rate, and K is the maximum growth rate. The solution of this differential equation is as follows:

$$p_i = \frac{K}{1 + \exp(-r_i + C)}, i = 1, 2, 3 \ldots \tag{8}$$

$$C = \ln\left[\frac{p_0}{K - p_0} \right] \tag{9}$$

where p_0 represents the per capita possession in the initial year, and i is the time difference between the selected year and the initial year.

Both the number of the urban and rural population and the average household size in this study are from the "China Statistical Yearbook". The output and sales of the semi-finished products and final products come from the "China Nonferrous Metals Industry Association", relevant report websites, and the collation of some scholars [42]. The output of tablets cannot be found directly. So, this study regards the sum of export volume and sales volume as output. The trade volume of products comes from "China Customs" and the "United Nations Comtrade Database".

Regarding the content of indium in LCD screens, some scholars have done relevant research. The average content of indium in each LCD TV, LCD monitor, and laptop is 0.6 g, 0.4 g, and 0.4 g [43]. The content of indium in the LCD screen is 380 mg/kg–410 mg/kg [44]. The weight of the phone LCD screen is 0.02 kg [45]. This study assumes that the content of indium in the LCD screen is 400 mg/kg, and the weight of the tablet screen is twice that of the phone. The average content of indium in cars is 0.3 g [46].

The hypothesis of K value and the recovery rate in this study refers to recent related research [36]. According to statistics from the China National Resources Recycling Association, in 2013, the proportion of formal dismantling of e-waste in China was 36.3%. In the same year, the number of scrapped cars flowing into formal recycling channels accounted for only 40% [47]. The content and recovery rate of indium in products are shown in Table 3.

Table 3. The content and recovery rate of indium in products.

Product		K	Average Content (g)	Regular Recovery Rate Increase (%)	Regular Recovery Rate (%)	Utilization Rate (%)
LCD TV	Urban	1.4 (per household)	0.6			
	Rural	1.2 (per household)				
LCD Monitor	Urban	1.0 (per household)	0.4			
	Rural	1.0 (per household)				
Laptop	Urban	1.5 (per household)	0.4	2	80	95
	Rural	1.5 (per household)				
Tablet	Urban	1.2 (per household)	0.016			
	Rural	1.0 (per household)				
Smartphone	Urban	1.0 (per capita)	0.008			
	Rural	0.85 (per capita)				
Vehicle	-	0.21 (per capita)	0.3			

3. Results and Discussion

3.1. Overview

Figure 2 presents China's indium stocks and flows along its lifecycle from 2000 to 2019. In the past 20 years, the amount of indium in ore mined in China was approximately 21,335.24 tons. In addition to the import of ore, the input of the entire system reached 24,980.32 tons. In the primary production stage, the loss of indium reached 19,112.85 tons, accounting for 77% of the input. From 2000 to 2019, China's cumulative production of primary and recycled indium was 5912 tons and 630.57 tons. Among this, 30% was exported, 20% was used for consumption, and 49% flowed into stock. In the use stage, the amount of indium in exported commodities reached 1681.77 tons, accounting for around 60% of the input in this stage. In the past 20 years, China recycled 78.86 tons of indium from electronic waste.
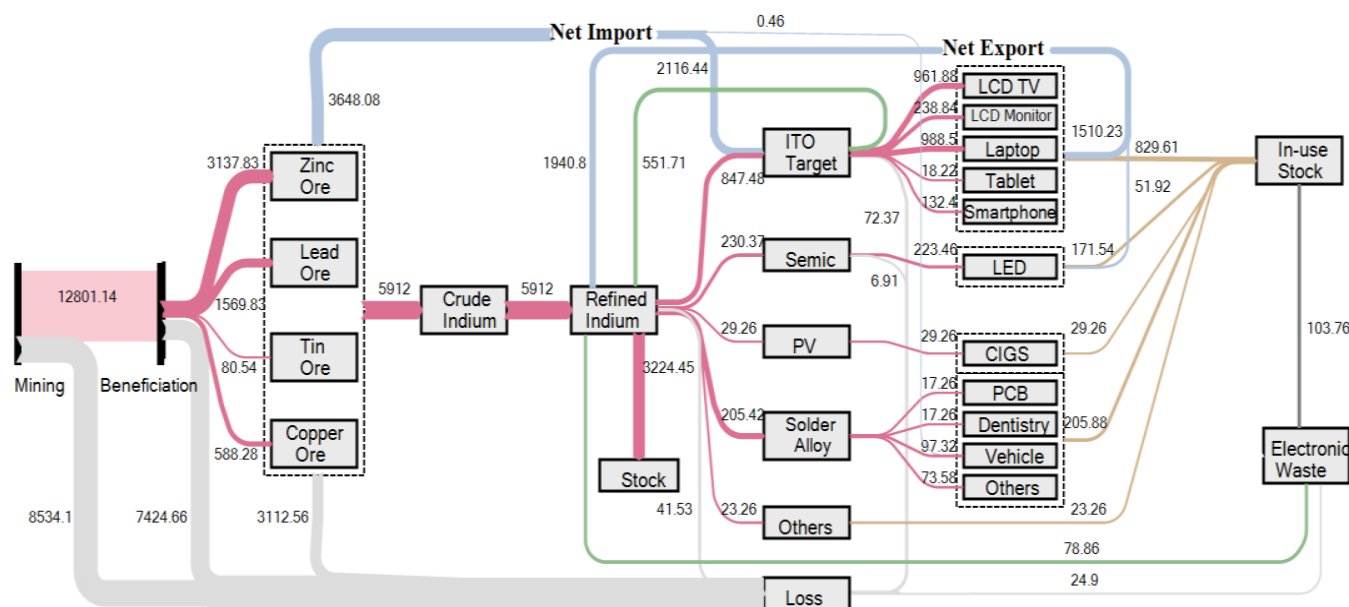
Figure 2. China's indium stocks and flows: 2000–2019 (unit: t).

3.2. China's Reliance on Indium Resources Gradually Shifts to the Upstream of the Industry Chain

In the 21st century, while China is becoming a major exporter of foreign trade, its trade policy on scarce minerals has undergone a fundamental change, from encouraging exports to planning exports. Figure 3 shows the evolution of the trade structure of each link in China's indium industry chain in the past 20 years. As Figure 3a depicts, China's domestic consumption of indium ore first increased and then declined, while the amount of ore imports gradually increased. The net export of indium continued to increase, reaching 368 tons in 2007. Since 2007, China has implemented quota license management for indium exports. China's export of indium has decreased. During the Pan-Asian incident around 2013, China purchased and stored a large amount of indium. Later, with the development of global liquid crystal technology, China imported a certain amount of indium while exporting indium for the repurchase of *ITO* targets to reduce the net export volume of indium (Figure 3b).
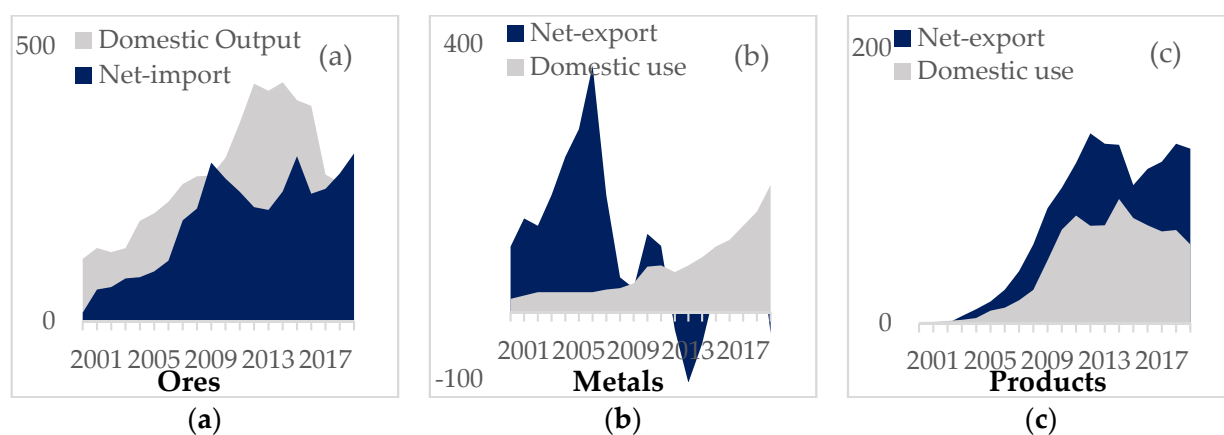

Figure 3. The trade pattern of indium in industry chain (unit: t): (**a**) output and trade of indium in four kinds of ores; (**b**) use and trade of indium; (**c**) use and trade of end products.

3.3. Technical Barriers Have Made China the Largest Smelting and Processing Plant

Developing countries such as China, Russia, and India have advantages in the number of minerals therein or their geography; they want to actively integrate into the global critical metal industry chain. However, technical barriers have greatly reduced their ability to control the industry chain. As a critical material for the manufacture of display products, *ITO* target has been monopolized by Japan and South Korea for its key technology.

Figure 4a shows the global industry chain division of indium and the trade price of indium and *ITO* targets, with the dashed curve indicating the countries involved in the corresponding industry and the solid curve representing the price of indium and targets. The production capacity and output of China's *ITO* target materials are in a period of growth and will become the main force in the global target production increase in the future [24]. Therefore, it can be seen that the consumption of *ITO* targets produced in China is increasing, while the import is slightly decreasing (Figure 4b). Figure 4b shows the consumption of indium used to manufacture *ITO* targets in China and the amount of indium in imported *ITO* targets. However, in the past 20 years, *ITO* target production technology has been monopolized by developed countries. China's indium industry chain was interrupted due to *ITO* targets. China exported large amounts of indium and imported *ITO* targets from countries such as Japan and South Korea at higher prices to meet the downstream market. It is also for this reason that China has accumulated about 3200 tons of indium stocks. In the upper reaches of the indium industry chain, China had a large number of indium resources and occupied a large share of the world. China produced a large amount of low-value metal and exported it abroad, and then repurchased a large amount of high-value *ITO* targets for manufacturing display products. Figure 4c shows China's share of In-containing products in the world at all stages and the corresponding prices of the products. The output of high-value end-products had a low market share. In the middle reaches, China was "stuck" by developed countries, resulting in an asymmetric output of resources and funds.
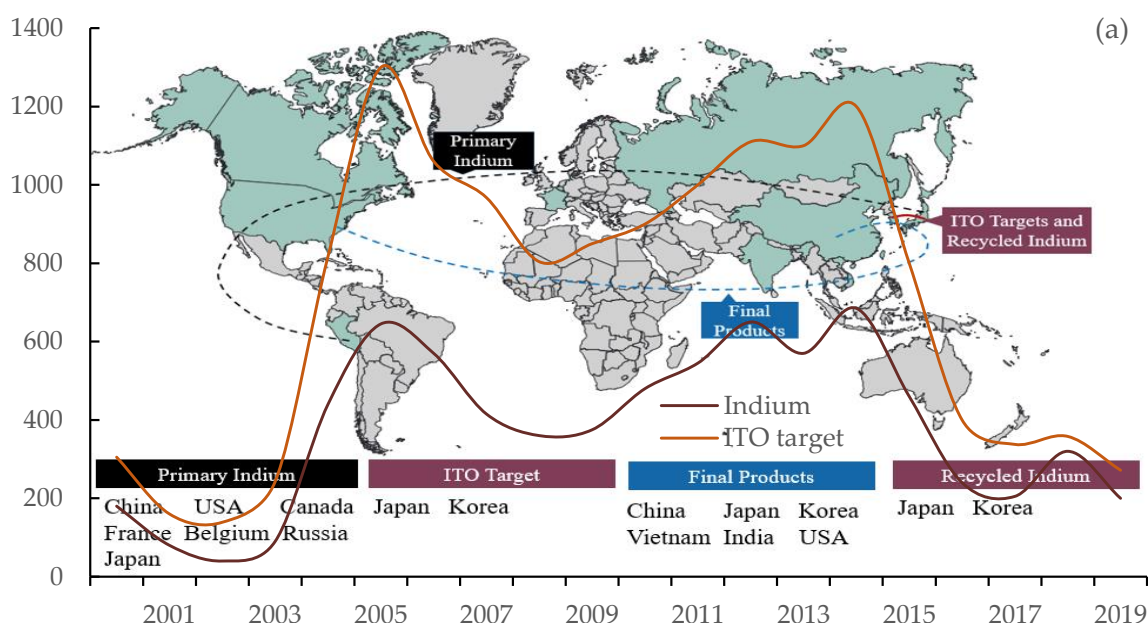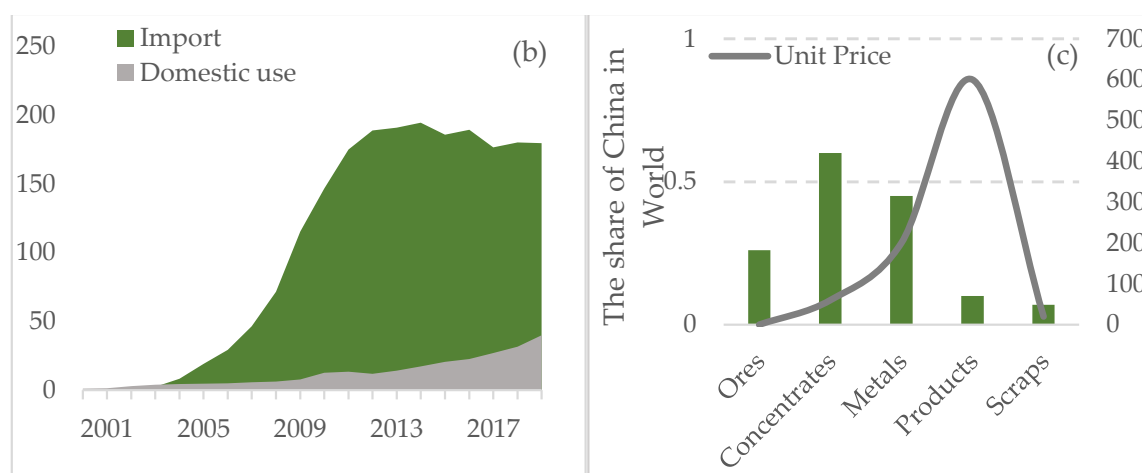

Figure 4. *Cont.*

Figure 4. Trade and price of In-containing products in China: (**a**) the division of labor in the global indium industry, the export price of indium in China, and the import price of targets (unit: dollar); (**b**) quantity of domestic and imported *ITO* target indium (unit: t); (**c**) China's share of In-containing products in the world at all stages (unit: dollar).

3.4. Domestic Demand and Exports Stimulate the Development of China's Indium Industry

As the global demand for large-size *ITO* target materials increases, and China gradually breaks through the production of *ITO* target materials, the display industry will promote the consumption of indium in China in the future. According to the forecast of the International Energy Agency, PV will provide 16% of global electricity by 2050, and China has a 35% share of total PV electricity production [48]. The development of the PV industry will also stimulate the consumption of indium in China. Figure 3c shows the use and trade of In-containing products in China. Domestic and foreign markets show great demand for China's indium-containing products, and the future consumption of downstream markets will continue to promote the development of China's indium industry.

3.5. China's Indium Recycling Industry Has Great Potential

Figure 5 shows the output, sales, export, and import of China's display products. It is converted into the amount of indium based on the indium content of the product.

From 2000 to 2019, the output, sales, and export volume of China's display products increased year by year. China is also a big consumer of display electronics products, after Japan and South Korea. In addition to meeting foreign demand, a large number of products are sold domestically. Therefore, from ore mining to product scrapping, a large amount of In-containing waste is generated in the entire industry chain. Figure 7b represents the amount of indium in the unrecycled waste generated during the production process and in the scrapped product that did not enter the regular recycling channel from 2000 to 2019. As of 2019, the indium resources in the eight products shown in Figure 6 exceeded 800 tons in China's social in-use stock. In addition to the increase in output and sales, one of the reasons for the increase in China's annual product in-use stock is that many obsolete display products that have not entered the recycling channel.
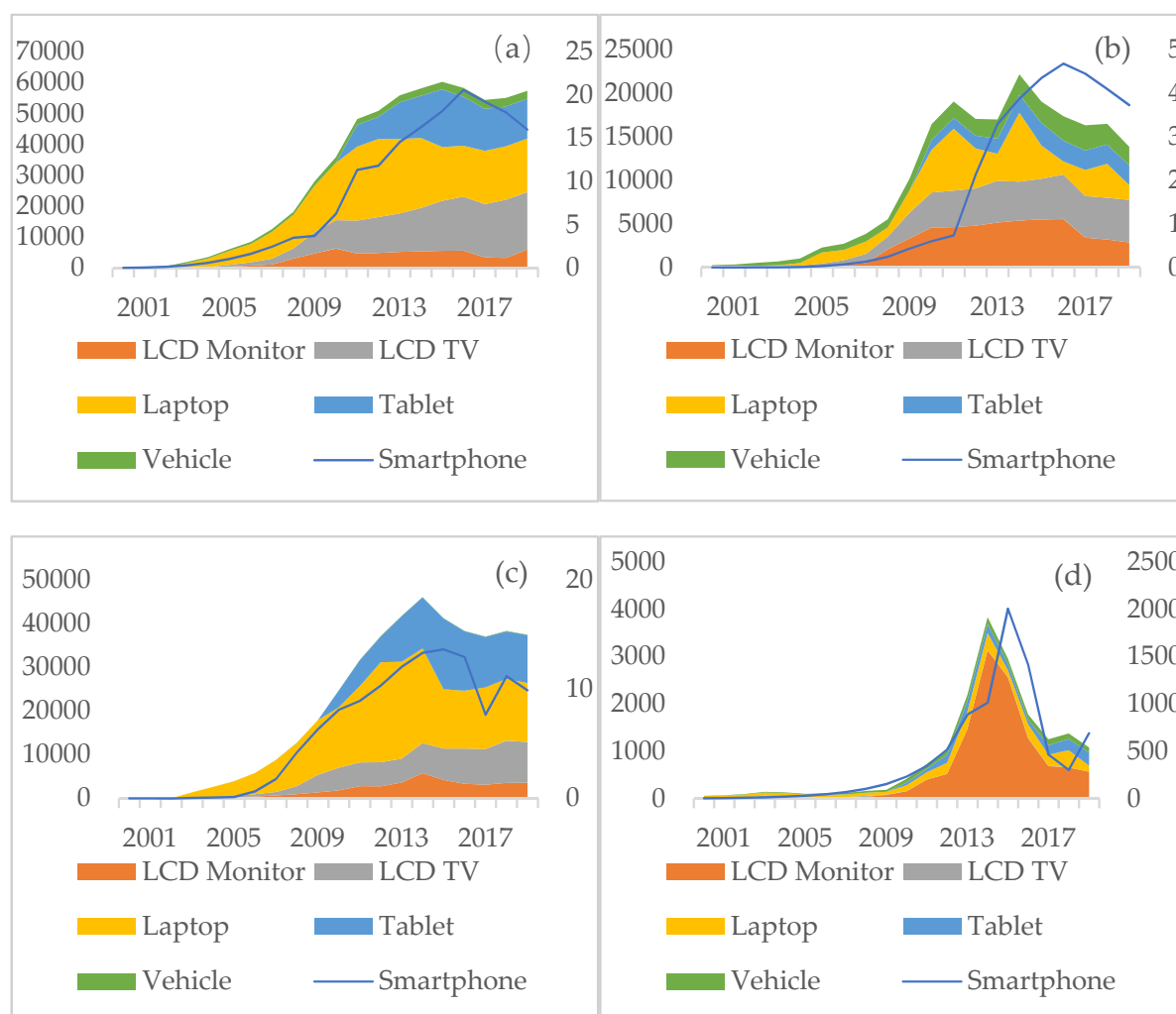
Figure 5. The output, sale, export, and import of display products (the main ordinate unit is 10k, the secondary ordinate unit of (**a**–**c**) is 0.1 billion, and the secondary ordinate unit of (**d**) is 10k): (**a**) output of display products from 2000 to 2019; (**b**) sales of display products from 2000 to 2019; (**c**) export of display products from 2000 to 2019; (**d**) import of display products from 2000 to 2019.
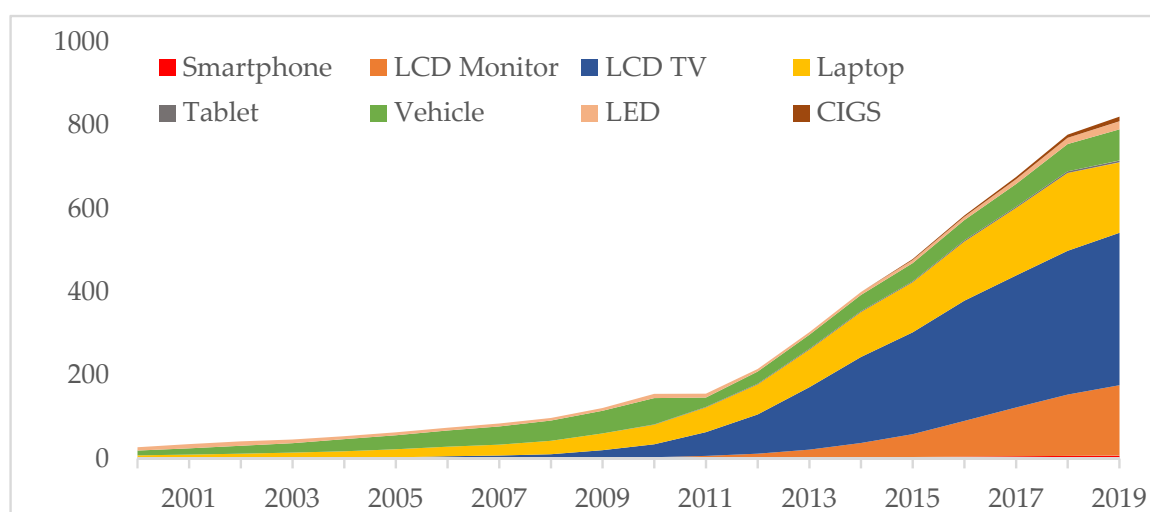
Figure 6. In-use stock of indium in China from 2000 to 2019 (unit: t).

Indium recycling technology is also monopolized by Japan and South Korea (Figure 4a). Figure 7 reflects the gap between China and the world's recycled indium production. A large amount of waste indium was generated during the smelting and scrapping stage, and only a small part was recycled. China's recycled indium production only accounts for about 10% of global recycled indium production (Figure 7a). However, after calculation, from 2000 to 2019, a total of more than 19,000 tons of indium in China was not recycled due to production losses and scrap (Figure 7b). Therefore, the recovery potential of indium in China is huge.
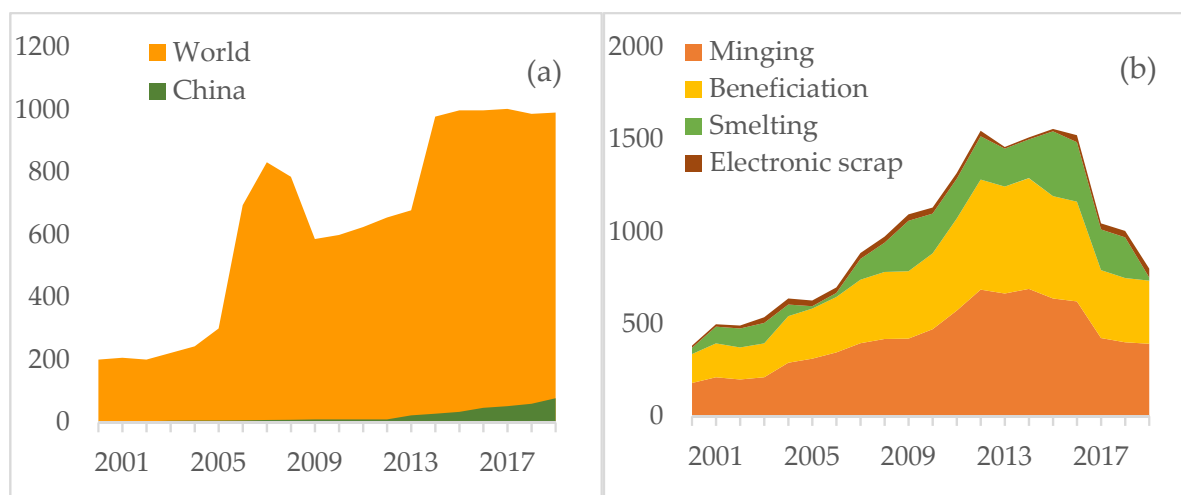
Figure 7. The development status and potential of China's recycled indium (unit: t): (**a**) comparison of China and the world's recycled indium output from 2000 to 2019; (**b**) China's indium scrap from 2000 to 2019.

4. Conclusions

Indium is an important resource for the development of China's strategic emerging industries. China is a major supplier of indium resources, but industrial development faces many problems. This study uses the method of SFA to study the flows and stocks of indium in China from 2000 to 2019. This study identified the problems faced by each link of China's indium industry chain, clarified China's role in the global indium industry, and identified paths toward the sustainable development of China's indium resources. This study will lay the foundation for future indium resource supply and demand analysis, environmental management, and global indium resource flow research. The key conclusions and suggestions are as follows:

(1) Encourage scholars to do research on the global dependence of indium to formulate a scientific and reasonable strategy for indium resources.

Although China is the country with the largest indium resource reserves and primary indium production, a large part of the ore required for the production of refined indium depends on foreign countries. Under the premise that many countries around the world regard indium as a critical metal, there is a lack of research on the dependence of each country. When the upstream industry is greatly affected by foreign countries, the entire industry chain will be affected to varying degrees. Therefore, a detailed global indium flow and trade network analysis is needed to illustrate this dependence, so as to formulate a scientific and reasonable strategic plan for indium resources.

(2) Encourage midstream enterprises to overcome technical difficulties to reduce the large outflow of China's indium resources and digest stock.

The downstream market demand of China's indium industry chain is huge, so it is necessary to overcome the technical difficulties of midstream products. From a strategic level, the government should use policies, funds, and market support to build key enter-

prises in *ITO* targets and CIGS films. While reducing the asymmetric outflow of capital and metal resources, it also addresses the accumulated indium resource stocks.

(3) Guide the entire industry chain to recover resources, establish an efficient recovery system, and improve the efficiency of indium resource utilization.

The upper end of the industry chain has gradually increased imports of foreign In-containing ores; the production of recycled indium can reduce this dependence. China's indium recycling industry is moving in a backward direction. At the end of the industry chain, fewer scrap products enter the formal recycling channels, and the recovery rate of indium in the recycling and primary production stages is low. Although China is the country with the largest primary indium production in the world, China's share of the world's indium reserves is limited, and China may lose its right to speak because it continues to lose a large number of indium resources. Chinese manufacturers and recyclers urgently need to recycle the In-containing waste accumulated in the past, increase the yield rate in indium extraction and refinery, and reduce the loss of indium resources. At the same time, policies should increase people's awareness of recycling, guide stakeholders to establish an effective recycling system, and improve the efficiency of indium resource recycling.

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