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The Dynamic Equilibrium Mechanism of Regional Lithium Flow for Transportation Electrification

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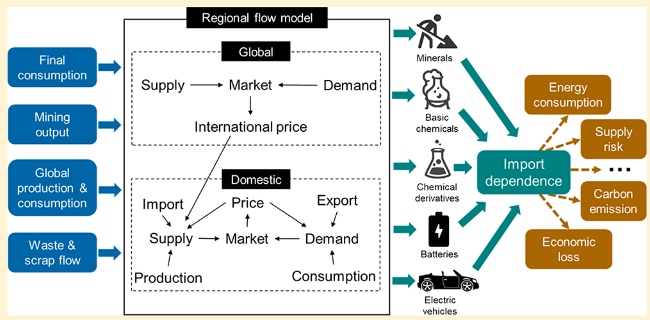
Supporting Information

ABSTRACT: To assess changes in the lithium supply chain resulting from the development of the electric vehicle industry and corresponding impacts, this study established a regional dynamic flow model of the entire anthropogenic life cycle of lithium in China from 2000 to 2050. Based on historical data, this model provides output data including production, consumption and international trade of lithium embodied in five types of commodities. Results indicate that the amount of lithium flow in 2050 will be 13−20 times greater than that in 2015. The lithium applied in electric vehicles will account for the largest proportion of in-use stocks of lithium starting in 2022. Lithium recovery will not play a big role in reducing supply pressure until 2030. Comparing all types of lithium-containing commodities, import dependence on minerals will remain the greatest within the temporal boundary. This factor reflects a nonnegligible risk to the supply demand balance considering the high concentration of mineral import structure in China currently. Several policy recommendations are offered for the optimization of China's flow structure. On the demand side, limited capacity expansion and cutting overcapacity of downstream commodities should be under consideration to distribute lithium import more reasonably. On the supply side, the potential oversupply issues caused by low-grade scrap require further development of recycling technology.



1. INTRODUCTION

With the aim of reducing greenhouse gas emissions and curbing global warming, the development of numerous clean technologies has been accelerated. In the transportation sector, the vehicle electrification is regarded as an effective measure for reaching this goal. Lithium is recognized as the key element of the power source in electric vehicles (EVs).[1] In 2015, rechargeable batteries replaced ceramics and glass (CG) to become the major application of lithium (39% share).[2] EVs contain the highest amount of lithium per unit among all products powered by lithium-ion batteries.[3] The predicted large-scale demand of lithium from the development of EVs resulted in an increase in the concern about the supply demand balance of lithium.

Against the backdrop, substantial work has been conducted on forecasting the supply and demand scenario of lithium. One common method is to contrast primary mineral production with end-use consumption. Some studies focused on investigating lithium resources and reserves availability. Based on the ultimate recoverability of the resource, such studies forecasted annual mineral output and compared the results with prospective demand.[4−9] Other studies mainly considered end-use products when attempting to determine the prospective demand for lithium and compared it with the annual lithium mining rate or currently known lithium reserve.[10−12] With these efforts, the future supply demand balance of lithium can be observed. However, lack of discussion about intermediate links of the supply chain left the detail of potential risk distribution unclear. Thus, it is difficult to provide specific recommendations on optimizing the supply structure.

Material flow analysis (MFA) is an effective analytical method for observing the supply demand framework for a material in conjunction with its anthropogenic cycle. It is a methodology that quantifies the flow of a material in a defined system to study the biophysical aspects of human activity.[13] Results of MFA studies can be applied in numerous aspects of researches, including industrial ecology, life cycle assessment, social metabolism, etc.[14,15] MFAs of lithium have been conducted in multiple levels in the past studies.[3,16−18] These MFA studies are all retrospective, showing material flows within a past time boundary. To study the future supply demand scenario, retrospective and prospective dynamic MFA are needed.[19]

Prospective dynamic MFA of metals could be done based on various stock-driven[20−22] or flow-driven model approaches.[23,24] To determine associations between supply and

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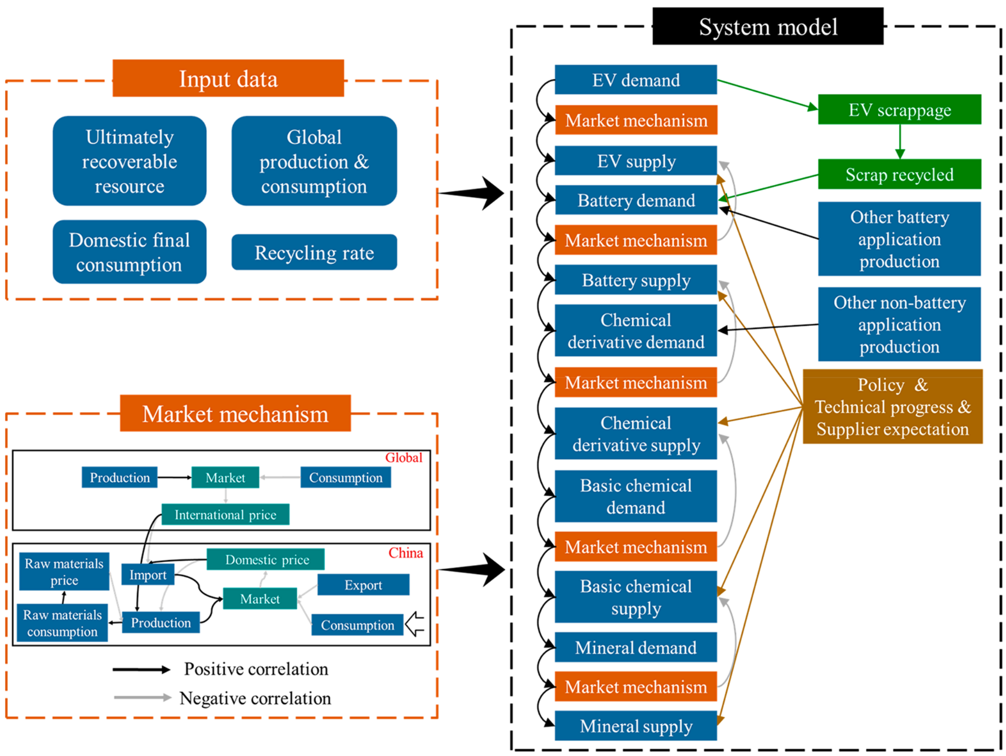

Figure 1. Model structure.

demand and how they affect material flows, system dynamics (SD) is an effective method. SD can model complex dynamic systems to better understand nonlinear behavior over time in a defined closed-loop system. Efforts have been made to adapt SD in dynamic MFA for several metals, such as copper, tellurium, indium, and tantalum.[25−28] With respect to lithium, Miedema et al. investigated its availability for EVs in the European Union considering the drivers of EV market growth, substitution, and recycle efficiency.[29] Sverdrup provided a system model including global extraction, resource grade, market, price and demand of lithium.[30]

The former studies have provided substantial contributions to the literature. However, the system boundaries of these studies are oversimplified leaving several research gaps. The material cycles considered in these prospective studies were limited to four processes at most: mineral production, product manufacturing, product use and waste management. Considering the entire supply chain of lithium-related commodities, chemical material production and battery packing are significant. In addition, the model developed in these studies are not regionally refined. The effect of international trades in different links were not considered. Thus, some issues related to resource security, such as import dependence (ID), are still unclear. In terms of national strategic policy considerations, the discussion on the resource security and efficiency calls for a regional-level material flow model.

In this study, a relatively integrated regional SD model is provided, including supply, demand, market, price, international trade and recovery, following the flow of lithium from minerals, intermediate commodities, to final consumed products. The purpose of this study is to determine (1) the prospective changes in the production, import, export and consumption of lithium-containing commodities resulting from the transportation electrification and (2) the potential opportunities to optimize the regional supply chain of lithium.

2. MATERIALS AND METHODS

2.1. System Definition. This study contributes to the literature by including all the significant links in the regional supply chain of lithium commodities relevant to EVs within the system boundary. The lithium anthropogenic cycle contains six processes: resource mining, basic chemical production, chemical derivative production, product manufacturing, product use and waste management. The types of commodities that flow through these processes are minerals, basic chemicals, chemical derivatives, products, waste, and scrap, respectively. The temporal boundary is set from 2000 to 2050. For the spatial boundary, China is selected as it is currently the largest automobile producer and market. We use historical data from 1994 to 2015 to test the accuracy of the system model (data extracted from our previous study).[18] The accuracy is tested by the value of linear fitting coefficient of historical data and model simulation results, R. When the model output results are sufficiently overlapped with historical data ($R > 0.8$), model is judged to be usable to simulate the future.

2.2. Model Structure and Equations. The regional flow model structure is shown in Figure 1. The detail interface, which was determined by the software Vensim (by Ventana Systems, Inc.), is shown in Supporting Information (SI) Figure S1. The SD analysis and dynamic MFA were the major methods used to establish the model, which is a combination of sale-driven and price-driven model. The causal cycle (SI Figure S37) starts from the increase in EV sales. This increase will cause a stimulation in the market of EVs and a positive reinforcement in EV price. As a result, suppliers will increase the domestic production and importation of EVs, causing a negative reinforcement in EV price. Then, raw material demand and supply will rise correspondingly. At the same time, increasing (or decreasing) price of raw materials will lead to an increase (or decrease) in the production costs of

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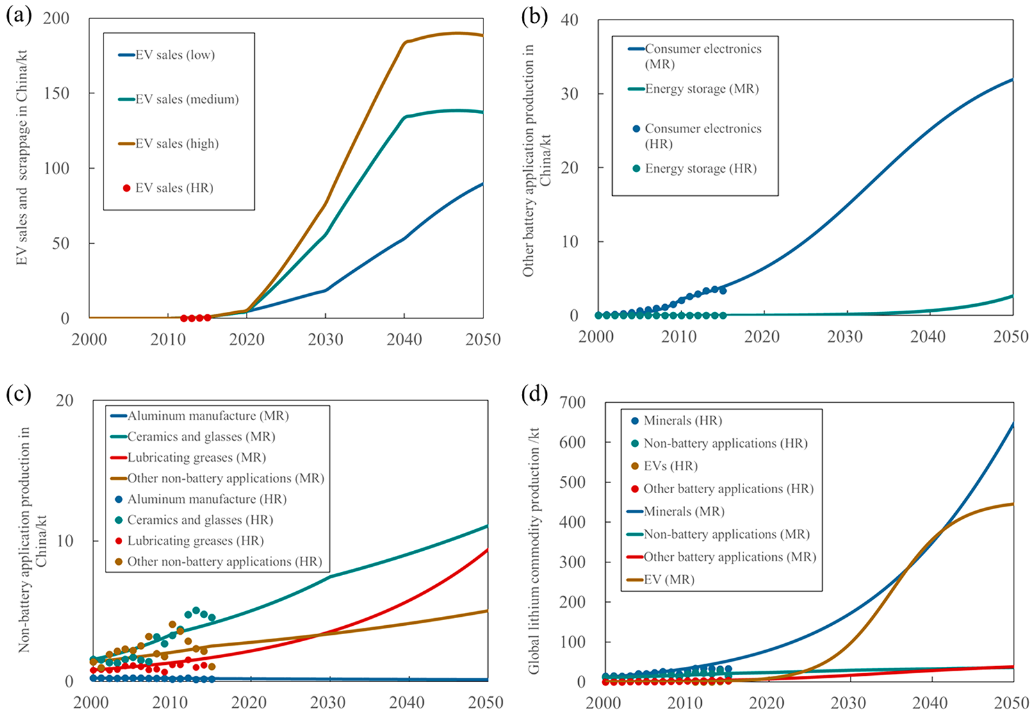

Figure 2. Input data. Note: The four parts from (a) to (d) show the four components of the input data. Part (a) shows EV sales in China for three cases. Part (b) shows the battery application production (except for EVs) in China. Part (c) shows the non-battery application production in China. Part (d) shows the global production of lithium minerals and products. "MR" in the legend represents the model simulation results. "HR" in the legend represents the historical data. All values are expressed as the kt lithium metallic equivalent unit.

downstream commodities as negative feedback. With similar connections between downstream commodities and raw materials, a supply chain framework is established. In addition, the influence of technical progress, policy drivers, supplier expectations and the recovery of scrappage are also considered in our system model. Assuming the market of EVs is independent of other lithium final applications, the markets of non-EV applications are not incorporated in the model for simplifying the framework.

The general formula applied in this study was the mass balance formula, which is the basic principle of MFA. As eq 1 shows, the input flow is equal to the output flow for each process.

$$\mathrm{IF} = \sum \mathrm{CO} + \sum \mathrm{RE} = \mathrm{OF} = \sum \mathrm{PO} \tag{1}$$

Where IF is the input flow; OF is the output flow; $\sum$CO is the gross raw material consumption; $\sum$RE is the gross scrap from postconsumer downstream commodities; $\sum$PO is the gross downstream commodity production.

Price is the intermediate variable by which supply interacts with demand. The factors that can influence the price of commodities are very complex, including manufacturing costs, management, market, economy, etc. In this study, the price is simplified as a unary function of the market, as in eq 2a.[31] The market value of each type of commodity is calculated by eq 2b.

$$\mathrm{PR}_{x,t} = \alpha_x \times (M_{x,t})^{-\beta_x} \tag{2a}$$

$$M_{x,t} = M_{x,0} + \int_0^t (\mathrm{PO}_{x,t} + \mathrm{IM}_{x,t} - \mathrm{EX}_{x,t} - \mathrm{CO}_{x,t}) \tag{2b}$$

Where $\mathrm{PR}_{x,t}$ is the price of commodity x at time t;$M_{x,t}$ is the market of commodity x at time t; $\mathrm{PO}_{x,t}$ is the production of commodity x at time t; $\mathrm{IM}_{x,t}$ is the import of commodity x at time t; $\mathrm{EX}_{x,t}$ is the export of commodity x at time t; $\mathrm{CO}_{x,t}$ is the domestic consumption of commodity x at time t; $M_{x,0}$ is the initial market value of commodity x; α_x is the price coefficient of commodity x; β_x is the price exponent of commodity x.

With respect to international trade, importation is considered a substantial part of this model, as imports are relatively significant to the domestic supply demand balance. In this study, we assumed export as a natural growth variable affected by the development of the global market. The import of a specific commodity is the function of its international price, domestic price and demand, as eq 3.[32−34]

$$\ln \mathrm{IM}_{x,t} = k_1 + k_2 \times \ln \mathrm{PR}_{x,t} + k_3 \times \ln \mathrm{GPR}_{x,t} + \ln(\mathrm{EX}_{x,t} + \mathrm{CO}_{x,t}) \tag{3}$$

Where ln $\mathrm{IM}_{x,t}$ is natural logarithm of import of commodity x at time t; ln $\mathrm{PR}_{x,t}$ is natural logarithm of domestic price of commodity x at time t; ln $\mathrm{GPR}_{x,t}$ is natural logarithm of international price of commodity x at time t; $\ln(\mathrm{EX}_{x,t} + \mathrm{CO}_{x,t})$ is natural logarithm of sum of export and domestic consumption of commodity x at time t;

The annual mining rate is calculated by combining the market driver and logistics model as in eq 4.

$$\mathrm{PO}_{m,t} = k_1 \times \frac{\mathrm{d}Q_t}{\mathrm{d}t} + k_2 \times \mathrm{DM}_{m,t-1} \times \mathrm{SE}_{m,t} \times \mathrm{DR}_{m,t} - k_3 \times \mathrm{PC}_{m,t} \tag{4}$$

Where Q_t is the cumulative production of lithium at time t; $\mathrm{PO}_{m,t}$ is the production of lithium minerals at time t; $\mathrm{DM}_{m,t}$ is the demand of lithium minerals at time t; $\mathrm{DR}_{m,t}$ is the price driver of lithium minerals at time t; $\mathrm{SE}_{m,t}$ is the supplier estimation of lithium minerals at time t; $\mathrm{PC}_{m,t}$ is the production cost of lithium minerals at time t.

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Environ. Sci. Technol. 2019, 53, 743−751

Table 1. Three Cases for EV sales, URR, and TRE

	EV sales (lithium content)		URR		TRE	
case	value	assumption	value	assumption	value	assumption
low	89 kt in 2050	EV demand grow slowly	3.2 Mt	URR is equal to the lithium reserves[2]	0%	future recycling circumstance is the same as it is currently[47]
medium	137 kt in 2050	EV demand grow steadily	7 Mt	URR is equal to the identified lithium resource[2]	50%	there is a significant improvement on the TRE
high	188 kt in 2050	EV demand grow fast	10 Mt	URR is equal to the sum of identified lithium resource and estimated hidden resource[31]	90%	TRE could reach the theoretically highest recycling efficiency[48]

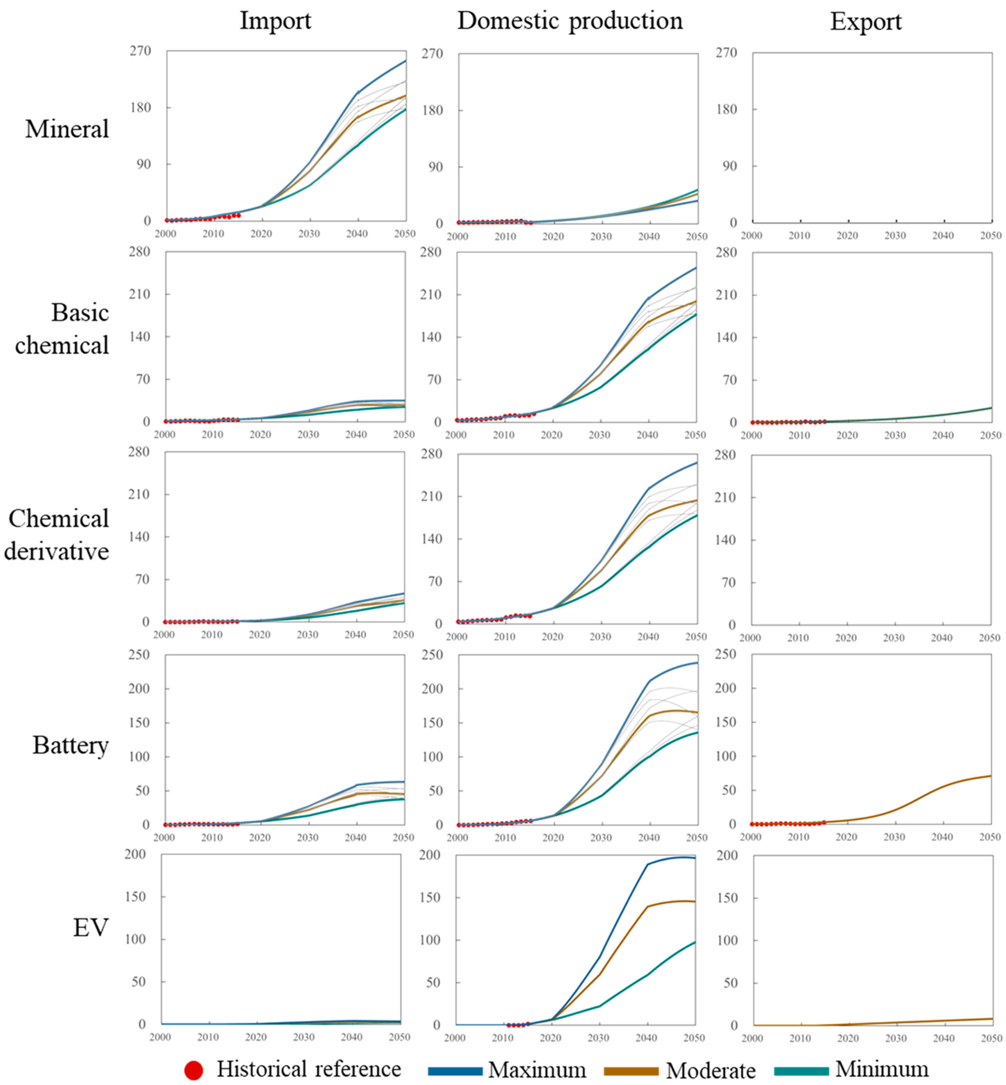

Figure 3. Output data for the 27 scenarios. Note: The fifteen parts of Figure 3 show the import, domestic production and export of five types of lithium commodities. Graphs from top to bottom represent minerals, basic chemicals, chemical derivatives, batteries and EVs respectively. The column on the left represents imports. The column in the middle represents production. The column on the right represents exports. The gray lines show the other 24 scenarios. All values are expressed as the kt lithium metallic equivalent unit.

The market driver factor contains two parts: market estimation and production cost. The logistics function is an "S-shape" growth model that is commonly used to forecast resource production and consumption.[9,26] The logistics function reflects the growth trend under natural development market circumstances. Based on the statistical regression of the historical mineral production data and ultimate recoverable resources (URR), the cumulative mining curve is simulated by the logistics function as in eq 5.

$$Q_t = \frac{\text{URR}}{1 + e^{[-k\times(t-t_0)]}} \tag{5}$$

Where Q_t is the cumulative mining output;t_0 is the peak year of annual lithium mineral production;k is the growth factor.

With respect to the waste and scrap flow, end of life product generation is estimated by Weibull distribution (SI Figures S15, S16 and Table S6). The recycling rate is the product of

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Environ. Sci. Technol. 2019, 53, 743−751

two factors: the collection rate of end of life products (CR) and the technical recycling efficiency (TRE), as in eq 6.[25]

$$RR_{x,t} = CR_{x,t} \times TRE_{x,t} \quad (6)$$

Where $RR_{x,t}$ is the recycling rate of end of life product x at time t; $CR_{x,t}$ is the collection rate of end of life product x at time t; $TRE_{x,t}$ is the technical recycling efficiency of end of life product x at time t;

To date, the recycling of lithium is almost nonexistent.[35] The CR and TRE are set to change from zero in 2016 for several companies began building production capacity to recycle lithium from dead batteries in this year.[36]

2.3. Input Data Generation and Scenario Analysis. Figure 2 shows the curves of various input data. The input data for the model contain four parts: (1) EV sales and corresponding scrappage in China; (2) other battery-powered commodities (except for EV) production in China; (3) nonbattery applications production in China; (4) global production of the lithium contained in minerals and end-use products. The value of these variables are only relevant with time and have no feedback connection with other variables.

The data of China and global EV sales are extracted from the upstream model results of ours. Detailed descriptions about this part are listed in SI Figures S2−S10, S12, and Tables S2−S3). For the lithium applied in other applications, such as consumer electronics (CEs) in China, the values are forecasted by the logistics model and exponential growth model.[10,37] The corresponding parameters are set based on the regression of the historical data and related studies.[38−41] Prospective global mineral production is calculated by a logistics function based on the estimation of global URR[4,6−8,42−44] (SI Figure S11). The global production of lithium end-use products (except for EVs) are estimated by the logistics model and exponential model.[45,46]

The major influencing factors considered for our model are EV sales, URR, and TRE. To determine the influence of these three factors, we considered three cases for each factor: low, medium and high. The typical values and assumptions for three factors in each case are shown in Table 1.With the combination of different cases for each factor, 27 output scenarios (i.e., SC1−SC27) were generated (SI Table S8). From the point of view of supply pressure, SC9 (EV sales in low case and others in high case), SC14 (all in medium case) and SC19 (EV sales in high case and others in low case) are selected as representative scenarios, named by minimum, moderate and maximum supply pressure scenario, respectively.

A detailed description of the model, including the input data and data sources, a derivation of all relevant equations, the results of sensitivity analysis, and further information on the survey work related to this study can be found in the SI.

3. RESULTS AND DISCUSSION

3.1. Flow and Stock. The major observational output data are the domestic supply and international trade flows of lithium commodities. Based on the simulation results, corresponding strategic policy recommendations are offered. Figure 3 shows the output data for the commodity flows contained in the lithium anthropogenic cycle for the 27 scenarios. Unless otherwise stated, the commodities mentioned below refer to lithium content. The amount of lithium flow through each stage of China in 2050 will increase 12−19 times as much as it was in 2015. It is pretty straightforward to see that except for resource mining stage, China's main source of supply in other stages will be domestic production.

The proportion of production occur in China to the whole world in 2050 of each type of commodity willbe minerals, 6%−8%; basic chemicals, 28%−41%; chemical derivatives, 29%−44%; batteries, 25%−45%; EVs, 22%−44%. China will be a net importer of minerals and basic chemicals, and a net exporter of chemical derivatives, batteries and EVs. Minerals will be the major imports, between 179 kt and 255 kt in 2050. Export of batteries will be the largest, reach 71 kt in 2050. The domestic EV production flow will grow fastest, with an annual growth rate of 17% from 2013 to 2050.

Comparing the output data of different scenarios, it can be found that the influence of URR is extremely tiny. The difference of lithium flow in the same EV sales and TRE case while in different URR case is no more than 7 kt in 2050. The sum of cumulative end-use consumption and export in China from 2015 to 2050 will be 2 to 4 million ton (Mt), less than China's lithium resource (7 Mt). It indicates that the URR will not be the bottleneck of China's lithium industry before the year of 2050. EV sales will be the major driving factor of lithium industry.

As Figure 4 shows, the average lithium in-use stock in China of the 27 scenarios will reach 1964 kt in 2050, equal to 62% of current China's natural reserve. In 2050, the lithium stock will mainly consist of EVs (95%) and CGs (4%).The stock embodied in EVs is the fastest-growing sector, attaining a value between 959 kt and 2698 kt in 2050, with an average annual growth of 44%. From 2000 to 2021, CGs were the main products of lithium stocks. Starting in 2022, EVs will become the major products of the lithium stock, representing the huge potentiality to mine the city resources (SI Figure S38).

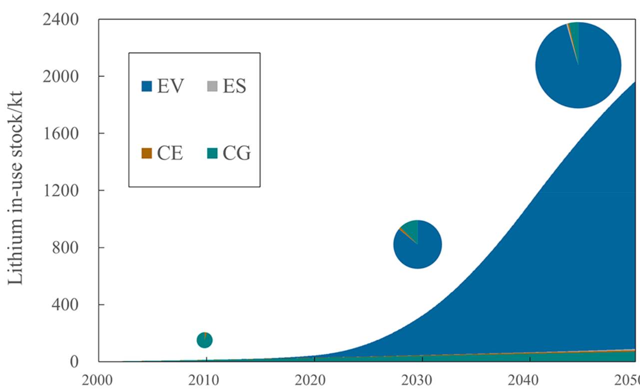

Figure 4. Lithium in-use stock. Note: EV: electric vehicle; ES: energy storage; CE: consumer electronics; CG: ceramics and glass. The pie charts show the proportions of lithium stock embodied in various products in 2010, 2030 and 2050. The values in this figure are the averages of all 27 scenarios. All values are expressed as the kt lithium metallic equivalent unit.

Based on the calculated data, analyses of the status, potential threats, and opportunities of China' prospective lithium flow structure are provided below. Then several policy recommendations are developed for the optimization on the supply side and demand-side, respectively.

3.2. Supply Side Structural Optimization. Supply source could be from domestic production or import. For national resource security consideration, ID is a critical evaluation index to provide insight into the potential risk of supply chain.[49] The ID is calculated by eq 7.

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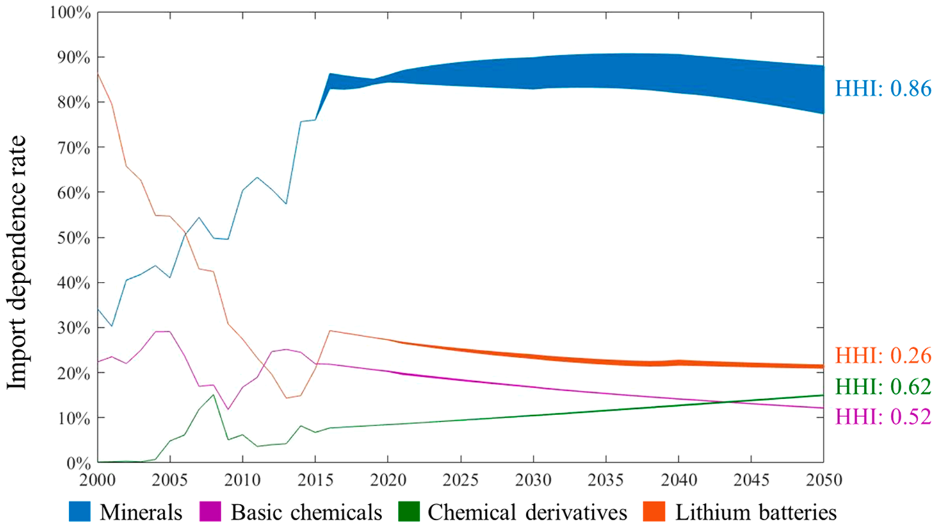

Figure 5. ID of various lithium-containing commodities. Note: The single lines show the historical data. The bands show the output data under 27 scenarios. HHI: Herfindahl-Hirschman index.

$$ID_{x,t} = \frac{IM_{x,t}}{PO_{x,t} + IM_{x,t}} \quad (7)$$

Where, $ID_{x,t}$ is the ID of commodity x at time t; $PO_{x,t}$ is the production of commodity x at time t; $IM_{x,t}$ is the import of commodity x at time t.

The ID of the raw materials of EVs under 27 scenarios are shown in Figure 5. Results indicate that the trend of ID change of various commodities is quite different with the development of lithium industry. The ID of basic chemicals will be decreasing while the ID of chemical derivatives will keep increasing. The development trend of battery ID will also decrease except for sharply increase in 2016. It is because that in the year the production of EVs in began to pick up speed. The domestic battery capacity is expanding at a slower rate, causing a large growth of imports. The trend of ID of minerals will be first increasing and then decreasing from the year of 2034. The span of ID of minerals under 27 scenarios is larger than that of other commodities. It is because that the mining industry is less sensitive to downstream commodity market changes comparing with chemical industry and manufacturing industry. The time required for capacity expansion of minerals is longer than others. Generally, it takes 5 to 7 years for a lithium mineral production line to be located and released while for batteries the time is about 3 years.[50] The longer development cycle makes lithium mining companies could not respond quickly to market changes. In addition, the mining industry is highly susceptible to geographical factors. For instance, in 2014 the mineral production in China has a sharp drop even though the demand was increasing. The reason is that major China's spodumene suppliers have had their mines blocked in this year. Unpredictable natural factors lead to relatively weak control over production by mining companies.

It can be seen intuitively that ID of minerals will be the highest in the future, far ahead of that of other commodities. Imports of different commodities play the same role in maintaining the domestic supply demand balance. However, the potential risk in import of different types of commodities are extremely distinguishing. Here Herfindahl-Hirschman index (HHI) is chosen to calculate the risk of import structure of China in 2015 (SI Figure S41). HHI is a commonly used index to calculate the concentration of supply groups, calculated by eq 8.[51,52] Higher HHI indicates the larger potential supply risk.

$$HHI_x = \sum_{i=1}^{N} \left(\frac{IM_{x,i}}{TIM_x} \right)^2 \quad (8)$$

Where,HHI_x is the HHI of commodity x imported by China; $IM_{x,i}$ is the amount of commodity x that China imported from country i; TIM_x is the total amount of commodity x that China imported; N is the total amount of countries that China imported commodity x from.

The calculation results are also shown in Figure 5. It can be found that the HHI of mineral import is the much higher than that of others. It means that based on current import structure of China, the risk of mineral import is the highest. As mentioned above, the model results show that minerals will be the biggest imports. These two factors indicate that the lithium supply chain of China faces a huge threat form potential import risks and needs to be optimized.

Two options could be considered to achieve this goal. One is to change the import structure, especially for the minerals. Trying to develop more foreign procurement sources could reduce the risk of invalidation of an import source. However, it is hard to reach this because alternative import sources are few. The concentration of global lithium minerals supply keep being higher for only a few countries own the plenty lithium resource.[18]

Another option is to change the domestic production structure to distribute import amount more becomingly. The approaches to reach this aim include scale up the mining output and slow down the expansion of downstream capacity. China has the second-largest available reserves of lithium around the world.[2] Abundant reserve is a prime opportunity for China to achieve national self-sufficiency without importing minerals. To take full advantage of China's abundant lithium resources, more efforts need to be put into technology research and the management of the mineral industry. In addition, cutting the overcapacity of downstream lithium-containing commodities is also an effective solution, especially for the battery industry in China. In order to seize the market, battery

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manufacturers keep expanding production, and new enterprises are entering the battery market constantly in recent years.[53] Rapid expansion of the EV market result in an increasing problem of excess capacity of power battery.[54] We recommend that the government should formulate strict laws and regulations to raise the threshold for enterprises to enter lithium chemical and battery market. Besides corresponding policy could be raised to encourage EV companies to import chemicals and batteries by adjusting import tariffs. Considering the length of time required to amend-capacity, establishing a national strategic reserve is essential to guaranteeing the supply demand balance in the near future.

3.3. Impact of Recycling and Substitutes on Demand-Side. Recycling is generally considered an effective way to reduce the final demand for primary supply. Model results show that the gross lithium contained in end-of-life (EOL) products will reach 45−121 kt in 2050 (SI Figure S39−S40). The average share of lithium contained in each type of EOL product will be the following: EVs, 85%; CGs, 10%; CEs, 3%; and ESs, 2%. The average total lithium recovery from product scrappage will be 35 kt in 2050 for the 27 scenarios. In 2050, the average share of lithium contained in each type of product scrap will be the following: EVs, 97% and others, 3%.

The lithium flow out of use will reach about half of lithium chemical consumption in 2050. These lithium contained in EOL products represent a large opportunity for secondary domestic supply. Under these circumstances, recycling of the lithium, especially in EV scrappage, needs to be given considerable attention. Currently, one reason for the barely recycling of lithium is the low CR of EOL products.[35] The use of glass, ceramics, consumer electronics and other products is often extremely dispersed. Another reason is the few desires of relevant companies to extract lithium from collected discarded product due to the low benefits.[55] Relevant regulations for enterprises and consumers for increasing their willingness to separate and collect discarded electronic equipment need to be published. The revenue of recycling not only includes the direct economic income, but also includes the environmental benefits of reducing energy consumption and carbon emission.[55,56] Thus, the fiscal stimulus providing corresponding subsidy to the external benefits created by recycling enterprises should be considered in the early stages of EV development. Sustainable recycling mechanism call for further effort on the researches of scrap price and government cost to induce recovery.

It is worth mentioning that the impact of lithium recycling will be limited in the near future. Results show that the growth of lithium scrap will not begin to pick up until 2030 for the service lifetime of EV is relatively long. Besides, whether recycling can reduce the supply pressure of lithium in EVs is still uncertain even if the scrap reach a certain scale. The grade required for lithium chemicals used in batteries is higher than that used in nonbattery applications.[57] With existing recycle technology, the lithium recovered could not be used in power batteries but only in the other products. Our model results show that the nonbattery application production in China will be 25 kt in 2050. It means that there will be a 10 kt oversupply for these products, whereas the demand for lithium applied in batteries will stay strong. Thus, the establishment of recycling system and the progress of recycling technology must be emphasized at the same time to deal with this potential threat.

More attention needs to be given to the lithium embodied in nonbattery applications. Most of these products, such as lubricating greases and medicines, are dissipative during use stage, which prevents them from being recycled. The profits of lithium recovery from the other products, such as CGs, are generally negative.[58,59] Under these circumstances, substitution for lithium in nonbattery applications should be considered.[29] For instance, calcium and aluminum soaps can work as substitutes for greases. Using sodic and potassic fluxes in CG manufacturing in place of lithium is technically feasible.[2] These substitutes would not have significant effect on product performance and supply demand balance of relevant resources (calcium, aluminum, etc.) Within this model temporal boundary, the lithium saved from these applications could also play a big role in holding supply demand balance.

3.4. Sensitivity Analysis. To test the influence of model parameters on the output data, the sensitivity analysis were performed. The sensitivity analysis results of various major parameters are shown in SI Figure S17 to S36. The observed output data is ID. The parameters could be divided into two groups: (1) model structure parameters, including price coefficients, technical progress coefficients, production cost coefficients, and policy driver coefficients; (2) input data parameters, including annual growth rate and average lifespan of end-use products, China's export of each type of commodity, global EV demand, and global mineral production. Comparing sensitivity of the model to all model structure parameters considered, sensitivity to the price coefficients α_x in eq 2a is the highest, much larger than that to other coefficients. Breakdown by commodity type, the ID of battery is mostly sensitive to its domestic price coefficient. The ID and price coefficients (both domestic and international) of chemical derivatives are positively correlated. While the ID and price coefficients of minerals, basic chemicals and batteries are negatively correlated. The price coefficients are given by the regression of historical lithium price and market value. The value of these coefficients reflect the characteristics of the past various types of commodity industrial structure and market characteristics in China. Underlying cause behind this phenomenon call for further explanations.

With respect to the input data parameters, the sensitivity of model output to the growth rate of domestic final demand is the highest. It is because that the ES and other nonbattery application demand are assumed to grow with a constant growth rate. Peculiarity of exponential growth makes the growth rate have a great influence on the flow size in the long time scale. Providing a more reliable prediction of lithium demand called for a high-level model with deeper insight into non-EV industry. The impact of global mineral production on the model output is in the medium level. The results of similar predictions vary greatly in the existing literature (SI Figure S11), from 0.1 Mt to 0.7 Mt in 2050.[7,9,30,42,60] Discrepancy in the mining output models applied and estimation of available reserve make this difference. It should be noticed that model results in relevant studies vary extremely greatly, as SI Figure S13 shows.[7,9,11,22,30,42,57,61] The range reaches approximatively 1.3 Mt in 2050. The huge difference comes from the various assumptions for the EV development speed, battery type mixes, and metal intensities. While the sensitivity of model to the global EV demand is relatively low, only 10% of that to global mineral production. Effect of product lifespans and China's export on model output are quite limited. And the value of lifespans estimated by several studies do not have a certain difference.[62−64] To summarize, the annual growth rate of

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Environ. Sci. Technol. 2019, 53, 743−751

domestic end-use demand and global mineral production are the major uncertainties.

3.5. Further Research. The greatest value of this study is the dynamic model we built, which could calculate the ID in each major process of the supply chain. This function could be very helpful to optimize regional supply chain. There is a huge disparity among the external influences brought by the import of different kinds of commodities. The policy advice raised above is in the term of supply risk. In addition to this view, external influences include implicit carbon emissions, energy consumption, economic losses, etc.[65−67] With combination of ID and these factors, we can compare the different supply chain scenarios quantificationally. Then policy recommendations for the regional import and domestic capacity establishing strategy can be proposed from the view of various critical aspects.

Besides, the dynamic model established in this study has a valuable expansibility. The system boundary of this model could be changed. The feature of our model framework is that it focuses on the EV development and it is totally data driving. Thus, the model could be applied to similar studies of other metal elements which are critical and essential for vehicle electrification, such as cobalt and nickel. And the spatial boundary could be changed to other countries with outstanding electric vehicle industry, like the USA, Japan, Germany, etc. These efforts can make a significant contribution to improving the sustainability of the EV supply chain.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.8b04288.

Details of the data source, model structure, additional explanations and graphics (PDF)

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Notes

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Environ. Sci. Technol. 2019, 53, 743−751