Resources Policy 51 (2017) 100–106

Contents lists available at ScienceDirect

Resources Policy

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

Material flow analysis of lithium in China

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ARTICLE INFO

Keywords:
Lithium
China
Material flow analysis
Lithium-ion battery
Electric vehicle

ABSTRACT

Lithium has an increasingly strategic role as clean technologies emerge. This strategic role is especially evident for electric vehicle technology with a critical dependence on lithium-ion battery technology. China is the world's largest lithium consumer due to its rapid economic development, large population, and soaring consumer demand for electric vehicles driven by stricter air quality control regulations. Given this background, this study introduces the first lithium material flow analysis (MFA) for China. This MFA will inform national lithium management plans. The MFA results indicate that China's consumption was 86.7 kt of lithium carbonate equivalent in 2015, accounting for 50% of the global total. China's lithium resource is highly dependent on imports, 70% of spodumene concentrate is imported from Australia alone. Along the material life cycle (value) chain, lithium outflows were primarily from exports of lithium chemicals and lithium-embodied products. Remaining lithium in-use stocks are embodied in electric vehicles, consumer electronics, lubricating greases, and glasses/ceramics. Electric vehicle sales growth projections will likely increase China's dependence on lithium imports, lead to potential lithium supply security concerns for China. Large amount of lithium stock embodied in electric vehicles and other lithium-ion battery-containing products implies more opportunities for lithium recycling in a circular economy context.

1. Introduction

Lithium, the lightest metallic element, is a relatively rare element on earth (Garrett, 2004). Lithium naturally occurs in compound forms because of its high reactivity. Lithium is found with very low concentrations in natural brines and pegmatites. These compounds include spodumene, lepidolite, and petalite. The global lithium reserve is estimated at 14.0 megatons (Jaskula, 2016), which is 74.5 megatons of lithium carbonate equivalent (LCE). Lithium reserves are mainly distributed in South America, Australia, and China (see Fig. 1).

Commercially, lithium is used to produce various chemicals, most of which are indispensable to modern industry. As an ingredient it has been used in various materials such as lubricating greases, glasses, and ceramics. Lithium has also seen application in critical energy storage products such as lithium-ion batteries. These batteries are essential components in consumer electronics, energy storage systems, and electric vehicles. In 2015 global lithium resource mining reached 0.17 megatons LCE (Jaskula, 2016). Lithium mining increased by 58% over the past decade because of growing and multiple industrial uses. It is expected that increasing global demand for electric vehicles will mean that global lithium consumption will also experience substantially greater demands over the next few decades (Hao et al., 2016). Consequently, understanding the potential impact of lithium supply, consumption and flows is critical for social and economic development during this time period (Dunn et al., 2012; Kang et al., 2013; Li et al., 2014; Majeau-Bettez et al., 2011) (Fig. 2).

China is the largest lithium consumer in the world. China has a relatively rich lithium reserve of 17.0 megatons of LCE accounting for 23% of global reserves. However, China's lithium reserve grade is relatively low resulting in high lithium resource mining costs (Zeng and Li, 2013). Thus, China's lithium demand is primarily met through foreign imports. In 2015, while China's share of global lithium production was 7%, its global share of consumption was 50% (Jaskula, 2016). China's domestic consumption was mainly met through spodumene concentrate imports from Australia.

Stricter air quality control policies in China have fueled electric vehicle demand growth. Electric vehicle production in China in 2015 reached 379,000 vehicles, a 400% increase from the previous year. This level of electric vehicle production has made China the world's largest electric vehicle producer. This electric vehicle production growth also increased the demand and market price of lithium carbonate from 43,000 Yuan/t in early 2015 to 129,000 Yuan/t in late 2015 (Zhang,

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http://dx.doi.org/10.1016/j.resourpol.2016.12.005
Received 6 November 2016; Received in revised form 3 December 2016; Accepted 5 December 2016
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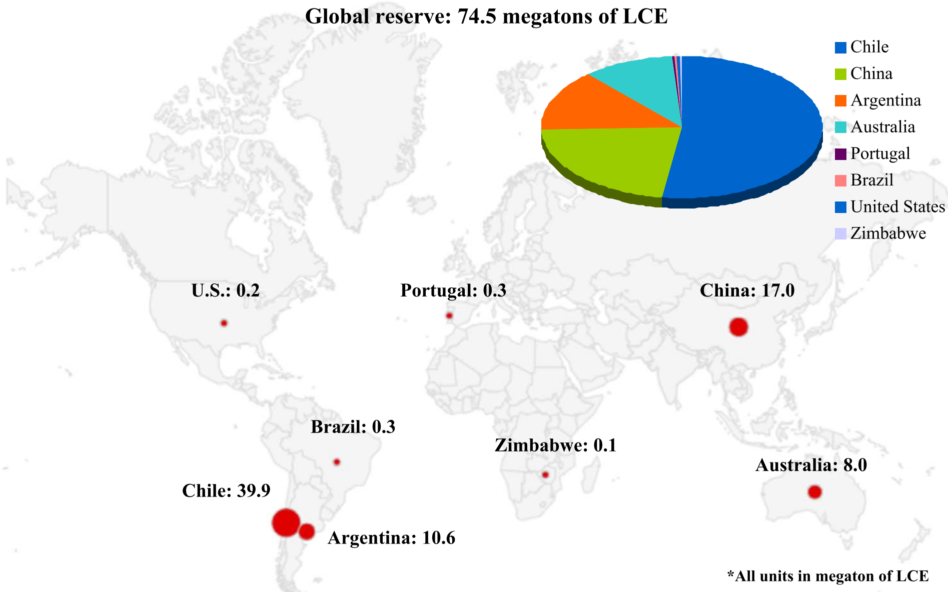

Fig. 1. Global distribution of lithium reserves.

2016). Thus, manufacturers have become concerned on how to maintain a sustainable supply of lithium compounds.

A material flow analysis (MFA) can help policy makers, researchers, and industry gain insights on addressing lithium scarcity concerns. Ziemann et al. developed the first global lithium flow model and found a noticeable discrepancy between production and consumption (Ziemann et al., 2012). Numerous studies investigated the global lithium supply-demand relationship in the context of corresponding lithium-ion battery demand (Habib and Wenzel, 2014; Pehlken et al., 2015; Speirs et al., 2014; Vikström et al., 2013; Chang et al., 2009). Global-level MFA studies have been conducted for many commodities such as aluminum (Liu and Müller, 2013) and copper (Gerst, 2009). However no peer reviewed publication has completed a lithium MFA within the Chinese context. This study seeks to fill this gap by developing a lithium flow chart for China. From this analysis we also identify major challenges and opportunities for lithium supply and identify how lithium resource efficiency can be improved.

The remainder of this paper begins by describing the MFA method. Section 3 presents the research results, including the lithium flow chart. Finally, Section 4 concludes the paper by identifying related policy issues.

2. Material flow analysis

MFA is a systemic assessment of the flows and stocks of materials defined in space and time (Brunner and Rechberger, 2004). This study is conducted by the following MFA steps: system definition, analysis of processes, schematic modeling and interpretation of results.

2.1. System boundary

The spatial boundary is mainland China (China for short). Taiwan, Hong Kong and Macau are excluded from the analysis. The analysis temporal boundary is the year 2015. The year 2015 is chosen to reflect lithium flow trends driven by electric vehicle market growth in China. Using lithium processing activities five basic stages along the life cycle chain are used in the analysis. These stages include resource mining, chemical production, product manufacture, product use and waste management. The inputs, outputs and stocks for each stage are calibrated using data from the Ministry of Industry and Information Technology MIIT (2016), General Administration of Customs GAC (2016), and the China Nonferrous Metals Industry Association CNMIA (2016). The details of data compilation and treatment are described in Supplementary Information (SI) documentation.

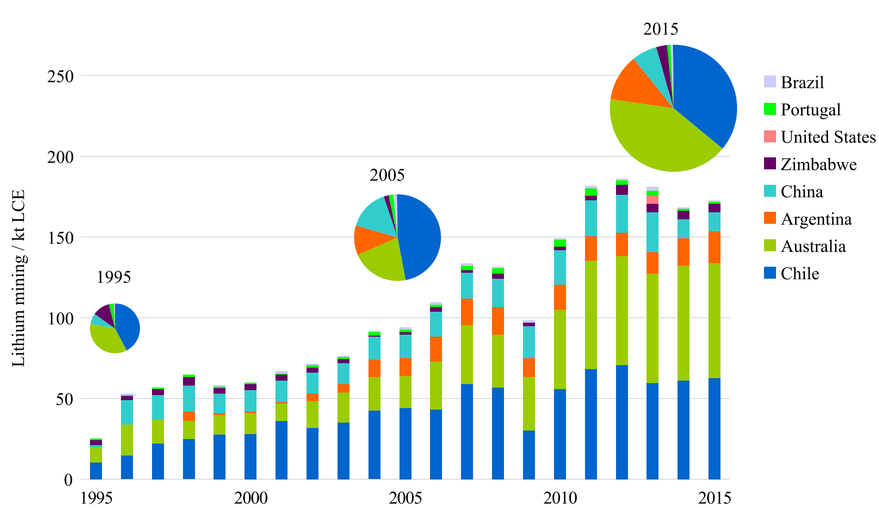

Fig. 2. Lithium mining in key countries.

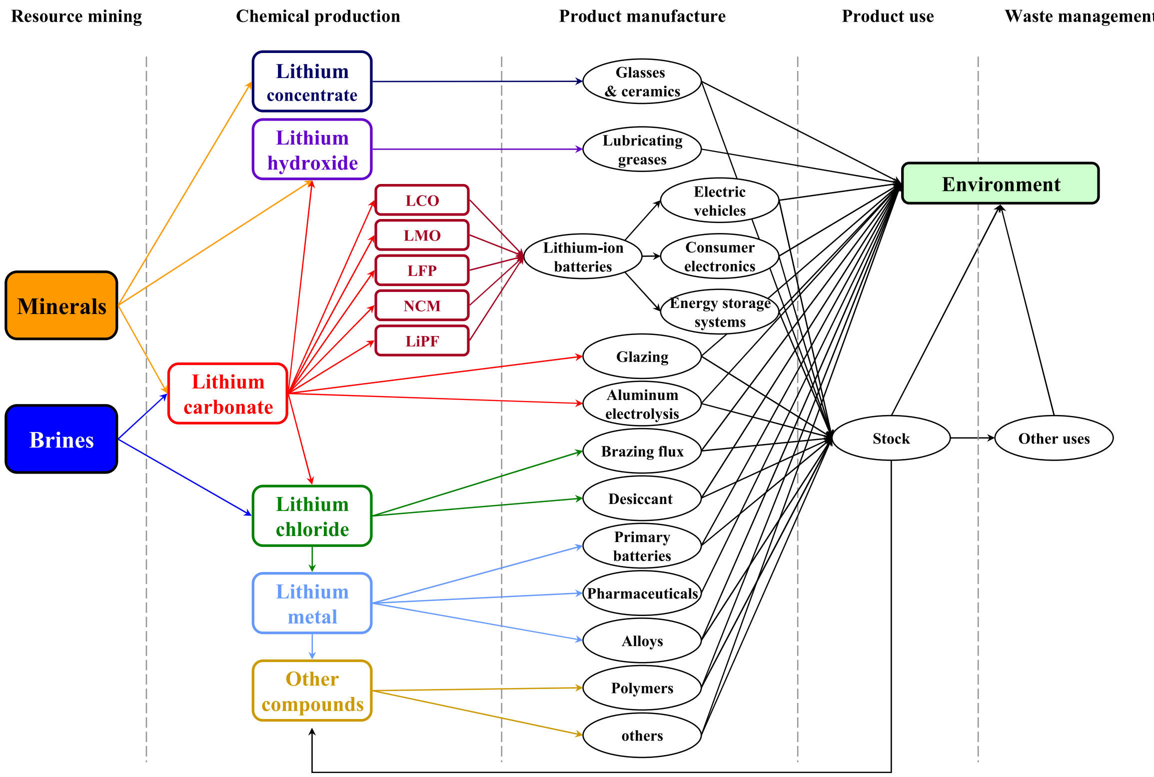

Fig. 3. Modern lithium industrial processing stages and activities.

2.2. Analysis of processes

Modern lithium industrial processing stages are summarized in Fig. 3. Resource mining, chemical production and product manufacture stages analyzed in this study include the various identified activities within this industrial value chain.

2.2.1. Resource mining

Lithium ore is mined pegmatite deposits using traditional drill and blast methods. The lithium ore, which contains 1.0–4.2% Li_2O, is then fed into the processing plants and processed with gravity, heavy media, flotation and magnetic processes to become lithium concentrate (Talison, 2012). Two types of lithium concentrate, technical-grade lithium concentrate and chemical-grade lithium concentrate, are simultaneously produced. The technical-grade lithium concentrate, with 5.0–7.5% Li_2O and very low iron levels, are primarily used for manufacturing glasses and ceramics. The chemical-grade lithium concentrate, with 6.0% Li_2O and relatively higher iron levels, is further processed in lithium chemical plants to produce lithium chemicals.

Brine is typically extracted from subsurface deposits and pumped into solar evaporation ponds for concentration. The concentrated brine is then fed into the chemical plants for processing of various lithium chemicals.

In China, lithium minerals and brines are sourced from both domestic deposits and foreign imports. Spodumene concentrate imports from Australia are the major source. Specific flow values are calibrated based on data sources detailed in the SI documentation.

2.2.2. Chemical production

A range of commercial scale lithium chemicals are currently produced including lithium carbonate, lithium hydroxide, lithium chloride, lithium metal, and their derivatives. Using lithium carbonate production as an example, the concentrated lithium mineral or brine is processed in chemical plants removing impurities, which is then processed with sodium carbonate to form lithium carbonate. Lithium carbonate is then used to produce a range of battery cathode and electrolyte materials including lithium cobaltate (LCO), lithium manganate (LMO), lithium iron phosphate (LFP), lithium nickel-cobalt-manganese oxide (NCM), and lithium hexafluorophosphate (LiPF).

Lithium chemical production estimations are primarily based on CNMIA data (CNMIA, 2016). Significant import and export of lithium chemicals also occur within this stage, this data is obtained from GAC (2016).

2.2.3. Product manufacture

Lithium carbonate is a necessary ingredient for such goods as battery cathodes production, ceramic glazing, and aluminum electrolysis. Lithium hydroxide is mainly used for producing lithium-base lubricating greases, with a minor but increasing amount for battery production. Lithium concentrate is typically used as a fluxing agent in the glass and ceramics industries. Other applications for lithium include, but are not limited to, pharmaceuticals, polymers, alloys, nuclear, optics, and air purification (Ebensperger et al., 2005). Both globally and in China, the three major lithium industrial applications include lithium-ion batteries, lubricating greases, and glasses/ceramics. These three applications account for approximately three quarters of lithium consumption.

For this stage estimations, lithium is allocated to different products using a bottom-up approach, as detailed in the SI documentation. For example, the lithium consumption by electric vehicles is determined by identifying the number of electric vehicles produced, battery capacity per vehicle, and lithium content per unit of battery capacity. The estimations of battery intensities and lithium intensities are summarized in Fig. 4, with details in the SI documentation. It should be noted that large-scale export of lithium products occurs at this stage. The exports of lithium-ion batteries, mobile phones, laptop computers and tablet computers are also considered.

2.2.4. Product use

For the product use stage the lithium embodied in the products has two potential outcomes depending on lithium product's dissipative or recyclability characteristics (Ziemann et al., 2012). For recyclable

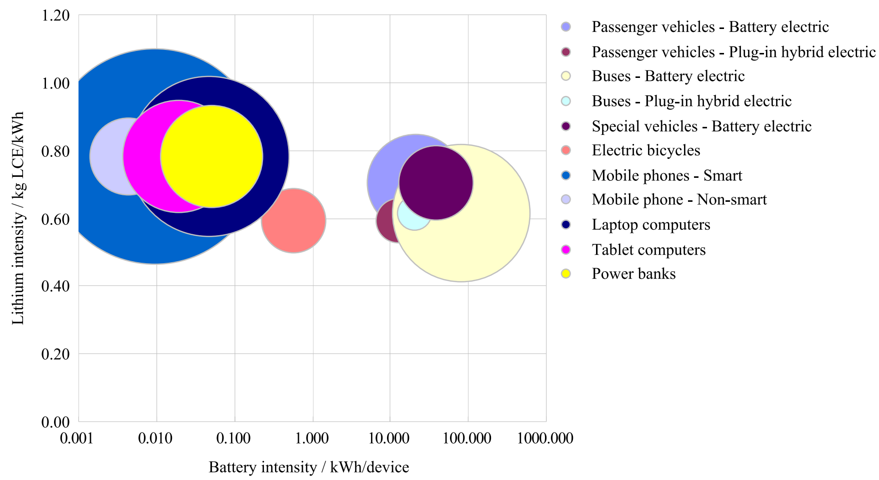

Fig. 4. Battery intensities and lithium intensities of lithium-ion battery-containing products. Note: Bubble size denotes the total relative lithium consumption by a product.

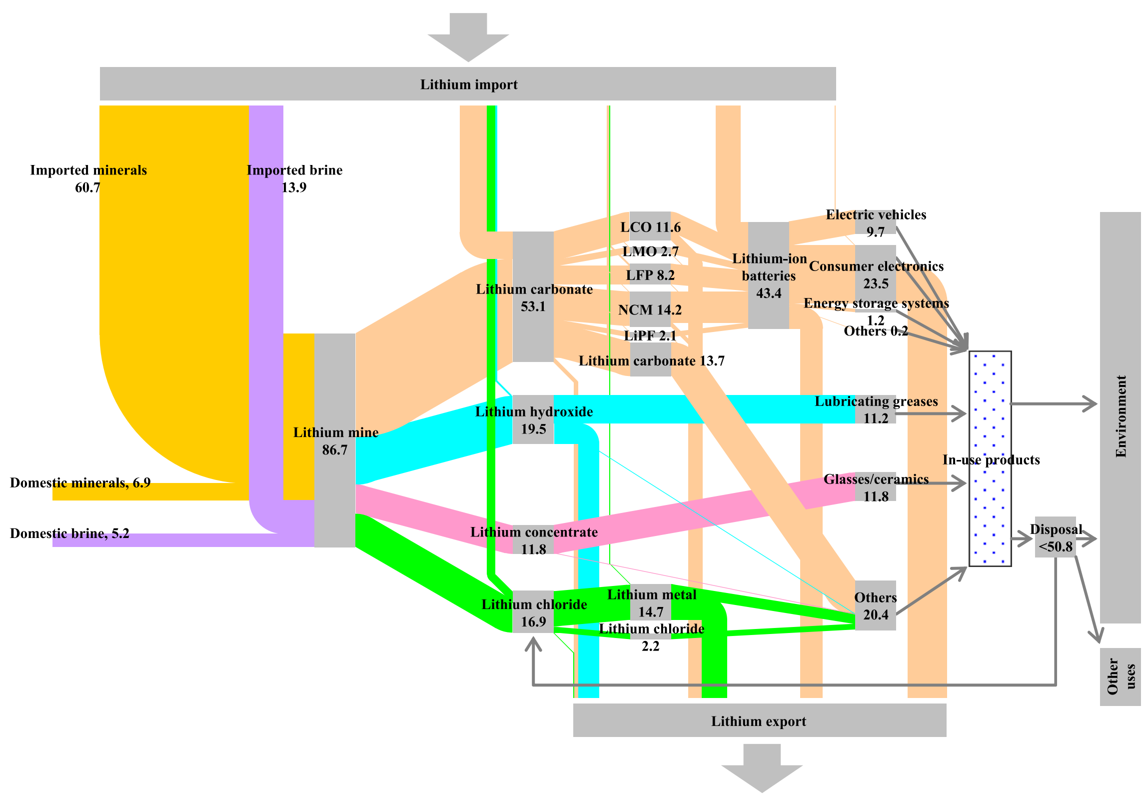

Fig. 5. Lithium flow in China for the year 2015.

lithium products, such as lithium-ion batteries, glasses/ceramics, and alloys, the lithium is either stocked in the products, or disposed of for further treatment. Disposed lithium can be theoretically recycled for further uses. For dissipative lithium products, such as lubricating greases and pharmaceuticals, lithium is released into the environment during the use stage. Dissipative products are typically not recycled. This outflow also contains minor dissipative lithium losses from the lithium products.

It is difficult to accurately aggregate lithium outflows at the product use stage due to poor data availability. For this study, the outflows are estimated for general ranges. The outflow to the environment is estimated using dissipative lithium production quantities in addition to minor losses accruing from recyclable lithium products. Disposed products are estimated using recyclable lithium production quantities, while subtracting stocked lithium and minor losses from the use stage. Since the stocked lithium within the use stage does not have concrete data and is vague, it is only symbolically marked.

2.2.5. Waste management

Disposed lithium material treatment methods during the waste management stage include three potential streams. The first flow stream returns to the manufacture stage. This flow is represented by recycling of primary and secondary lithium batteries. In this flow lithium carbonate, lithium hydroxide and other lithium chemicals can be recovered for further reuse (Dunn et al., 2012). These recovery operations have been commercialized at a small scale in China (GEM Co. LTD, 2016). The second flow goes to other uses, where lithium is not a functioning unit. An example of this flow is represented through use of waste ceramics in road construction (Ziemann et al., 2012). The third flow goes to the environment. Lithium-containing wastes treated with general waste management such as landfill and incineration, are included in this flow.

China's recycling industry data are limited. It is currently difficult to accurately determine each waste management flow quantity. An assumption is that the major flow stream is to the environment. The lithium recovered for secondary uses are limited. Current lithium-ion battery recycling in China has a weak infrastructure and is also limited. A vast majority of disposed lithium-ion batteries is treated as general waste. When lithium-ion batteries are recycled most operations aim at recovering precious metals such as cobalt and nickel. Recycling purposes for lithium recovery are relatively unknown. However with an increasing lithium market price it is expected that recycling of lithium-ion batteries will increase.

3. Results

The resulting lithium mass analysis flow chart for China is summarized in Fig. 5. More specific numbers can be found in the SI documentation.

China's total lithium resource consumption was 86.7 kt of LCE in 2015, accounting for 50% of the global total. This consumption was primarily supported through lithium resource imports, which contributed to 86% of the total lithium supply. Whereas general global supply relies primarily on brine-dominated lithium, China's supply primarily relies on minerals lithium sources, which account for 78% of China's total supply.

Lithium carbonate production in 2015 was 42.0 kt of LCE, accounting for 48% of total lithium chemical production. A majority (73%) of lithium carbonate was used for production of battery materials, including NCM (27%), LCO (23%), LFP (15%), LMO (5%), and LiPF (4%). The production figures of lithium hydroxide, lithium concentrate, and lithium chloride were 19.4, 11.8, and 13.5 kt of LCE, respectively. Lithium chloride major usage (87%) was for lithium metal production, which forms the basis for producing other derivatives. Considerable lithium flow occurs in international trade of lithium chemicals, which is represented by lithium carbonate imports (11.1 kt of LCE), lithium hydroxide exports (8.3 kt of LCE), and lithium metal exports (10.2 kt of LCE). Thus, there is a net outflow of 10.0 kt of LCE lithium chemicals out of China, or 12% of the entire flow.

As Fig. 6 shows, the lithium consumption figures for the three major lithium applications, namely lithium-ion batteries, lubricating greases, and glasses/ceramics, were 33.3, 11.2 and 11.8 kt of LCE, respectively. These three applications account for 73% of all lithium consumption. The other 27% can be attributed to pharmaceuticals, dyes, and catalysts, which are not further specified due to lack of data. Lithium-ion battery usage includes: consumer electronics (68%), electric vehicles (28%), and energy storage systems (3%). Electric vehicle lithium-ion battery for the production of electric vehicles was led by pure electric buses (13%) and pure electric passenger vehicles (7%). Significant quantities of lithium outflow were embodied in the export of lithium products, estimated to be 14.7 kt of LCE and representing 17% of the entire flow.

4. Discussion

Lithium mass flow analysis in China can provide a number of insights for Chinese policymakers. Insights can be gained for general resource scarcity environmental concerns and recycling, but issues will also be tied to development of environmental technologies.

Lithium is likely to become a resource constraint electric vehicle technology both in China and globally. Historically, adequate lithium resources for industrial applications were believed to exist. Demand for consumer electronics and mobile telecommunications technology growth over the past decade increased demand for lithium-ion batteries. But, development of improved lithium mining technologies and low battery capacities needs for consumer electronic devices meant that the lithium resource supply-demand balance was not substantially affected.

But, there also has been greater pressure to reduce vehicle emissions that cause localized pollution including smog and particulate matter and global greenhouse gas emissions. These pressures have caused growth in electric vehicle demand. These vehicles are heavily dependent on high capacity batteries, with lithium a primary ingredient resulting in demand for exponentially greater demand for lithium resources. For example, the battery capacity of a Tesla Model S 85D car (85 kW h) is more than ten thousand times the battery capacity of an Apple iPhone 6 (6.9 W h) mobile phone.

In response to the aforementioned environmental issues from transport technology, governments and private corporations have set ambitious targets for market penetration of electric vehicles (Zhou et al., 2015). Greater goals and potential growth in electric vehicle demand, means greater need for vehicle batteries. The lithium-ion battery is currently the most technologically mature and economically feasible solution. Other emerging technologies such as graphene batteries and metal-air batteries are still relatively immature technologies with significant uncertainties and risks. Although, there is some disagreement on whether lithium resources for electric vehicles are tightly constrained (Egbue and Long, 2012; Gruber et al., 2011; Kesler et al., 2012; Scrosati et al., 2011; Wanger, 2011), more and more studies, especially the recent studies, tend to believe that electric vehicle development will be an issue for lithium supply, both on the global scale (Sverdrup, 2016) and the regional scale (Miedema and Moll, 2013; Richa et al., 2014). In China, the government set very ambitious targets for the market penetration of electric vehicles, which are 7% by 2020 (around 2 million), 15% by 2025 (around 5 million) and 40% by 2030 (around 15 million). If the electric vehicle market grows as expected, a general estimation is that lithium demand from electric vehicles will be around 3, 5 and 15 times the current level by 2020, 2025 and 2030. It is clear that government and industry will need to pay greater attention to conservation and recycling of lithium resources.

Not only is the lithium quantity an issue for Chinese policy makers, but sourcing also plays an important role. Substantial dependence on lithium imports threatens China's national resource security. In 2015, reliance on lithium imports by China reached 86% of all lithium

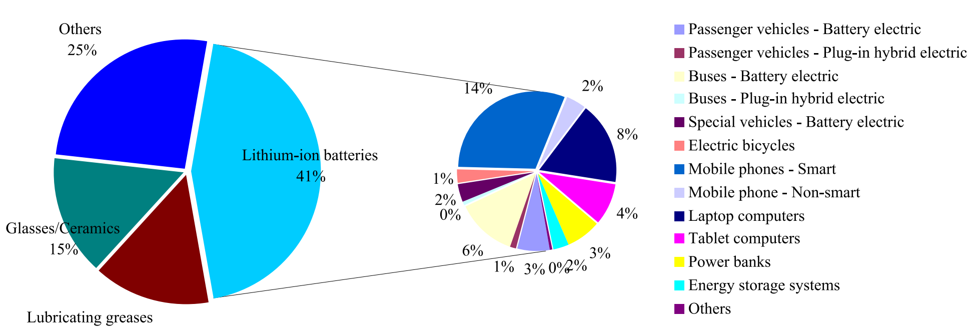

Fig. 6. Lithium consumption by application.

supplied to China. Given rapidly increasing lithium demand due to production needs and lack of increased domestic resource finds, it is expected that lithium imports dependence will increase. Given that crude oil imports at a 60% dependence level is widely considered a threat to China's national energy security, higher dependence on lithium imports is also likely a national resource security risk. Consequently, for both strategic economic and environmental reasons, establishing lithium reserves is a prudent national policy. Globally, it has been observed that a significant gap between lithium production and consumption exists and it is in the strategic interest of nations to stockpile lithium for future technologies (Ziemann et al., 2012).

Stockpiling through imports or greater exploration and domestic mining is not the only approach for government policy makers. Significant opportunities exist with lithium recycling. As discussed, embodied lithium in different products have varying recycling potential. Batteries represent the most significant potential for secondary lithium recovery. Lithium embodied in used batteries are high-quality lithium sources. In 2015, lithium consumption from lithium-ion battery production accounted for 43% of all applications. Given high demand for lithium-ion batteries and the high-quality embodied lithium in these batteries greater attention on recycling them is a judicious policy. There is substantial opportunity for government and industry to establish a recycling-based lithium supply system.

One substantial initiative that can be tied to managing scarce lithium resources domestically in China is through China's circular economy policy. China's policy can target lithium flows as a critical strategic flow for supporting its circular economy. The circular economy policy has invested billions in setting up structures such as eco-industrial parks, municipal recycling, and various industrial waste exchanges to help address resource and energy dependence limitations. Integrating lithium resource flows into this broad-based economic and environmental policy is a strategic opportunity for policy makers. Industry has been an important partner in this voluntary policy with development of new technologies and infrastructure. These developments have also provided competitive opportunities for industry such as decreased import costs and technology that can be developed and marketed. Deep and profound technological and economic opportunities currently exist for the lithium cycle. With some of these policies lithium scarcity pressures will not only be mitigated domestically for China, but also globally.

The circular economy policy in China is domestic. Significant lithium resources are exported in battery-containing products, which challenge Chinese domestic lithium recycling and circular economy policies. Export flow estimates in this study showed that 14.7 kt of LCE was exported in 2015. Lithium-ion batteries, mobile phones, laptop computers, and tablet computers accounted for 17% of the entire flow. Exporting makes it difficult for domestic battery manufacturers to manage and plan for the characteristics of the batteries. Tracing the use, recycling batteries, and maintaining information is a very difficult task. In the absence of this battery manufacturer information and management international recycling efforts cannot be optimized. Although, international regulatory policies like take-back legislation can be better managed to gather and manage this information of flows. Such an effort will require significant global data control, integration and management. If the circular economy context for lithium flows is to be expanded as a global policy, unifying battery manufacturing and recycling standards across different nations is needed. Establishing a rigorous, transparent, and accurate information platform for the import and export of lithium-ion battery-containing products will benefit the growth and improvement of lithium resources without further depletion of these resources and the commensurate environmental burden of mining.

Meanwhile, the government must be fully aware that although recycling promises potentials for solving lithium scarcity, over-optimism should be avoided. First, for the recycling of exported lithium-containing products, because the e-waste will not return or be re-imported, the recycled lithium does not flow back to China's domestic system. Second, the lifetime of an electric car is normally above 10 years, much higher than mobile phones. This delay between acquisition and disposal of an electric car will reduce further the contribution of recycling to solving lithium scarcity and price problems, especially in the case of a strong growing demand for electric vehicles.

It is recognized that the economics of lithium resources shows increase in costs of lithium, especially in China. This study sets the foundation and presents a clearer picture of these flows. This picture is an important and necessary first step to help manage lithium resources from an economic, environmental and technological perspective.

Acknowledgement

This study is sponsored by the National Natural Science Foundation of China (71403142, 71690241, 71461137008, 71325006, 71311140172), State Key Laboratory of Automotive Safety and Energy (ZZ2016-024). The authors would like to thank the anonymous reviewers for their reviews and comments.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.resourpol.2016.12.005.

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