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UPSCALING LITHIUM IRON PHOSPHATE (LFP)
BATTERY PRODUCTION FOR BOLIVIA

Global material flows of lithium for the lithium-ion and lithium iron phosphate battery markets

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Global material flows of lithium for the lithium-ion and lithium iron phosphate battery markets

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Editor

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Lithium-ion rechargeable battery pack. © iStock.com/ JanakaMaharageDharmasena.

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) funded by the Energy Catalyst Round 7 programme. The concept of this study has been developed in collaboration with our project partners University of Cambridge and Nyobolt, as well as our industrial collaborators in Bolivia (YLB) and the British Embassy in Bolivia.

BGS staff that contributed to this study include Dr Evi Petavratzi and Dr Pierre Josso.

The report was edited by Richard Shaw and reviewed by Andrew Hughes.

Acknowledgements

In addition to the BGS staff acknowledged in the Foreword we would like to acknowledge the contribution of our project partners (University of Cambridge and Nyobolt), our industrial partner YLB, the support and assistance of the British Embassy in Bolivia, as well as a range of stakeholders who we had discussion with over a period of years and who have assisted us to improve data availability regarding the lithium extraction and processing stages. Many of them provide ongoing support and data to our World Mineral Statistics database.

Of the many individuals who have contributed to the project we would particularly like to thank our colleagues from the Norwegian University of Science and Technology, who have provided support with the MFA modelling and contributed to useful discussions on the lithium cycle.

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Summary

We conducted a material flow analysis (MFA) model for a single year (2018) to understand the global flows of lithium from primary extraction to lithium-ion battery (LIB) use in four key sectors: automotive, energy and industrial use, electronics and other. A specific focus and quantification of lithium use in lithium iron phosphate (LFP) cathodes for LIB batteries is also given. This is to align with the overall focus of the project on LFP cathode materials and to assist in decision making for the Bolivian stakeholders of this project.

The stages included in the model are: extraction, processing, cathode manufacture, other manufacture (non-battery), lithium-ion battery (LIB) manufacture, lithium iron phosphate battery manufacture (LFP) and the end-use sectors of automotive, energy and industrial use, electronics and other. We visualised the model using a Sankey diagram.

Some of our key conclusions are summarised below:

- The hard rock deposits dominated production of lithium in 2018. This was not the case a few years back, where lithium from brine deposits constituted the primary source.
- There are significant losses of lithium to waste both at the extraction but also at the processing stages. This is due to low recovery rates.
- The battery compound market did not monopolise the global lithium markets in 2018, but it has been growing fast for several consecutive years. In 2010 the lithium battery market share was estimated to be 31%, in 2018 46%, and in 2021 71% (USGS 2021b).
- We have identified an oversupply of lithium compounds used in cathode manufacture in 2018. This finding is in line with several reports mentioned by market analysts suggesting oversupply of lithium in the market in this year (Shabalala 2018, Erkan 2019).
- LIB LFPs were the second largest cathode market after NMC cathodes. Their manufacture and use have been taking place almost solely in China. In recent years however LFP cathodes seem to have made a comeback and projections suggest increasing demand for them from the automotive and energy storage sectors. This is an opportunity for countries like Bolivia who are willing to proceed with the commercialisation of LFP batteries.
- In 2018 LFP cathodes for the automotive sector was the largest consumer of lithium, with energy storage and industrial uses being the second dominant end-use consumer.
- There are data uncertainties associated with all stages of the supply chain. Data are dispersed and not fit-for-purpose, especially for the cathode and LIB manufacturing stages. Considering the global focus on decarbonisation technologies and LIBs, this means that these markets are likely to increase significantly in the short-term. It is therefore essential that material requirements and use are reported accordingly to ensure frictionless supply and proper use of resources at the end of their life.
- The lithium market is extremely dynamic with significant changes occurring from one year to the next. There is a need therefore for further enhancement of our current model to a dynamic form that explores transformation pathways, develops future scenarios, looks in more detail at the environmental impacts of different stages and also includes the 'use' and 'end-of-life' stages.

1 Introduction

This report describes the approach we undertook in quantifying global lithium flows from primary extraction to lithium-ion battery use, with additional focus given to lithium use in lithium iron phosphate (LFP) cathode materials.

The approach is based on material flow analysis (MFA), which is an assessment of the flows and stocks of materials based on a system defined within space and time. The MFA approach utilises the law of conservation of matter and therefore input, output flows and stocks of materials are quantified using the mass balance principle (Brunner and Rechberger 2017). Material flow analysis is a common method used to understand and monitor the physical economy and its results could be utilised in decision making and for strategy development associated with sustainable resource use.

The lithium market is rapidly developing due to the global focus on decarbonisation technologies, in particular the electrification of transport and the development of energy storage solutions, but also throughout the past decade with increasing demand for lithium-ion batteries in electronic devices. Projections suggest that the demand for lithium may have to increase 42 times relative to the 2020 demand to support the clean energy transition (IEA 2021). This would require a significant increase in supply over a very short period of time. It therefore requires very close monitoring to quickly identify hotspots that may disrupts supply, but also lead to unsustainable practices, environmental degradation and social issues in producing countries.

The aim of this work was to develop a MFA model for monitoring the global lithium flows with focus on the battery market. Althought this has been investigated to some degree in the past by others (Hao, Liu et al. 2017, Sun, Hao et al. 2017, Calisaya-Azpilcueta, Herrera-Leon et al. 2020), the focus on LFP cathodes is missing and the latest models in publication are for 2015. We provide an updated approach and data that correspond to 2018. Although our current model is for a single year, this forms the basis for developing a dynamic assessment in the future to monitor the lithium stocks and flows over many years.

2 System definition

A system is the description of the stages, processes and steps included in a material transformation journey. It describes without quantifying the point in a process and locations of materials (stocks) and how they flow across an economy (MinFuture 2021). Setting the system definition is the first step in the process of material flow analysis and it requires substantial background work through literature searches and stakeholder engagement. Very often our system understanding is poorly defined and highly fragmented, especially so for minor elements such as lithium.

For developing the system definition, we reviewed numerous reports, scientific papers, but also used information we collated from stakeholders through discussions held prior and during this project. Our lithium system is illustrated in Figure 1. The system includes the processes taken into consideration in our analysis (in yellow boxes), the flows of materials between processes and how they link to each other (arrows in grey, turquoise for LFP related flows and blue for waste flows), the points where losses are quantified (blue boxes) and the points where stocks are estimated (red boxes). The legend under the diagram provides some more detailed information on the lithium flows.

The stages/processes are described as follows:

- **Extraction** This refers to mining of lithium brines and hard rock lithium deposits. Due to the diversity of different lithium deposits the complexity associated with understanding the

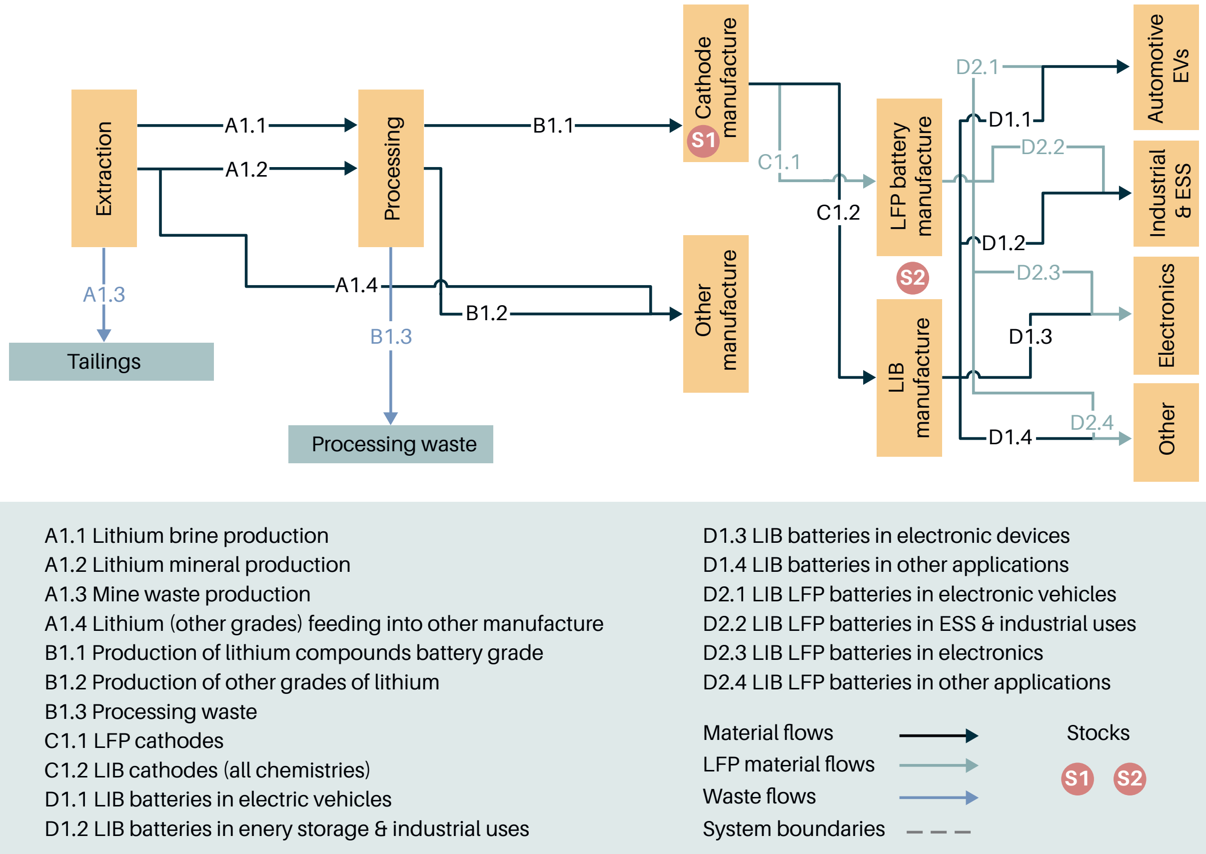

Figure 1 The global lithium system definition for LIB and LIB LFP batteries.

processes of lithium production and therefore material flows is substantial and likely to increase further as production from more diverse sources may take place in the future. Overall, this is the stage better understood and with better data reported across the overall lithium cycle.

- **Processing** This stage refers to the processing and refining of lithium to produce material grades that can reach the downstream supply chain and lithium markets. In this case and considering that the focus of this system is on batteries, we consider that the input form of lithium in the processing stage represents either a concentrated brine or a mineral concentrate from hard rock deposits, with the output material to be battery grade lithium compounds, and other lithium compounds.
- **Cathode manufacture** This stage represents the manufacturing of LIB cathodes. The input material is the battery grade lithium compounds, whilst the output forms of material are the various LIB cathodes. We consider the cathode chemistries in our analysis, as presented in Table 1. The market shares of different cathodes used in our analysis are as shown in Figure 2.
- **Other manufacture** This stage represents the use of lithium in markets other than batteries, for example in ceramics and glass, lubricating greases, continuous casting mould flux powders, polymer production, air treatment and others (Figure 3). Lithium compounds entering this stage could be of a diverse range of forms and chemistry, such as lithium hydroxide, lithium chloride and different grades of lithium carbonate.
- **LFP battery manufacture** This stage refers to the LIBs using LFP cathodes in their manufacture only. The input material stream is LFP cathodes and the output material is LIB batteries with LFP cathodes.
- **LIB manufacture** This stage represents the total LIB batteries market including LFP cathodes. The input material stream is the total LIB cathodes produced (all chemistries) and the output represents the total LIB battery production. The LIB market shares for 2018 are presented in Figure 2.
- The final stages represent key end-use sectors for the LIB batteries market. These include the automotive, industrial uses (e.g. in power tools) and energy storage, electronics and other minor uses of LIB batteries.

Table 1 LIB cathode chemistries considered in the MFA model.

Cathode chemistry	Formula	Li(%)
Lithium Iron Phosphate (LFP)	$LiFePO_4$	4.40
Lithium Nickel Manganese Cobalt Oxide (NMC 532)	$LiNi_{0.5}Mn_{0.3}Co_{0.2}O_2$	7.19
Lithium Nickel Manganese Cobalt Oxide (NMC-111)	$LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$	7.19
Lithium Nickel Manganese Cobalt Oxide (NMC-622)	$LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$	7.16
Lithium Nickel Manganese Cobalt Oxide (NMC-811)	$LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$	7.13
Lithium Manganese Oxide (LMO)	$LiMn_2O_4$	3.84
Lithium nickel cobalt aluminium oxide (NCA)	$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$	7.22
Lithium Cobalt Oxide (LCO)	$LiCoO_2$	7.09

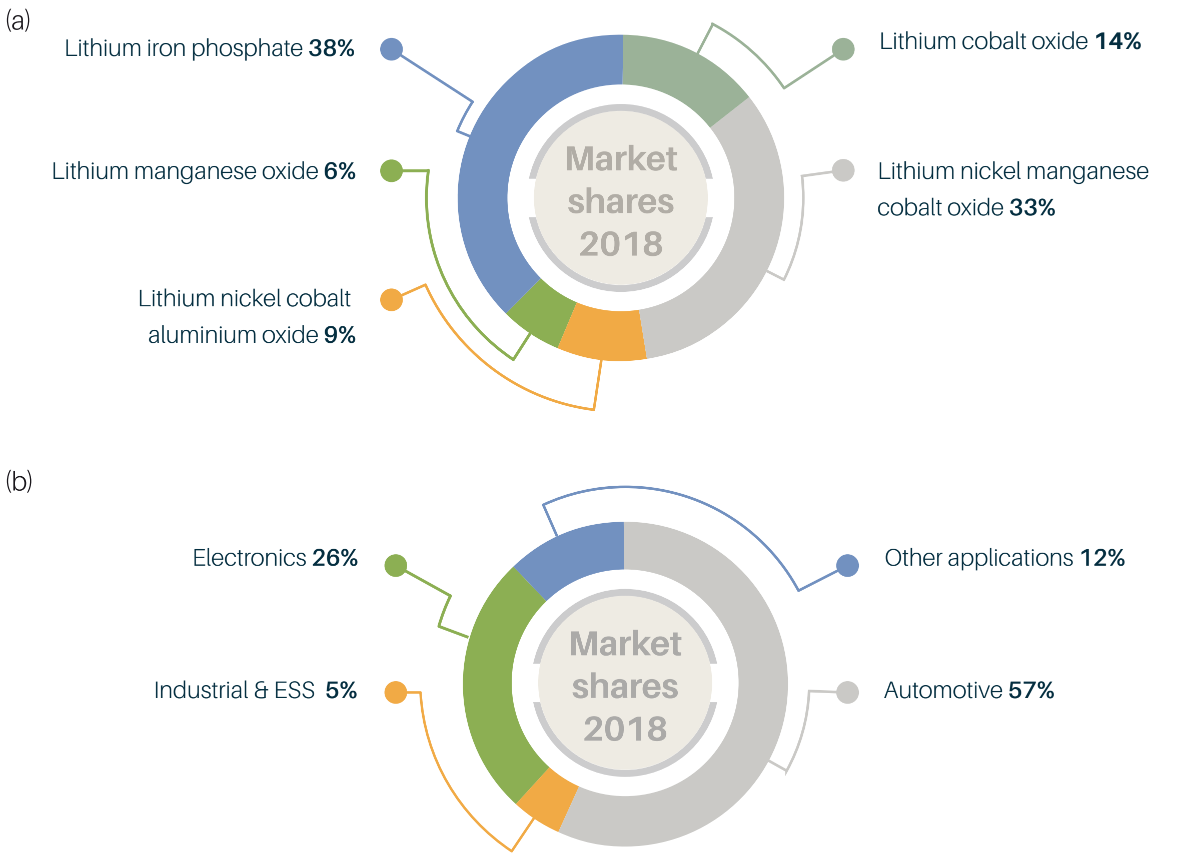

Figure 2 (a) Cathode active materials market shares for 2018, reproduced from (Or, Gourley et al. 2020), (b) LIB market shares for 2018. Modified after Sanders, 2017 (Sanders, 2017).

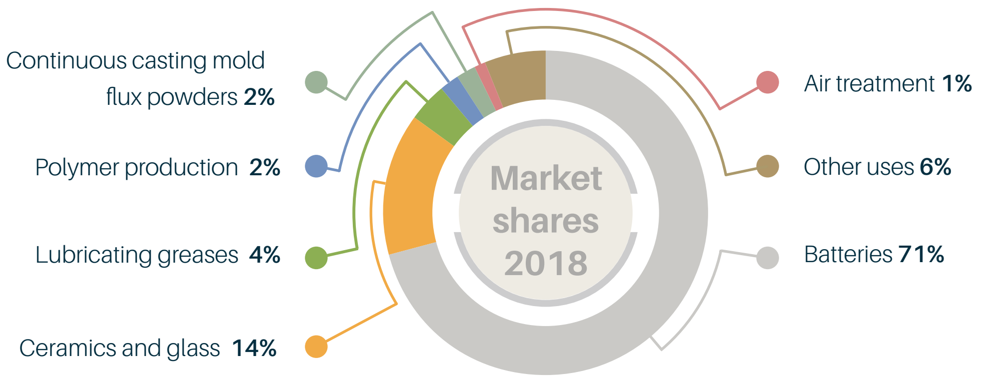

Figure 3 End use market shares of lithium compounds. Data from US Geological Survey (USGS) (USGS 2021a).

3 Quantification of material flows

The material flows analysis model developed is presented in Figure 4. The calculations undertaken to quantify the flows of lithium across this cycle are presented in the spreadsheet attached to this report. A variety of calculations are required to come up with the figures presented in the model and a wide range of data sources have been used to produce these.

Some key points to consider when exploring this model are:

- The visualisation used is a Sankey diagram. The width of the Sankey bars is proportional to the mass of the lithium found in a particular stage. All figures are reported in tonnes of contained lithium.
- This is a static model developed for a single year (2018).
- For the first two stages (extraction and processing) we follow the flows of materials based on the two key geological lithium sources. Lithium is produced either from lithium brines, or from hard rock deposits producing the lithium bearing mineral spodumene.
- Data availability and accessibility is a major obstacle to undertaking this type of work. Information available from reported sources is very limited, so several calculations are based on our own estimates using informed assumptions and mass balances.
- Stakeholder consultation is critical for refining the system understanding, gathering data and evaluating calculations. We have engaged with a range of stakeholders from the mining, processing and beneficiation, as well as battery chemistry domains to refine and inform some of our figures.
- For lithium derived from brine deposits, our calculations have considered the following figures:
    - average brine density of 1208 kg/m^3
    - average lithium concentration of 0.083 wt. %
    - average lithium recovery rate of 50%
- For lithium derived from hard rock deposits the following are considered:
    - only the spodumene production is going into the battery market
    - average recovery of spodumene at the mine stage is 60%, the rest ending in mine waste
    - non-spodumene lithium production is utilised in applications and markets that are not related to batteries
    - average recovery of lithium carbonate from spodumene is 85%
- For quantifying the lithium in the cathode and battery manufacture stages we utilised the market shares presented in Figure 2. For LIBs we assumed an average lithium concentration of 0.12kg/kWh.
- The stocks of lithium in cathode manufacture and LIB manufacture are calculated by mass balance. They are likely to include not just material in stocks collected in a particular stage, but also losses of material e.g. from manufacturing waste which we were not able to quantify.
- The uncertainties associated with data are likely to be high in particular for the cathode and LIB manufacturing stages as the majority of data are not found in open public data but in private databases. Also, both of these manufacturing stages are dominated by China, meaning that related data are even more difficult to locate and access.
- The model developed is by no means complete and without uncertainties. Nevertheless, it provides important insights regarding the lithium availability and potential for growth of the battery market.

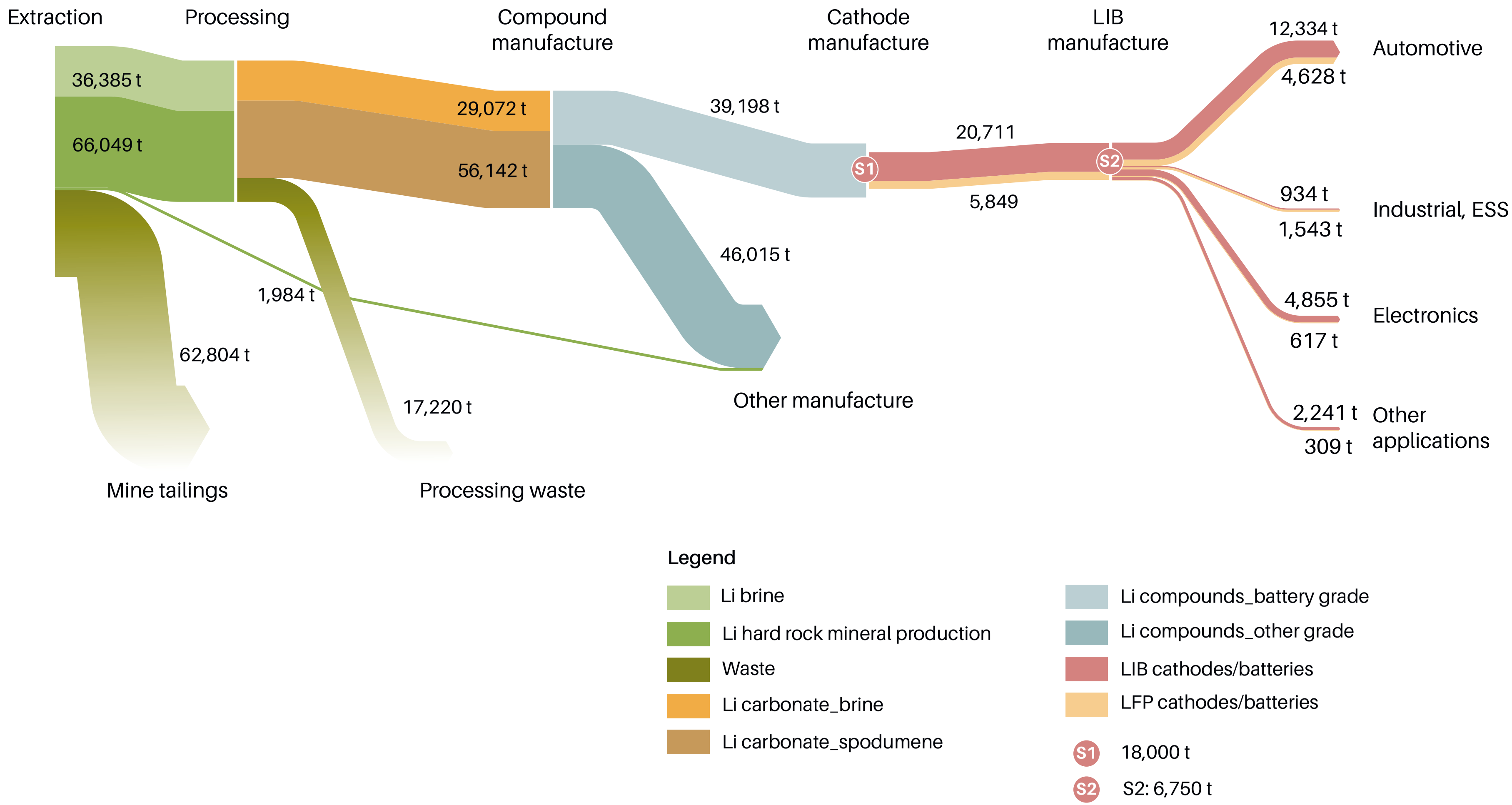

Figure 4 Material flow analysis model of the global lithium to LIB and LIB-LFP cycle. All values are in tonnes of contained lithium.

4 Conclusions and recommendations

The model outlines the lithium journey from extraction to lithium-ion battery (LIB) manufacture with additional information provided on the lithium iron phosphate (LFP) batteries flows (Figure 4). Although the demand for lithium is a subject of constant discussion due to its use in LIBs supporting a range of decarbonisation technologies (e.g. electric vehicles and energy storage solutions), our understanding of the supply of lithium and potential bottlenecks has been based on qualitative rather than quantified information. Attempts to quantify the global lithium cycle were undertaken in the past, but this information requires further refinement and update, which we hope to have enhanced through our work. Previous models (Hao, Liu et al. 2017, Sun, Hao et al. 2017, Calisaya-Azpilcueta, Herrera-Leon et al. 2020) are based on 2015 figures, have specific geographical focus (e.g. China) or a different perspective (e.g. trade linked global model), the system understanding of the upstream stages (mining, refining) is missing the geological understanding and therefore is not properly defined, and finally losses to the environment are not quantified.

Our key findings and recommendations are summarised below:

- The hard rock deposits dominated production of lithium in 2018. This was not the case a few years back, where lithium from brine deposits comprised the primary source. The change in the primary source supply dynamics has geographical implications i.e. for the first time Australia has become the biggest lithium producer with Chile coming into the second place in 2018 and 2019 (Figure 5). An additional implication of this change is in the processing and beneficiation stages as brine producers would commonly trade lithium compounds (i.e. lithium carbonate), whilst Australia would trade a concentrate which requires further processing, often taking place in China, to produce lithium compounds (Figure 6).

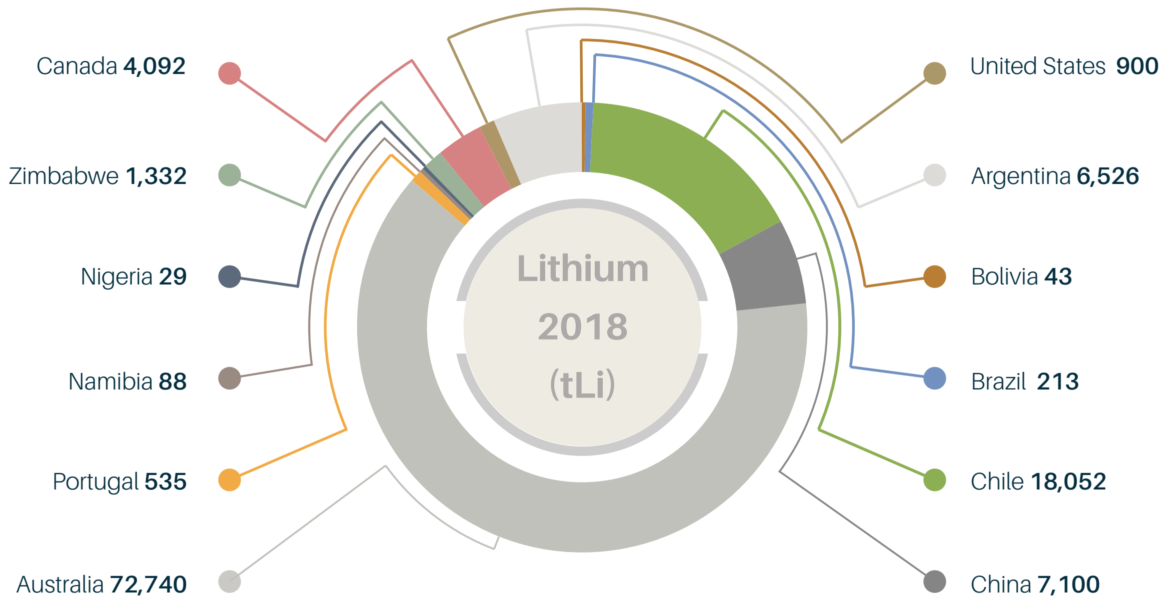

Figure 5 Global mineral production of lithium in 2018 in tonnes of contained lithium (BGS 2021).

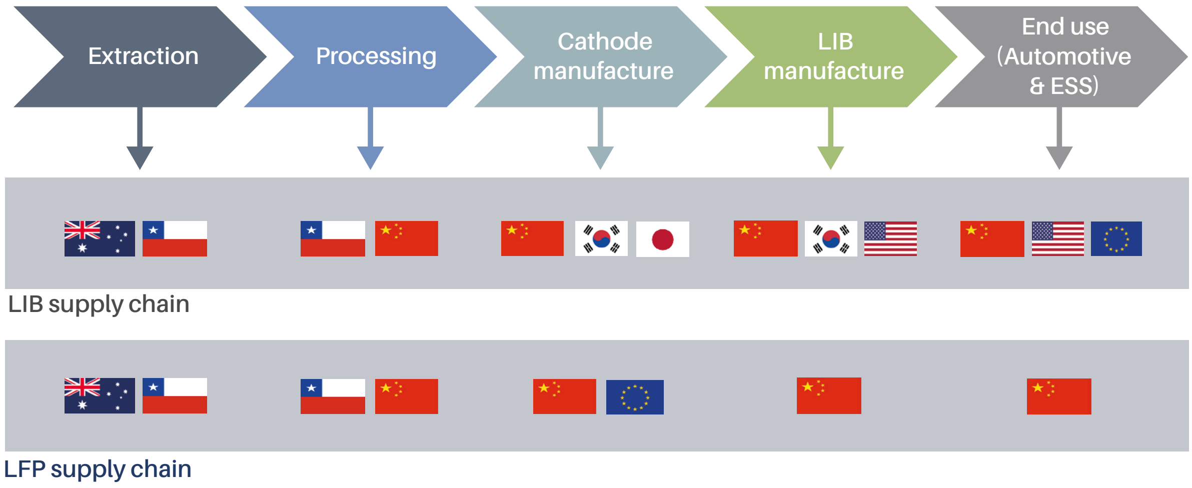

Figure 6 The LIB supply chain and key counties participating in this. Differences between the LIB and LFP supply chains are presented.

- An important result of the MFA model are the losses of lithium observed in waste both at the mining but also at the processing stages. These figures should be treated with caution however, as the recovery rates and processing technology varies between different operations. Nevertheless, overall the recovery rates from brine deposits are about 50% and from spodumene deposits around 60%, which means that significant quantities of lithium are not recovered and ends up in the waste stream. In the processing stage recoveries are higher (~85%), but not as high as for other industrial metals that are often above 90%.
- The battery compound market did not monopolise the global lithium markets in 2018, but it has been growing fast since 2015. In 2010 the lithium battery market share was estimated to be 31%, in 2018 46%, and in 2021 71% (USGS 2021b). The lithium battery compounds market is developing at pace, but without new supply coming on stream at the same rate means that supply issues are likely to occur in the future. This could likely cause competing demands with other lithium markets and potential disruption, but also price spikes and impacts on the downstream supply chain.
- There is an important imbalance between the cathode and LIB manufacturing stages, which we can only explain with stocks of lithium being built up in the system. This finding is in line with several reports mentioned by market analysts suggesting oversupply of lithium in the market in this year (Shabalala 2018, Erkan 2019).
- LIB LFPs were the second largest cathode market after NMC cathodes. Their manufacture and use have been taking place almost solely in China. In recent years however the LFP cathodes seem to have made a comeback and projections suggest increasing demand for them from automotive and energy storage applications. This is due to several reasons, including new EV safety regulations in China, the fact that patent restrictions over LFPs are expiring in 2022 and supply restrictions with materials essential in other cathode chemistries, such as cobalt (Roskill 2020). Changes such as these are likely to have impacts across the whole lithium supply chain. At the same time, this is an opportunity for countries such as Bolivia who are willing to proceed with the commercialisation of LFP batteries.
- There are data uncertainties associated with all stages of the supply chain. The stages of cathode and LIB manufacture are not reported in a consistent and comprehensive way. Data are dispersed and not fit-for-purpose, whilst common reporting of statistical data do not offer the resolution required to undertake this type work. Considering the global focus on decarbonisation technologies and LIBs means that these markets are likely to increase significantly over the short-term. There is a need for data reporting to change

to allow the monitoring of the decarbonisation transformation taking place. Reporting of production, sales, consumption and trade data should be accompanied by good metadata information. For example, for cathodes and batteries distinguishing the different chemistries and material content is of critical importance not only for understanding material consumption and demand, but also for exploring resource efficiency routes at the end-of-life. Reporting of waste, scrap and recycling data should link to industrial production processes and provide information on material and substance content. Only through good data reporting we can ensure frictionless supply and proper use of resources at the end of their life.

- In 2018, the automotive manufacture comprised the largest consumer of lithium in comparison to all other end uses, followed by electronics, energy storage and industrial uses. For the LFP cathodes, the automotive manufacture was also the largest consumer of lithium, with energy storage and industrial uses being the second dominant end use consumer.
- The lithium market is extremely dynamic with significant changes occurring from one year to the next. There is a need therefore for further enhancement of our current model to a dynamic form that explores transformation pathways, develops future scenarios, looks in more detail at the environmental impacts of different stages and includes the 'use' and 'end-of –life' stages too. This would require a deep-dive in lithium and significant stakeholder engagement to produce such an enhanced model.

Appendix 1

The calculations, data and data sources utilised for this model development can be found in the supplementary information and by clicking the link below.

References

BGS. (2021). World mineral statistics dataset. UK, British Geological Survey.

Brunner, P H and Rechberger, H. (2017). Handbook of material flow analysis. For environmental, resource, and waste engineers London, CRC Press.

Calisaya-Azpilcueta, D, Herrera-Leon, S, Lucay F A and Cisternas, L A. (2020). 'Assessment of the Supply Chain under Uncertainty: The Case of Lithium'. Minerals **10**(7): 604.

Erkan, B. (2019). Lithium outlook uncertain amid growing demand, oversupply and potential disruptive technologies, Proactive — Mining.

Hao, H, Liu, Z, Zhao, F, Geng, Y and Sarkis, J. (2017). 'Material flow analysis of lithium in China'. Resources Policy **51**: 100–106.

IEA. (2021). The Role of Critical Minerals in Clean Energy Transitions. France International Energy Agency.

MinFuture. (2021). 'Global material flows and demand-supply forecasting for mineral strategies'. Retrieved 14/09, 2021, from https://www.minfuture.eu/.

Or, T, Gourley, S W D, Kaliyappan, K, Yu, A and Chen, Z. (2020). 'Recycling of mixed cathode lithium-ion batteries for electric vehicles: Current status and future outlook'. Carbon Energy **2**(1): 6–43.

Roskill. (2020). Batteries: The true drivers behind LFP demand — new safety standards, costs, IP rights, ESG & simplified battery pack designs, Roskill.

Sanders, M. (2017). Lithium-ion battery raw material supply and demand 2016–2025. 17th Annual Advanced Automotive Battery Conference. San Francisco, Avicenne Energy.

Shabalala, Z. (2018). Solid demand to underpin lithium as price slides in 2018., Reuters Commodity News.

Sun, X, Hao, H, Zhao, F and Liu, Z. (2017). 'Tracing global lithium flow: A trade-linked material flow analysis'. Resources, Conservation and Recycling **124**: 50-61.

USGS. (2021a). Mineral Commodity Summaries — Lithium USGS.

USGS. (2021b). Lithium Statistics and Information, National Mineral Information Center.

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