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Global Lithium Flow 1994−2015: Implications for Improving Resource Efficiency and Security

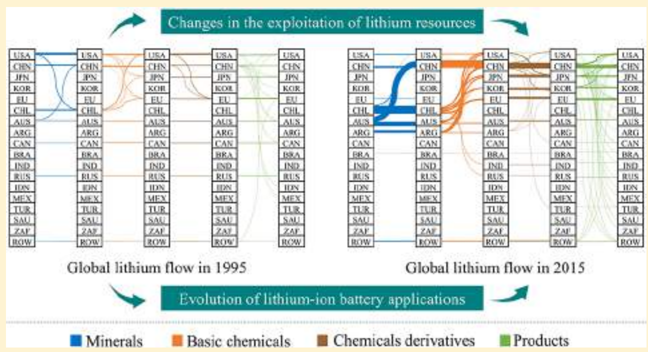
Xin Sun,[†] Han Hao,[*,†,‡] Fuquan Zhao,[†] and Zongwei Liu[†]

[†]State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, P. R. China

[‡]China Automotive Energy Research Center, Tsinghua University, Beijing 100084, P. R. China

Supporting Information

ABSTRACT: Lithium has been widely recognized as an essential metal for next-generation clean technologies. With the aim of identifying opportunities for improving lithium resource efficiency and security, this study establishes a long-term trade-linked material flow analysis framework to analyze lithium flow throughout the technological life cycle and across national boundaries during the 1994−2015 period. The results indicate that with broader purposes identified, global lithium production and consumption experienced rapid growth over the past decades. A widely distributed, actively functioning lithium trade network has been established, with the United States, China, the European Union, Chile, and Australia playing essential roles. Global lithium in-use stock, which is mainly embodied in ceramics and glass, reached 29 kilotons in 2015. The lithium stock contained in battery-related applications, together with the huge potential production of stock in future decades, represents a major opportunity for secondary lithium recovery. In the context of intensive international trade, international cooperation on lithium waste management is extremely important. It is also suggested that there is a high risk of lithium shortage for countries with strong dependence on lithium import. The establishment of domestic lithium reserves may be an option for these countries.



1. INTRODUCTION

Global lithium production and consumption have experienced steady growth since the 1950s.[1] In the 1990s, lithium was mainly used for glass production, ceramic production, and aluminum smelting. Lithium applied in these three applications accounted for approximately 38% of the total lithium consumption. After the 2000s, the utilization of lithium in lithium-ion batteries (LIBs) gained prominence owing to their high energy density and durability. Gradually, LIBs have become widely used in consumer electronics and electric vehicles.[2] Due to the rapid development of these two industries, lithium consumption has skyrocketed over the past few years with a 6% annual growth rate.[3] Lithium consumption reached 31 kilotons (kt) in 2015, i.e., a 4-fold increase over the 1994 level.

The rapid growth of lithium consumption has raised concern regarding its resource security and utilization efficiency. Zeng et al. forecasted the future lithium demand in China until 2030. Their study ignored the impact of technical and economic factors on the available lithium reserve within the time boundary. By comparing the current lithium reserve with prospective cumulative lithium consumption, they found that with the rapid increase in lithium use, the lithium recycling rate needed to be at least 90% to reach the domestic supply demand balance.[4] Miedema et al. investigated lithium availability for electric vehicles (EVs) in the European Union (EU). Their study revealed that even if the lithium resource was not a restricting factor, the limited flow rate of LIB raw materials into society might cause an undersupply of more than 0.5 million tons by 2045.[5] Vikström et al. estimated the ultimately recoverable lithium reserve using complete statistics of all known lithium deposits. On the basis of the estimation, the annual global lithium extraction was modeled from 1900 to 2100. These authors found that if LIBs kept being used as the main power storage device in EVs, then the lithium supply would not be able to fulfill the EV deployment target proposed by the International Energy Agency.[6,7] The results of these studies indicate that further efforts are needed in lithium resource management.

Material flow analysis (MFA) is one of the most widely used approaches to address these long-term issues. Thus far, numerous MFA studies have been conducted in surveys on lithium flow. Ziemann et al. established the first global lithium flow model that included raw materials production, product manufacture and use for the year 2007.[8] This global lithium flow framework laid the foundation for further lithium MFA studies. Hao et al. analyzed lithium flow for the world's largest

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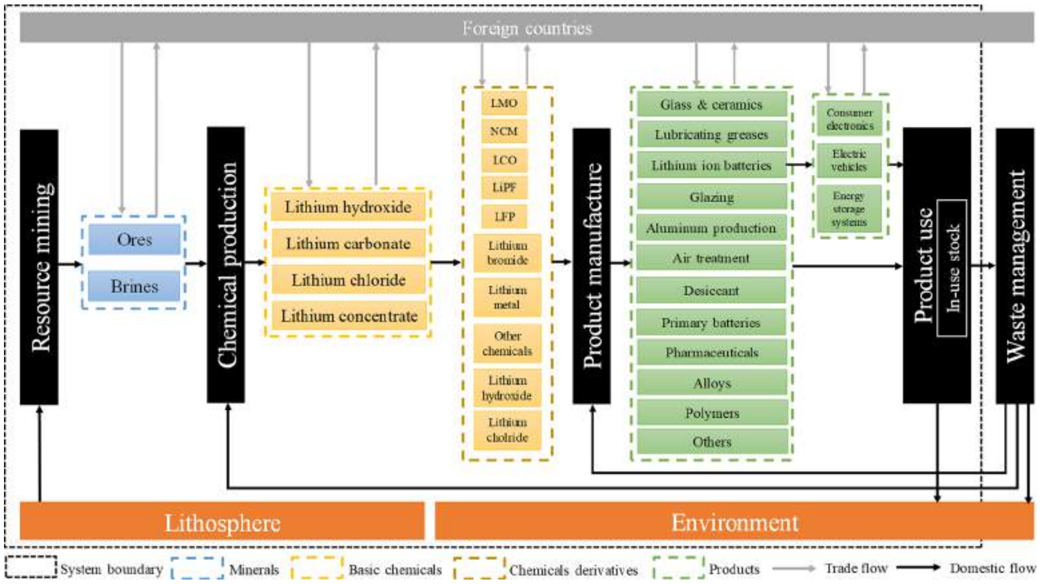

Figure 1. Processes and flows throughout the lithium life cycle. Note: The black rectangles represent various stages; the colored rectangles represent commodities covered; the objects outside the system boundary (black dotted box) are not covered in this study.

lithium consumer, China, for the year 2015.[9] Their study revealed that the growth of the EV market would possibly increase China's dependence on lithium import, which aroused supply security concerns. Our previous study traced the global network of lithium production and trade in 2014,[10] representing a further step to observe global lithium flow. Significant studies have been conducted based on the static MFA method. However, due to the limited time frame, some important factors, such as the lithium stock, remain unclear.

According to Muller et al.,[11] retrospective dynamic MFA work is essential to trace the past stocks and flows of a certain material. Many studies have chosen this approach to analyze various metals such as steel[12] and copper.[13] These studies were designed within specific geographical boundaries, either a specific country or the whole world. However, the resource trades among the entities within the system are normally ignored. Under such circumstances, the resource distribution routes and the impacts of trade partners cannot be observed. To fill this gap, this study establishes a dynamic trade-linked MFA framework throughout the anthropogenic life cycle and across national boundaries. By applying this model, the quantities, qualities, transformation, transport, and locations of lithium-containing commodities accumulated in the past can be determined. The aim of this study is to determine: (1) the lithium flow on the global scale over the past two decades and (2) the changes in lithium flow over time and the associated driving factors.

2. MATERIALS AND METHODS

To quantitatively study the stocks and flows of various commodities, the lithium life cycle is divided into five stages: resource mining, chemical production, product manufacture, product use, and waste management, as shown in Figure 1. By following the basic principle of MFA, the input flows (consumption of raw materials) equal the output flows (domestic supply of downstream commodities) in the first three stages assuming no commodities are stored. The explanations of the commodities and their relationships can be found in the Supporting Information (SI). The lithium contents of all commodities are calculated by using the conversion coefficients. The lithium content is measured by using the unit of lithium metallic equivalents.

In the product use stage, the net addition to stock is the difference between inflows (consumption) and outflows (scrappage). The stock consists of two parts: in-use stock and hibernating stock.[14] The hibernating stock refers to stock that is no longer in use but remains unscrapped. The impact of hibernating stock is not significant, and hibernating stock data are highly insufficient. Consequently, the stock in this study includes only in-use stock, which is calculated using a "top-down" approach,[11] following eq 1. The inflows can be calculated by using the historical sales data of variable commodities. For the outflows, the situation is much more complicated due to the considerable variation in commodity classification. There are numerous existing models for the calculations of waste electrical and electronic equipment, whereas models for other products are rare. To unify the calculation, the outflows are quantified using the "batch-leaching" method, which is generally used for estimating the generation amount of retired products.[15,16] This method needs the input data of lifespans. Despite the fact that the lifespan of each type of commodity differs across different areas and times, this study uses the average lifespan of each type of commodity incorporated from relevant studies.[4,5,15,17−19]

$$ST_i = ST_{1993} + \sum_{k=1994}^{i} (IN_k - LO_k) \tag{1}$$

$$IN_k = \sum CO_{x,k} \tag{1a}$$

$$LO_k = \frac{\sum OW_{x,k}}{n_x} \tag{1b}$$

$$OW_{x,k} = CO_{x,k} + ST_{x,k-1} \tag{1c}$$

where, ST_i is the in-use stock in year i; IN_k is the inflow in the product use stage in year k; LO_k is the loss in the product use stage in year k; $CO_{x,k}$ is the consumption of product x in year k;

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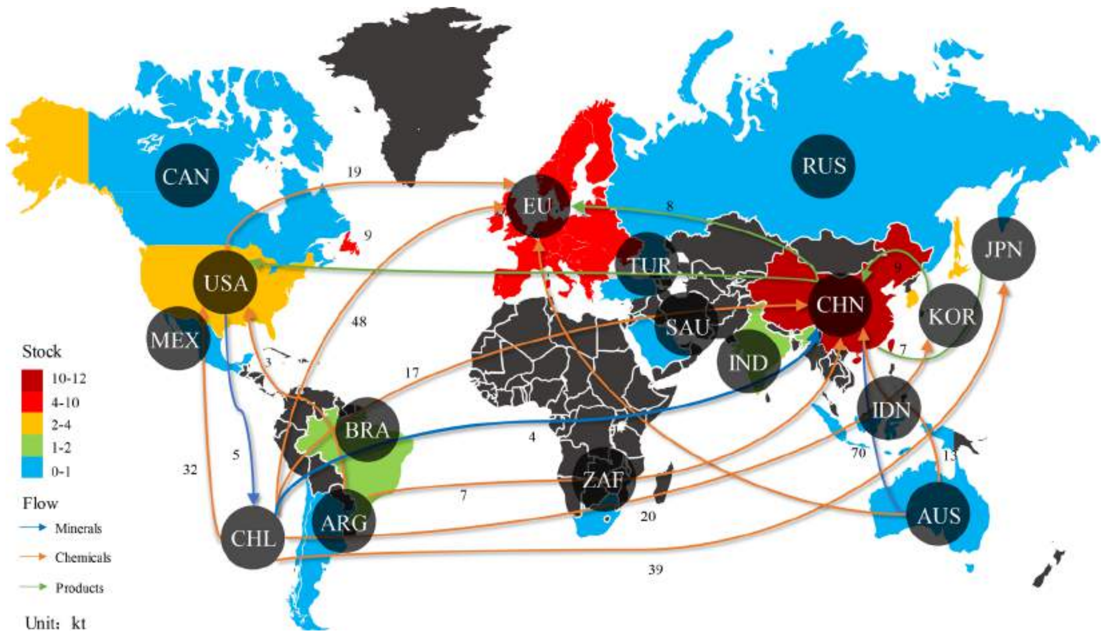

Figure 2. Major global lithium trade flows and stocks. Note: The lines in this graphic represent the trade flows of various commodities. The numbers associated with the lines represent the flow volumes. The colors from blue to red indicate the abundance of lithium in-use stock in each country. The countries with black color are the ROW. All values have the unit of kt lithium metallic equivalent.

$OW_{x,k}$ is the ownership of product x in year k; and n_x is the average lifespan of product x.

For the end-of-life products, only LIB-related products can be recycled using current technology and prices. Currently, the recycling of these products is aimed mainly at the recovery of cobalt and nickel elements.[20] Due to these facts, the recycle rate of lithium is lower than 1%. However, this information is unavailable in many regions.[21] Consequently, the waste management process and scrap flows of lithium are ignored in this study.

The system boundary in this study is characterized by spatial and temporal boundaries. Regarding the spatial boundary, the Group of Twenty (G20) countries, as the global leading economic and political powers, is considered. Moreover, Chile is also considered in this study due to its dominant role in lithium resource production. These countries are estimated to account for 97% of global lithium production and 99% of the international lithium commodity trade.[10] With the consideration that other countries have very limited influence on the global lithium flow, the G20 countries and Chile are considered to reflect the whole world's lithium activity. The rest of the world (ROW) is treated as a whole entity. The temporal boundary is 1994−2015, which can sufficiently reflect the development of lithium utilization in modern industry.

The data in this study can be generally categorized into two groups: the production data and the international trade data. The production data of lithium minerals and primary chemicals were obtained mainly from the mineral yearbooks of the United States Geological Survey[3] and several relevant studies.[22−28] The lithium-containing products production data were compiled from national statistical yearbooks[29−31] and several research institutes.[32−46] The international trade data were mainly adopted from each country's customs database,[30,47−49] the United Nations Commodity Trade Database,[50] the Eurostat database[31] and other trade statistics institutes[51−53] using the customs code of a specific commodity. Although we have high confidence in the effective coverage of existing data sources, the obtained data are not sufficient to calibrate all lithium flows for the selected countries. Thus, further data treatment was conducted based on several reasonable assumptions. The details of the data treatment are described in the SI.

3. RESULTS AND DISCUSSION

3.1. Global Overview. The overview of global lithium flow is shown in Figure 2. Here, we sum all the same forms of trade flows over the past 21 years. To simply the graphic, Figure 2 shows only the relatively significant flows. The lithium mineral trade occurred mainly in the United States (U.S.), China, Chile, and Australia. Among these countries, Chile and Australia were the major exporters. The maximum mineral trade occurred between Australia and China in the form of lithium ore (70 kt), followed by the brine trade between the U.S. and Chile (5 kt). Regarding the chemicals, the major trade flows were exports from Chile, Australia, and Argentina to all other areas of the world. The exports from Chile were mostly in the form of lithium hydroxide. Lithium concentrates were the major form of export commodities for Australia. Argentina exported the maximum amount of lithium chloride. The largest trade flow originated from Chile to the EU (48 kt), followed by imports from Chile to Japan (39 kt). The products flows were mainly in the form of LIBs. The largest flow was LIB export from Korea to China (9 kt). The trade flow originated from China to the U.S. (9 kt), followed by the EU (8 kt).

According to the computations, global lithium in-use stock reached 29 kt in 2015 with an annual growth rate of 15% since 1994. Most of the stock was concentrated in five countries, China (37%), the EU (22%), the U.S. (12%), Japan (10%), and Korea (7%). The huge stock is a reflection of the mass consumption in these countries. Among these countries, the stock in Japan mainly originated from glass consumption, compared with consumer electronics in Korea. China, the EU, and the U.S. occupied the leading positions for the consumption of all commodities. The stock did not exceed 1 kt for the remaining countries. A breakdown by product

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category indicated that the lithium stock embodied in glass and ceramics represented the largest share in 2015 (59%). EVs were the fastest growing lithium stock, with a growth rate of 396% on average, which far exceeded the total lithium in-use stock growth rate.

3.2. Shifts in the Lithium Flow Network. The global lithium flow networks are shown in Figure 3. Three representative years, i.e., 1995, 2005, and 2015, were chosen as examples. The detailed production and trade of each country is shown in Figures S1 and S2 in the SI. The results indicate that the lithium network covered an increasing number of countries over time, resulting in an increasingly complicated lithium network. The U.S., China, the EU, Chile, and Australia retained their dominant positions in the global lithium network. Chile and Australia were the major upstream suppliers of lithium, and the U.S., China, and the EU were the major consumers of lithium commodities.

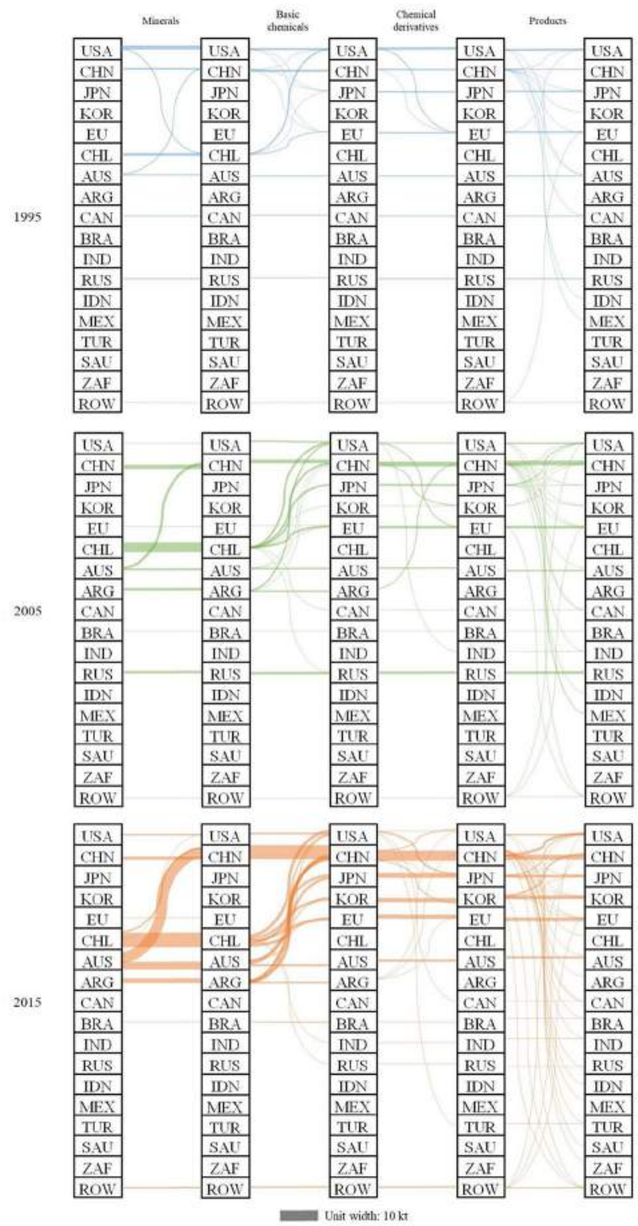

Figure 3. Lithium flow sankey diagram for 1995, 2005 and 2015. Note: The blue, green, and orange lines represent lithium flows in 1995, 2005, and 2015, respectively. The line width represents the flow volume. The width of the black line at the bottom of the figure represents 10 kt as a reference. To retain the mass balance of each stage and to simplify the graphic, the flows of LIB derivatives are not shown.

In the resource mining stage, the U.S. was the largest producer and exporter of lithium minerals from 1994 to 1996, accounting for 32% of the global production on average. Lithium-rich brine resources were found in Chile from 1997 to 2012. Chile became the largest producer of lithium minerals, most of which were used for domestic chemical production. After 2013, Australia replaced Chile as the largest producer, with the largest capacity of lithium ore, and was the largest lithium mineral exporter from 1997 to 2015.

In the chemical production stage, Chile produced the largest amount of basic lithium chemicals from 1994 to 2012. After 2012, China became the largest producer as a result of the combination of domestic and imported lithium mineral supply. Chile continued as the largest exporter of lithium chemicals, similar to the EU as the largest importer, followed by China. China, with an average growth rate of 8% since 1996, replaced the U.S. as the largest producer of chemical derivatives.

In the product manufacturing stage, China continued as the world's largest producer of lithium-containing products. This huge capacity resulted from the contribution of Chinese firms as well as the foundries of foreign countries. The EU followed China in production with its outstanding manufacturing industries, and Japan and Korea gradually became the major producers and exporters of lithium in products due to the rapid development of the domestic electronics industry. A comparison of the global lithium flow network in different years indicated that changes in the exploitation of lithium resources in various countries and the evolution of battery-applications were the main driving forces behind the shifts in the global lithium flow network.

3.3. Regional lithium flows. Figure 4 shows the lithium flow at the country level from 1994 to 2015. The U.S., China, Japan, Korea, the EU, and Chile were chosen as examples. The lithium flow in other countries is presented in Figure S3 in the SI. The lithium-related industry structure of each country can be observed in these regional level diagrams. Only the U.S., China, Chile, Australia, and Argentina had the capacity to produce basic lithium chemicals over a certain scale (over 20 kt total output). Among these countries, China was the most dependent on imported minerals, which accounted for 54% of its lithium resources required for domestic chemical production. Regarding the product manufacturing stage, the U.S., China, Korea, Japan, the EU, and Australia produced products containing over 20 kt of lithium. Except for China, Chile, and Australia, all other countries depended on imported chemicals during the product manufacturing stage. A comparison of chemical production stage and product manufacture stage indicated that the supply chain of lithium commodities in the U.S., China and Australia was better integrated.

The lithium mining capacity is not exactly proportional to the reserve (resources that are economical to extract). The lithium reserve is mainly distributed in Chile (52%), China (22%), Argentina (14%) and Australia (11%). As a comparison, the mineral production proportions are as follows: Chile (35%), Australia (27%), China (13%) and Argentina (8%). The high exploitation rate of Australia is a function of its well-established mining industry and superior mineral quality. By contrast, the low mineral quality and lagging mining technology

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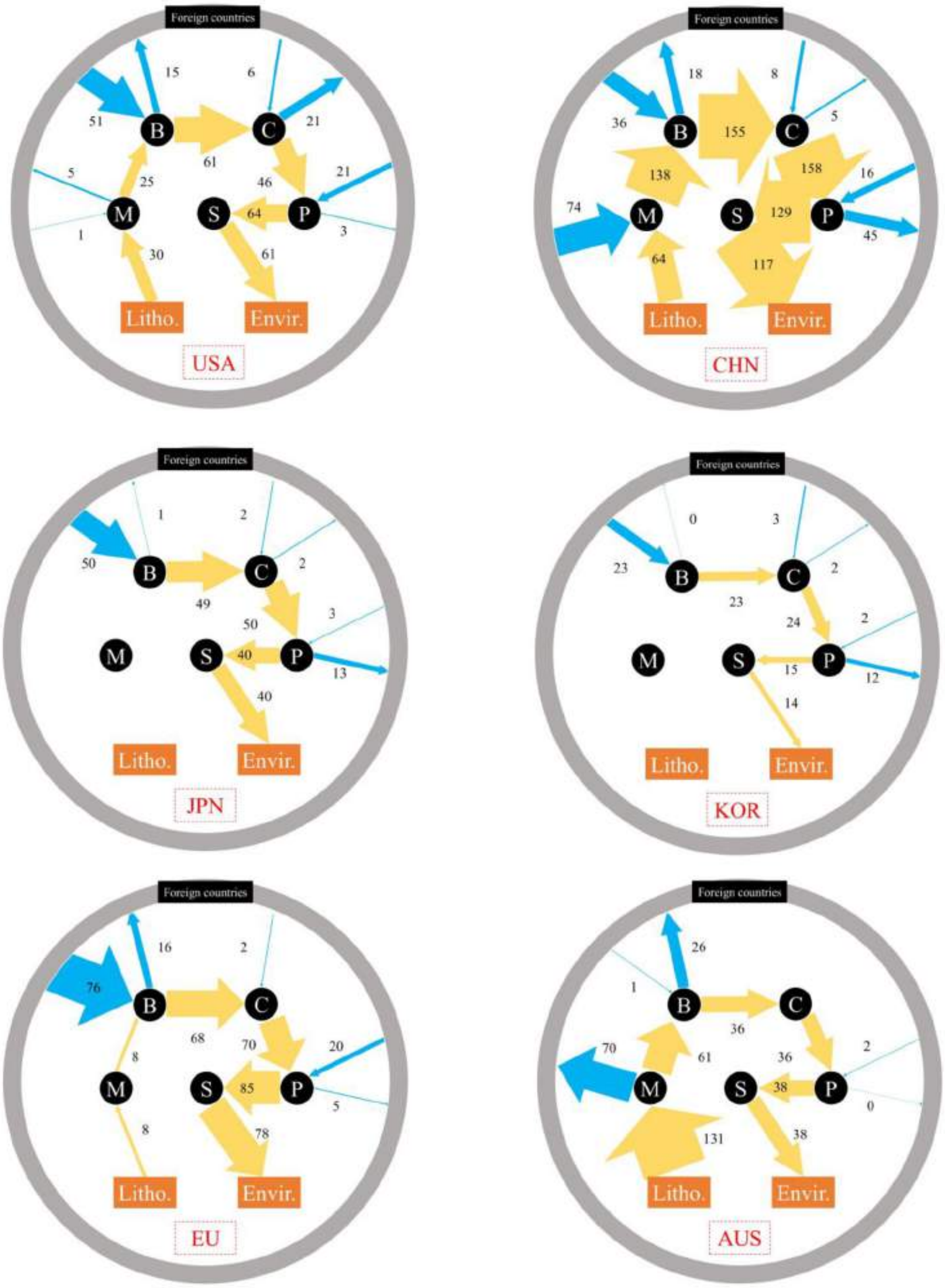

Figure 4. Sum of regional lithium flow from 1994 to 2015. Note: Litho.: lithosphere, where lithium minerals exist; Envir.: environment; M: minerals; B: basic chemicals; C: chemical derivatives; P: products; S: in-use stock. The gray circles represent foreign countries. The yellow arrows represent the domestic commodity flows, and the blue arrows represent the international trade flows. The value of each flow is the accumulation from 1994 to 2015. All values are expressed as kt lithium metallic equivalent.

of China have resulted in a mineral production shortage, even with abundant reserves.

A comparison of the regional trade volumes indicated that China, Chile, the U.S., the EU, and Australia occupied the dominant positions, accounting for 22%, 18%, 13%, 13%, and 11%, respectively, of the global total trade volume. The huge trade volumes were mainly attributed to export products from China, and the export of raw materials from Chile and Australia. The trade volumes of the U.S. and the EU were mainly associated with the import of chemicals and products.

3.4. Production and Trade of Lithium Commodities. Figure 5 shows the global production and trade of lithium according to the commodities. The production and trade of lithium commodities has maintained an increasing trend over the past two decades. The production of lithium commodities increased from 10 kt in 1994 to 34 kt in 2015. Lithium production exhibited a dramatic decrease in 2009, which can be attributed to the financial crisis in that year. The lithium resource supply was mostly in the form of brine because of its lower mining cost. The lithium chemicals extracted from the minerals were mostly in the form of lithium carbonate, which accounted for an average of 63% of the basic lithium chemicals. With respect to the products, glass and ceramics are long-term major applications of lithium. The LIBs utilized the highest

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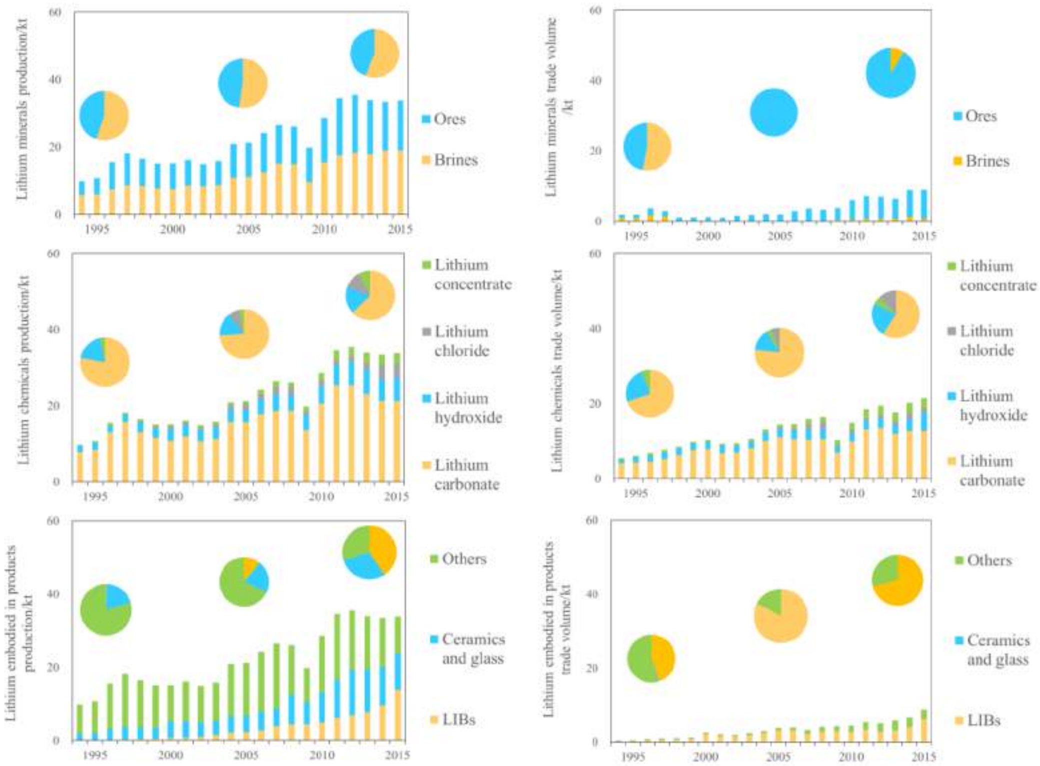

Figure 5. Production and trade of types of lithium commodities over the years. Note: The pie charts show the proportion of lithium embodied in commodities in 1995, 2005, and 2015. With respect to the "lithium embodied in products production", "Others" do not include LIB derivatives to prevent double-counting. In "lithium embodied in products trade volume", "Others" include LIB derivatives. All values are expressed as kt lithium metallic equivalent.

amount of lithium in 2015, accounting for 39% of the total consumption. The average growth rate of lithium consumption for LIBs was 22% from 1994 to 2015, i.e., much higher than that of total lithium production (6%). The lithium used for LIB derivatives reached 6 kt in 2015, with an annual growth rate of 27%. Subdivided by specific applications of LIBs, lithium was mainly used for mobile phones (50%) and notebook computers (50%) in 1994. In 2015, EVs became the major user of lithium, accounting for 44% of the total, followed by mobile phones (28%) and notebook computers (26%).

The total trade volume of lithium commodities reached 43 kt in 2015, with a growth rate of 8%. The trade of lithium chemicals was also influenced by the financial crisis in 2009. Even so, the production and trade of LIBs and LIB derivatives maintained an increasing trend in 2009. The mineral trade volume accounted for 16% of the lithium production. Lithium ores were the major form of the lithium mineral trade, which can be attributed to the intensive trade between Australia and China. The lithium chemical trade volume accounted for 61% of the total production. Lithium carbonate occupied a key position among traded chemicals. The total trade volume of lithium-containing products, mainly in the form of LIBs, accounted for 14% of production. A comparison of all lithium commodities indicated that the lithium carbonate trade accounted for the maximal proportion (44%), followed by lithium ores (16%). This finding implies that the trade of lithium commodities concentrated on upstream materials.

3.5. Discussion. This study established a trade-linked long-term MFA model to trace the global lithium flow. This flow can be observed through both the lithium life cycle and the global trade network. On the basis of the findings, several features of global lithium flow can be summarized, with quite important implications for resource efficiency and security improvements.

First, lithium production and trade included an increasing number of countries and maintained an upward trend. For example, the number of countries that traded more than 100 tons of lithium-containing products increased from 10 in 1994 to all studied countries in 2015. The gradual increase in the use of lithium reflects its growing position as an important metal resource.

Second, the global lithium supply chain is dominated by a few leading countries. For example, Australia's share in the mineral mining stage was 40.7% in 2015, followed by Chile (35.5%) and Argentina (11.5%). In the chemical production stage, China accounted for 35.4% of the global production, followed by Chile (33.1%) and Australia (15.9%). In the product manufacturing stage, China accounted for 41.3% of the global production, followed by Korea (12.2%), i.e., a huge gap compared with China.

Third, even though lithium has been used mainly in ceramics, glass, lubricating grease, and other dissipated products for many years, the recyclable lithium stock still reached a certain scale, approximately equal to the average annual lithium output. Currently, the LIB industry is the largest consumer of lithium and will continue to increase with the development of consumer electronics and electric vehicles. It can be predicted that the recyclable lithium stock will increase rapidly in the future.

With insights into the global lithium flow, valid policy recommendations can be proposed for supply chain management. From the resource security perspective, most countries do not have a complete domestic industrial chain and are highly

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dependent on a few countries that supply raw materials. The lack of self-sufficiency is a high potential risk for domestic supply demand balance. In particular, the major lithium resource suppliers, Chile and Argentina, are in earthquake-prone areas. Unpredictable natural disasters may have a significant impact on the global supply of minerals. With this consideration, policies for establishing national lithium reserves should be considered for strategic economic reasons. Increasing the primary resource supply is an effective solution for this problem. This can be realized through more intensive domestic resource mining or more aggressive imports.

Further exploitation of global lithium resources should be considered. The lithium reserve was 14 million tons in 2015, distributed among the major producing countries. However, the identified lithium resource exceeded 47 million tons, with Bolivia responsible for the largest share (19%).[54] If the resources in Bolivia could be fully utilized, then the global lithium supply and demand stress can be greatly alleviated. The lithium resources in Bolivia have not been exploited because of the government's restriction on foreign mining companies and the lack of electricity.[22] This situation might be improved through effective international cooperation.

From the resource efficiency perspective, a secondary resource supply should be enhanced through a well-established recycling system. Considering the large market demand and technical recycling feasibility, the recycling potential of LIBs should receive greater attention. Various policies and regulations have been launched for the recycling of LIB-powered products. These policies promote lithium recycling by defining responsibility, formulating plans and improving access conditions.[55−58] However, the aims of these policies and regulations are mainly to promote the recycling of batteries in new energy vehicles. The recycling systems of retired batteries embodied in consumer electronics and energy storage systems still need to be improved. Moreover, the extensive lithium trade network could have a negative impact. Waste management will become difficult with the growth of the global trade of lithium commodities. It is also difficult for manufacturers to manage products after they are exported to another country. For this reason, the cooperation between trade partners in establishing a cross-boundary recycling system is essential. The various partners should take their respective responsibilities for this work by sharing information, technology, and related equipment.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.7b06092.

The model details and additional graphics (PDF)

■ AUTHOR INFORMATION

Corresponding Author

*Tel: +86-10-62797400; fax: +86-10-62797400; e-mail: hao@tsinghua.edu.cn (H.H.).

ORCID

Han Hao: 0000-0001-7542-4746

Notes

The authors declare no competing financial interest.

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