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Environmental and socio-economic challenges in battery supply chains: graphite and lithium

Short study prepared within the framework of the BMBF joint project Fab4Lib - Research on measures to increase material and process efficiency in lithium-ion battery cell production along the entire value chain (FKZ 03XP0142E)

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List of abbreviations

Al	Aluminium
Co	Cobalt
CO	Carbon monoxide
CO ₂	Carbon dioxide
Cu	Copper
EHS	Environment, health and safety
EPI	Environmental Performance Index
EV	Electric vehicles
GHG	Greenhouse gases
GIS	Geographic Information Systems
km	Kilometre(s)
ktpa	Kilotonne(s) per year
Li	Lithium
Li ₂ O	Lithium oxide
LTO	Li ₄ Ti ₅ O ₁₂ , lithium titanate
Mt	Mega tonne(s)
NG	Natural graphite
NIOSH	National Institute for Occupational Safety and Health
NO _x	Nitrogen oxide
PARI	Protected Areas Representativeness Index
SG	Synthetic graphite
Si	Silicon
SO _x	Sulphur oxide
T	tonnes (metric)
TSF	Tailings storage facilities

1. Battery supply chains - towards sustainable cell manufacturing in the EU

The European Commission set a clear goal with the Green Deal to establish a transition towards a greener economy with the transport sector being one of the main pillars. A key ingredient are lithium-ion batteries required for the uptake of electric vehicles. The Green Deal underlines the goals formulated in the Strategic Action Plan on Batteries. Establishing a battery value chain in Europe including cell manufacturing is a key component towards a greener economy (European Commission 2019a, 2019b).

The collaborative research project Fab4Lib funded by the Federal Ministry of Education and Research, investigates innovative solutions along the value chain of lithium-ion technology and to validate them in demonstrators in preparation for a cell manufacturing in Germany. Within the project the Oeko-Institut already published a report on the development of the demand of raw materials needed for the electric vehicle (EV) uptake (Buchert et al. 2019). In this short study Oeko-Institut will highlight some of the environmental and socio-economic challenges of graphite and lithium in the upstream.

A significant number of projects that aim at manufacturing Li-ion battery cells in Europe are already scheduled with some being already in production. In 2019 a total of 16 cell manufacturing plants are in the pipeline according to Benchmark Minerals (Benchmark Minerals 2020a). With the aim of moving towards a cleaner environment and a greener economy it is crucial to think the process across the whole supply chain. Although the manufacturing of cells might move towards Europe a large portion of the raw material supply still is and will take place in third countries. Oeko-Institut clearly showed in their Fab4Lib short study that raw material volumes required for the manufacturing of batteries for EVs will increase significantly (Buchert et al. 2019). This paper aims at giving an overview on two raw materials that are crucial in current generations Li-ion batteries and focusing on sustainability aspects in the upstream supply chain, since these characteristics are increasingly in the focus of the public. Actions for other raw materials such as conflict minerals have been already taken. Starting in 2021 companies importing tin, tungsten, tantalum and gold (3TG) will have to ensure that the metals are from responsible and conflict-free suppliers. Accordingly, sustainability aspects in mineral supply chains are increasingly in the focus of policy makers, society and companies.

The paper will first look at graphite which is the most important anode material used in lithium-ion batteries. The two main production methods mining of natural graphite and producing synthetic graphite will be compared. Secondly, the paper will investigate lithium with a focus on hard rock mining in Australia, since it became the main source of lithium in the last years.

2. Graphite

Anode materials derived from carbon and especially graphitic carbons are the state-of-the-art anode material for lithium ion batteries, as they combine exceptional electrochemical properties (high energy density and efficiency) with a long cycle life¹. Furthermore, they are relatively low-cost, especially compared to the usually used cathode material, e.g., layered transition metal oxides. Historically, there has been a development from coke-based anodes (soft carbons) in the early 1990s to hard carbons and particularly to graphite, which went along with an increased energy content, however, also a more moderate rate capability (Dühnen et al. 2020).

¹ Cycle life of an automotive battery is usually defined as amount of charge and discharge cycles until the energy content reached 80% of the initial one.

There are two different types of graphite, which can be distinguished by their origin. The first is natural graphite (NG) and the second is synthetic graphite (SG), synthesized by heat treatment of a coke-based precursor (see Figure 2-1 and Figure 2-2, respectively). Although the chemical structure is similar, they differ in electrochemical behaviour and price. Generally, NG is mainly mined in China (over 60% in 2019), (USGS 2020) as they have a high interest on graphite for their battery production and low environmental regulations making the processing cheaper than elsewhere (Robinson et al. 2017). However, China's market share decreases over time, as other countries also ramp up their graphite production (USGS 2019, USGS 2020). One of these countries with already the second largest graphite production is Mozambique ($\approx 9\%$ in 2018, USGS 2020). Its main share of graphite results from the Balama mine, the largest natural graphite and processing plant on the planet measured by annual flake concentration production capacity.² These figures of global market shares include total NG for all industry outlets. However, the share of NG anode materials manufactured in China is even larger compared to mining of NG. (Pillot 2019) While in 2018, natural graphite anode material price was between ≈ 4 and $8 \text{ \$ kg}^{-1}$, the price of synthetic graphite was nearly twice as high ($\approx 12\text{--}13 \text{ \$ kg}^{-1}$). The production of SG is very energy and time intensive, as long calcination/graphitization times (up to weeks including cooling times) at temperatures $\geq 2500 \text{ }^\circ\text{C}$ are necessary (Gomez-Martin et al. 2018), however, greenhouse gases (GHG) emissions are estimated on similar level of NG due the environmentally more critical refining and production steps of NG (see also chapter 2.2).

Despite its higher price, the market share of SG for automotive batteries is growing over time, as the quality fluctuates less than for NG and SGs demonstrate extremely high levels of purity (Schmuck et al. 2018). In the year 2018, SG had already a market share of $\approx 56\%$ in comparison to $\approx 35\%$ for NG. (Pillot 2019) The rest consists of amorphous carbon, silicon composites or lithium titanate ($\text{Li}_4\text{Ti}_5\text{O}_{12}$, LTO). This will continue as long as the price for graphite is not the most important parameter, as the prognoses for the NG price decrease is even stronger than for SG due to an oversupply. (Dühnen et al. 2020) However, as the graphite market in general is growing fast due to the strong drive to replace fuel-driven cars by electric vehicles and their need for large battery cells, also the NG market is increasing further. (Dühnen et al. 2020) Naturally, graphite is also used in a lot of other applications, especially steelmaking, refractories and brake linings, although, one usually knows it from the graphite pencil. How the current Corona crisis and the resulting economic recession in many countries will affect the graphite market is difficult to predict. (Benchmark Minerals 2020b)

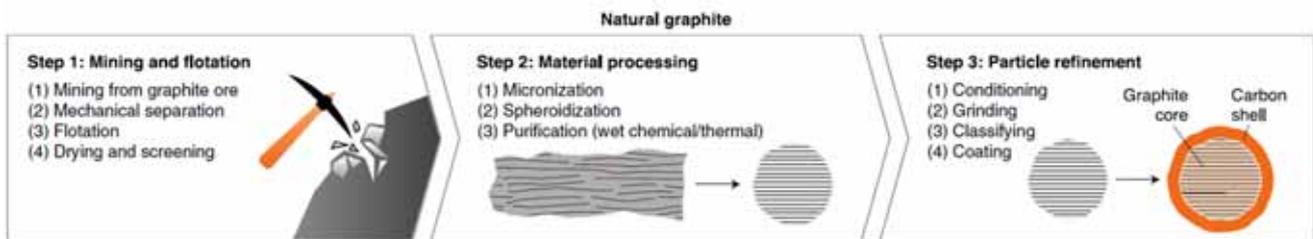
Although graphite as material itself is nontoxic to humans and the environment, its production or mining and subsequent processing produces emissions, which – if not properly controlled by EHS (environment, health and safety) measures during processing - can impact the health, and other concerns, (USGS 2017) which will be discussed in more detail in the following chapters.

2.1. Natural graphite

After mining from the ore, the NG has to be separated from the surrounding matrix, first, by mechanical separation, and second, by flotation (Figure 2-1). Important to note is that only special fractions of NG (i.e. selected flake types without heavy metal contaminants, e.g. vanadium) can be used to produce anode materials in required quality and at competitive costs which reduces the number of usable deposits and available volumes, respectively. (SGL Carbon 2020) After drying and screening, the graphite particles have to be reduced in size and then spheroidised in a “potato-shaped structure” as required for anode materials. The reason for that lies in the orientation dependent properties of graphite. Lithium ion intercalation - i.e. the insertion of lithium ions between the individual graphene

² <https://www.mining-technology.com/projects/balama-graphite-project/>, <http://www.syrahresources.com.au/overview>, both accessed on 08.06.2020

sheets³ - only takes place at the edges or defects of a graphite flake during the charging phase of a battery. This is not possible at right angles to the basal plane. By selective grinding, the shape of graphite flakes is changed so that the graphite flakes obtain a round shape by rolling them in. There are several advantages resulting from this procedure. First, this has the consequence that the surfaces available for intercalation with lithium ions increase. On the other hand, the achievable packing density during anode production is improved, thus increasing the capacity of the battery. (Lämmerer & Flachberger 2017) nevertheless, the yield of spheroidised graphite is only ≈30%, when produced out of flake graphite, which makes spherical graphite three times more expensive. (Jara et al. 2019). The product, known as "potato-shaped graphite", is subsequently cleaned by chemical or thermal treatment (Lämmerer & Flachberger 2017). The full NG production process from mine to NG anode material results usually in less than 5% overall yield (based on the content of NG in the deposit and the following processing steps), i.e. is highly waste creating (>95%).



Taken from Schmuch et al. 2018 with permission, Copyright 2018, Springer Nature

Figure 2-1: Overview over the production process of natural graphite.

For the chemical treatment, inorganic acids like hydrofluoric, hydrochloric or sulphuric acid are used. Hydrofluoric acid has favourable properties concerning the cleansing from silicates, while the others are better for contamination with pyrite. This is the main route for purification in China. As alternative or additional treatment, the graphite powder can be heated to over 3000 °C under inert atmosphere to vaporise the contaminants. As this process is energy and cost intensive, it is mostly conducted for special applications such as aerospace, (Lämmerer & Flachberger 2017); it could become more important for the future due to increasing environmental requirements but is also expected to increase NG costs to a similar level of SG (SGL Carbon 2020).

After chemical or thermal purification, the particles are refined, and the surface is coated with carbon to improve electrochemical performance like e.g. the cycling stability. Thus, the graphite particles are mixed with a carbon source like, e.g. poly(vinyl alcohol) and heated up (≈700 °C) under inert conditions (Nozaki et al 2009). These refinement steps have hence a positive effect on charging and discharging times as well as the capacity of the batteries (Lämmerer & Flachberger 2017).

However, mining and especially purification is connected to a series of environmental challenges. First, when mining is conducted on the surface (open pit operation), it leads to scared landscapes similar to other surface mining activities. Nevertheless, it is preferred by companies compared to underground mine operations, as it is cheaper (USGS 2017).

Graphite itself is inert and does not pose a direct threat to the environment. Other minerals, however, like the iron sulphide minerals pyrite and pyrrhotite, which are sometimes part of the graphite deposit, can cause acid mine drainage. If they are exposed to water and air, their dissolution and resulting decrease in pH value of the water can lead to serious consequences for the surrounding environment. (USGS 2017, Letterman et al. 1978) Additionally, to access the graphite in the mines, often a

³ Graphite consists of layers of graphene, bonded via relatively weak van der Waals bonds. Therefore, lithium can be stored in between them.

large amount of rock has to be removed, contributing to waste piles. Depending on the mine, these waste piles can contain different amounts of elements, leading to problems by their own. Examples apart from iron sulphide are uranium, nickel and mercury (USGS 2017).

Flotation as a refining method leads to tailings, which have to be disposed. Their exact composition depends on the mine. The tailings do not only occupy a large amount of landfill but can also lead to serious pollution. However, it is also possible to use them for other purposes like, e.g. as replacement of sand in concrete (Kathirvel et al. 2018) if maximum levels of critical contaminants are met.

Furthermore, the mining and subsequent processing of the mined ore to extract the graphite results in a serious amount of dust, which leads to several problems as containment of dust faces limitations in mining and deposit processing operations. First, the health of the workers and inhabitants of the surrounding area can suffer. According to the National Institute for Occupational Safety and Health (NIOSH) from the U.S. Department of Health & Human Services, exposure to natural mined graphite dust can lead to cough, dyspnoea (breathing difficulty), black sputum, decreased pulmonary function and also lung fibrosis, similar to coal dust (CDC 2019). However, it has not yet been finally clarified if the graphite dust itself or other components of the dust, like e.g. quartz, could be responsible for several of the symptoms (USGS 2017). Apart from the black colouring of the surroundings, including plants, houses and people, there is little evidence that this actually harms the flora and fauna in the small quantities occurring. Especially, a damage on plants could not be determined yet. However, more studies have to be made to be able to exclude any harm from graphite dust in this case (USGS 2020).

The biggest concern at this point results from the purification of graphite with inorganic acids, when they are not sufficiently contained. All acids, which are part of the chemical purification process, can cause environmental damages, when exposed. Especially hydrofluoric acid is extremely toxic and dangerous. (Gomez-Martin 2018) This problem can be in part mitigated in countries with sufficient environmental regulations. In countries like China, where the environmental regulations and the penalties for not following them are comparably low, incidents of exposure of the drinking water to sewage from the graphite mines are reported in the media. (Washington post, 2017, <https://www.washingtonpost.com/graphics/business/batteries/graphite-mining-pollution-in-china/>) At least neutralisation of the acids should be conducted, which is supposed to increase due to stronger environmental restrictions. (SGL Carbon 2020, Roskill 2019) To cope with the problems, in 2013, China has (temporarily) closed mines as a reaction on negative reports and protest from the communities against pollutions.⁴ However, these measures seem not to have shown a large improvement, as the media reports appeared afterwards.

Thermal purification could be a solution, at least concerning the direct emissions to water. However, due to the large amount of energy needed, the amount of GHG produced during this process could be even higher, (SGL Carbon 2019) considering the highly coal-based energy mix in China. Although their renewable energy sector is expanding quickly, over 50 new coal power plants are installed in China per year.⁵ As the thermal treatment is more expensive, it is still hardly used (Lämmerer & Flachberger 2017). Nevertheless, there are new studies developing different processes leading to less environmental pollution, like, e.g. microwave treatment. (Chehreh Chelgani et al. 2016).

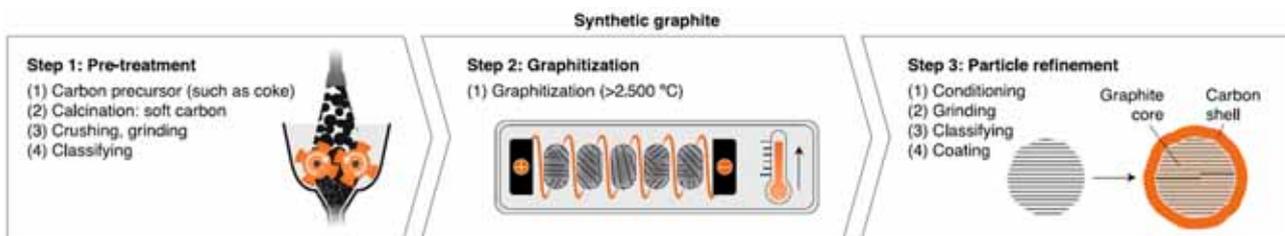
⁴ <https://www.indmin.com/Article/3290097/Shandong-China-ordered-to-halt-flake-graphite-production.html>, accessed on 28.07.2020

⁵ <https://www.welt.de/wirtschaft/article165201633/So-geht-Deutschland-Klima-China-auf-den-Leim.html>, <https://www.novo-argumente.com/artikel/chinas-energiehunger-teil-2-kohle-bleibt-kernenergie-kommt>, <https://www.industryweek.com/operations/energy-management/article/21964111/china-to-cap-coal-use-at-42-billion-tons-by-2020>, accessed on 28.07.2020

However, even in the unlikely event that such niche technologies will be able to prevail, it will take a long time before they will be able to develop a significant market share.

2.2. Synthetic graphite

For the production of SG, also called artificial graphite, a carbon source is needed as starting material, usually originating from the petroleum and coal industry value streams as a sub-product used in a wide range of industry segments, only a small share (lower single digit %) of the total global output thereof is consumed by SG production. Examples are petroleum coke or coal tar pitch. First, the starting materials are calcined at lower temperatures (800–1200 °C) at inert atmosphere⁶ to generate soft carbon (amorphous) and which is accompanied by a weight loss (see Figure 2-2). Depending on the starting materials and maturity of process, yield is 90% if conditions are optimized but can be as low as 70% if not. (SGL Carbon 2019) This can be conducted in an oven powered by natural gas or by electrical energy, depending on cost of gas vs. energy and energy mix. (Dunn et al. 2015) The main processing steps are depicted in Figure 2-2.



Taken from Schmuch et al. 2018 with permission, Copyright 2018, Springer Nature

Figure 2-2: Overview over the production process of synthetic graphite.

After pre-treatment of the starting materials (calcination, crushing, grinding and classifying), the resulting soft carbon is graphitized, again under inert atmosphere. The procedure takes three to five days and needs temperatures up to 2500–3000 °C for the duration of the heat treatment. Reaching these high temperatures is possible in a specialized electric oven and consumes a large amount of electric energy. Together with the cooling times, the whole process can take up to three weeks (Dunn et al. 2015); part of the energy can be recovered during cooling (SGL Carbon 2020). The high temperatures purify the material and lead to a perfect crystalline graphite structure (Wurm et al. 2018). After graphitization, the similar particle refining steps as for NG are necessary to gain a well performing anode active material for lithium ion batteries (conditioning, grinding, classifying and carbon coating, see chapter 2.1) (Dühnen et al. 2020).

There is some research going on to replace the carbon source from the non-renewable by-products of the coal and crude oil industry with biomass precursors, from more applicable ones like different kinds of wood, to more exotic ones like human hair or pollen. (Dühnen et al. 2020, Tang et al. 2016). Another approach is the use of carbon-containing waste materials like plastic bags or wooden bamboo sticks (Dühnen et al. 2020). Apart from reproducibility and the large amounts of material necessary to cope with the growing market for anode materials, it is difficult to actually gain a soft carbon as precursor for a highly graphitized material. The process can be improved by adding a metallic additive like, e.g. iron chloride to the mixture, which also reduces the necessary graphitization temperature. (Dühnen et al. 2020, Gomez-Martin et al. 2018) As the additive has to be removed again and could lead to impurities, it is so far not relevant for commercial applications as battery anode material, to the best of our knowledge (SGL Carbon 2020). All these approaches are in early stage of research and far away from industrial realization. Furthermore, given the very low carbon yields inherent for such alternative precursors, (Bengtsson et al. 2018) overall energy and emission

⁶ Contains no oxygen, usually nitrogen or argon gas.

balance of the full process as well as costs are expected to turn out disadvantageous vs. the today's precursors.

An advantage of SG compared to NG is the independence of natural graphite resources, as raw materials are established and readily available. This could lead also to an independence from countries like China, where the largest share of NG is mined. Today, China also produces the largest amount of SG ($\approx 78\%$ in 2018, Pillot 2019). However, given the easier scalability of the SG process, licence procedure and technical realization time is faster (1-2 years compared to 8-10 years for a new mining site). Furthermore, the independency from mine locations as in case of NG is an advantage of SG production.

During the two heat treatment steps, several air emissions evolve, including mostly CO_2 , but also NO_x , SO_x and CO , the amounts of which are strongly related to the carbon source of the graphite. The total amount of GHG, however, is strongly dependent on the source of electrical energy for the oven. Taking calculations of SGL Carbon, verified by Shariff et al. from Berenberg Thematics, the GHG of the mining and processing of NG lie in a similar range (4 – 14 t CO_2 / t graphite). Other data actually comparing the two processes concerning their emissions could not be found. The potential of improving the environmental footprint, especially for synthetic graphite, is high if only renewable energies could be used. This is, however, mostly not the case yet. The production of SG is another example, where the environmental impact is largely connected to shift in energy production from fossil fuels to renewable energies. As an example, synthetic graphite producers located near the French Alps are already producing SG based on electricity from surrounding hydropower plants.

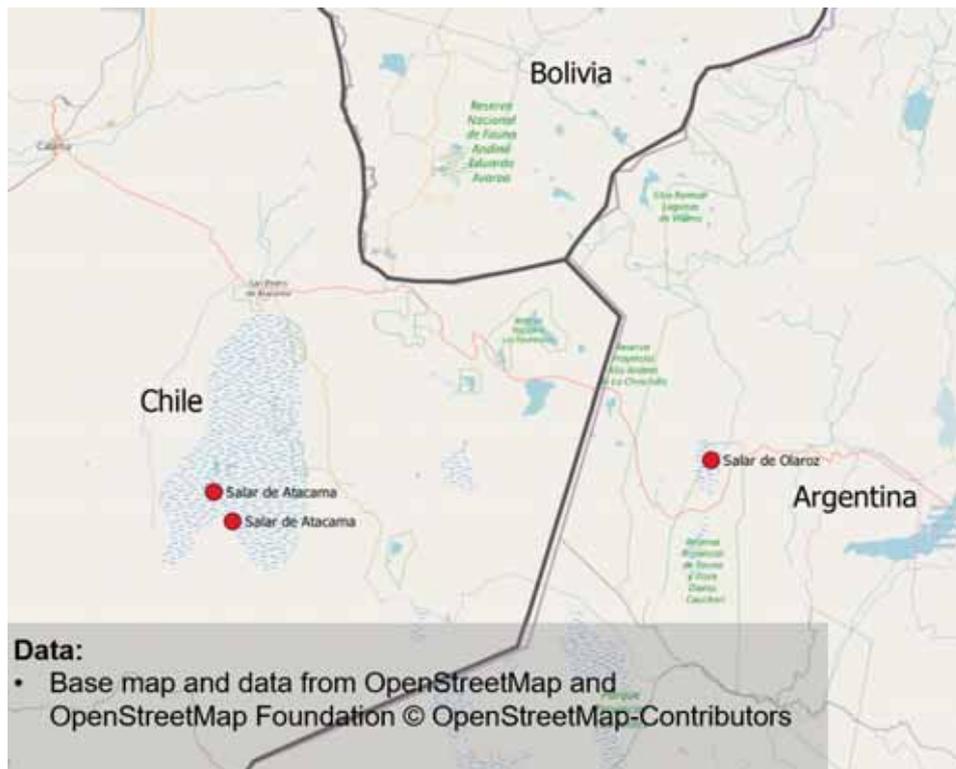
Direct comparability between NG and SG is limited due to different technical performance profiles though. Moreover, while NG has given product properties from a certain origin/mine, which can only be influenced to limited extent by further processing steps, SG provides high versatility for final anode material through raw material selection and possible processing variations. Compared to the mining and processing of NG, the production of SG itself is supposedly clean, however, the amount of (electrical) energy needed is larger. SG production as an industrial operation allows to apply the high EU EHS standards of chemical industry in terms of handling, hazard and emission control which on contrary, are known weaknesses of mining operations in particular in countries where most and volume-wise major NG deposits are located. However, as long as the electric energy is widely produced from fossil sources, it is difficult to state that SG is generally connected to less environmental impact than NG without a detailed and specific evaluation. Fortunately, the production of renewable energy is increasing in large parts of the world, thus implying a significant reduction in emissions in the future.

3. Lithium

Lithium is the key element in all Li-ion batteries, regardless of the cell chemistry. The global demand for lithium in mobility applications could rise to 240.000 t in 2030 and up to 1.1 million t in 2050 if the Paris agreement goals are to be achieved (Buchert et al. 2019). This significant increase will have to be fuelled by the additional extraction of raw materials. Lithium is extracted from two very different sources. On the one hand it is extracted from brines mainly in South America. On the other hand, hard-rock mining takes place largely in Australia. In the following brines will be discussed very briefly, followed by a more in-depth investigation of lithium mining in Australia.

3.1. Brines – Lithium triangle

Discussions about the light metal often circulate around its extraction from brines. The commercially most important brines are in salt flats in the lithium triangle. The lithium triangle refers to the South American countries Chile, Argentina and Bolivia⁷, where currently more than two thirds of global reserves are located (USGS 2020, Agusdinata et al. 2018). The most important brine deposits are located in the Atacama Desert in Chile (compare Figure 3-1). Often Bolivia is represented as an upcoming global player in the upstream sector of the lithium value chain. However, to date no large-scale production is reported by geological surveys (USGS 2020, BGS 2020).



(OpenStreetMap 2020)

Figure 3-1: Map of currently active lithium brines

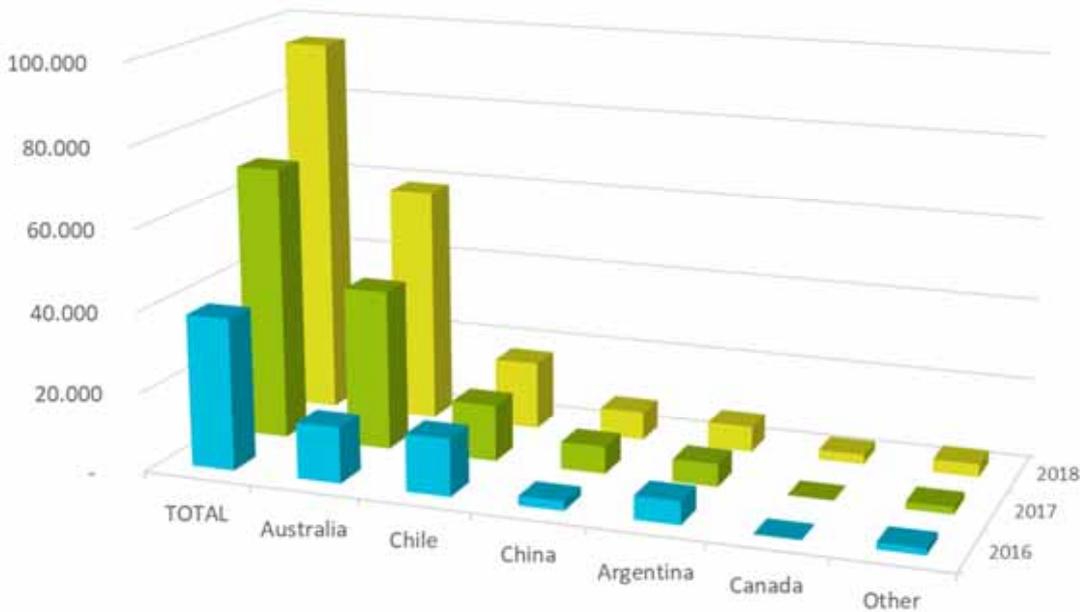
Issues resulting from the Li-extraction from salt lakes most prominently are mentioned in relation to water scarcity. The extraction of lithium from brines uses solar energy to evaporate the lithium-containing brines in large ponds. The brines are pumped from underground aquifers to the surface (Agusdinata et al. 2018). The lithium is then concentrated until it reaches a high enough concentration (e.g. 6 % lithium chloride at the Salar de Atacama) for further processing at a chemical plant (Evans 2014). Since, the areas where this kind of process is taking place are very arid, the impact on the hydrology can be severe. Liu & Agusdinata (2020) argue that between 2002 and 2017, the total water storage at the Salar de Atacama in Chile declined at a rate of 1.16 mm/year. Moreover, social conflicts have been reported as a result of water scarcity in the region (Schüler et al. 2018).

The developments regarding lithium extraction from brines are covered widely in the media. Also, a number of studies, papers, media articles and publications covering different aspects of lithium extraction from brines have been published (e.g. Liu & Agusdinata 2020). The following chapter will focus on lithium hard rock mining which has not been covered as prominently in the public discourse.

⁷ Bolivia currently only holds resources.

3.2. Spodumene – Lithium from Australia

In the course of the last three years Australia became the largest global supplier of lithium. Until recently the lithium supply has been dominated by brine production due to cheaper production costs (Dessemond et al. 2019). In 2016 Chile was the top producer and enlarged its production steadily until 2018. Australia on the other hand increased its production threefold between 2016 and 2017 and again by almost 50% until 2018. Accordingly, currently (2018) almost two-thirds of the lithium supply are extracted in Australia in hard-rock mining and only approximately one-third is extracted from brines (compare Figure 3-2).



Li content in metric t (data USGS 2020)

Figure 3-2: Global lithium production from 2016 to 2018 by country

The mineral spodumene

Lithium minerals are mostly extracted from granitic pegmatites. Pegmatites are igneous rocks with a coarse grain size composed of a large variety of minerals such as e.g. granite, quartz and feldspar etc. The lithium bearing minerals contained in pegmatites are the lithium aluminium silicates spodumene and petalite and the potassium lithium aluminium silicate lepidolite. Pegmatites are often also containing tantalum, caesium and tin ores. Spodumene is the mineral of most commercial interest and is mainly mined in Australia. Pegmatite deposits represent ca. 26 % of all potential lithium sources worldwide (Bradely et al. 2017). Spodumene ($\text{LiAlSi}_2\text{O}_6$) has a theoretical content of 7.9 % Li_2O , however usually naturally occurring grades range between 1 and 2 %. The Greenbushes mine is an exception with grades exceeding 3 % Li_2O (Dessemond et al. 2019, Evans 2014).

Mining and Extraction process of lithium from spodumene

The mined spodumene ore is sorted, crushed, grinded, gravity separated, magnetically separated, then goes through a flotation process and is washed filtered and dried producing a spodumene concentrate (Dessemond et al. 2019, DERA 2017). According to Dessemond et al. (2019) the lithium production process from spodumene concentrate applied at most commercial operations dates back to a patent from 1950. First the spodumene concentrate is grinded and then is heated in a furnace to at least 1000°C for half an hour. During the process α -spodumene changes to β -spodumene which is soluble in acids. Afterwards the spodumene concentrate is mixed with hot sulfuric acid from which lithium sulphate solutes in water. Then sodium carbonate is added to extract contaminations of iron,

aluminium and manganese. Calcinated soda and calcium oxide are added and the alkaline solution is neutralized with sulfuric acid and heated and finally lithium carbonate is precipitated by adding sodium carbonate (DERA 2017, Dessemond et al. 2019, Evans 2014)

There are new approaches to spodumene processing beside the established acid-roast process, where lithium hydroxide monohydrate is directly extracted from spodumene (DERA 2017). Spodumene ore is processed using a pyrometallurgical and hydrometallurgical refining process to produce the lithium hydroxide product and sodium sulfate as a by-product (Albemarle 2018). The spodumene ore is calcined followed by a sulphate roasting process, leaching and purification. Then is crystallised and dried to produce high purity lithium hydroxide monohydrate (Simpec 2020).

Increasing Production volumes – Overview of Australian mines

As mentioned earlier, Australia has significantly increased its production. This can be attributed to the expansion of the largest Australian lithium mine Greenbushes, which provided ca. 30% of world production in 2017. Moreover, other mines opened recently or are soon to be opened. Currently the six mines Bald Hill, Greenbushes, Mount Cattlin, Mount Marion, Pilgangoora (Altura) and Pilgangoora (Pilbara) are operating. Another large mine Wodgina is currently under care and maintenance (Hughes 2020, Champion 2019) (compare Figure 3-3). Below the most important mines are described in short.



map based on UNEP-WCMC 2017, OpenStreetMap 2020, Hughes 2020

Figure 3-3: Map of Australian lithium mines

Greenbushes is the largest lithium producing mine located ca. 250 km south of Western Australia's capital Perth and named after a town nearby (Fawthrop 2020). The mine has been in operation since 1888 producing tin and tantalum (Evans 2014). In 1985 a processing plant has been established also extracting lithium. The deposit contains approximately 1.7 Mt of lithium representing

approximately 10% of global reserves graded at 2.8 % Li₂O (USGS 2020, NS Energy 2017, Fawthrop 2020). It is estimated that the mine will be in operation for another 40 years (Fawthrop 2020). The two shareholders Tianqi and Albemarle have both announced that they will also produce battery-grade lithium hydroxide in Australia. Tianqi will build its plant in Kwinana ca. 40 km south of Perth with a production capacity of 48 ktpa (Champion 2019, Tianqi 2020). Albemarle began the construction of a lithium hydroxide plant in Kemerton ca. 20 km north-east of Bunbury with an initial capacity of 60 to 75 ktpa expandable up to 100 ktpa of lithium hydroxide (Albemarle 2020a, 2020b).

Mount Cattlin is an open-pit lithium-tantalum mine that has been in production between 2010 and 2012 and recently reopened (Champion 2019). The ore body consists of flat lying pegmatites allowing mining with constant strip ratios at relatively low-cost (Galaxy Resources Limited 2020, Mining Data Online 2020a). The mine is located in the south of Western Australia and ca. 500 km south-east of Perth. The ore mined at the deposit is also spodumene with a grade of 1.08% Li₂O (Champion 2019). The mine is owned by Galaxy resources who produce a 6% Li₂O grade concentrate that is shipped from Esperance Port (at the southern coast of Australia, ca. 600 km south-east of Perth) to Asian customers. Ore reserves amount to ca. 8.2 Mt grading at 1.29 % Li₂O. In 2019 the mine produced 191.570 dry metric t of concentrate (Galaxy Resources Limited 2020).

Bald Hill is an open pit mine located north of Lake Cowan and ca. 700 km east of Perth in Western Australia. Similar to Greenbushes initially tantalum has been mined at Bald Hill. In 2016 it has been announced by the owners that spodumene was also present in the deposit. In 2018 first lithium concentrate shipments have been reported (Champion 2019). Bald Hill has reported reserves of 11.3 Mt of regarding at 1 % Li₂O and a production capacity of 155.000 t of spodumene concentrate per year (Alliance Mineral Assets Limited 2020).

Mount Marion is located approximately 40 km south-west of Kalgoorlie and commenced production in 2016 (Champion 2019). The mine has been upgraded between 2018 and 2019 increasing the capacity of the plant (Mineral Resources 2020a). The open pit mine produces a 6% Li₂O concentrate from spodumene ore. The mine life is approximately 20 years (Mining Data Online 2020b) According to Mining Technology (2020) Mt Marion is the second largest high-grade lithium deposit in the world.

Pilgangoora (Pilbara) is located in the north of Western Australia ca. 150 km southeast of Port Hedland. The mine host spodumene and lepidolite as lithium-bearing ores and also tin and tantalum bearing minerals. In 2018 the mine's life has been estimated at 17 years (Champion 2019). The mine currently has a production capacity of 330.000 t of 6 % Li₂O concentrate (Pilbara Minerals 2020).

Pilgangoora (Altura) is located north of Pilgangoora Pilabara and has a projected life of mine of 13 years according to Champion (2019). The open pit mine produces ca. 220.000 t of spodumene concentrate and an expansion to 440.000 t per annum is planned (Altura 2020).

Wodgina is located ca. 110 km south of Port Hedland. Same as the Greenbushes mine Wodgina was initially extracting tin and tantalum, until it has been closed in 2012. Wodgina is one of the largest tantalum deposits. Since 2017 also spodumene is mined at the deposit. It is planned to further process the ore at a chemical plant in Kemerton to produce lithium hydroxide (Champion 2019, Mineral Resources 2020b). Currently the mine has a production capacity of ca. 750.000 t of Li₂O concentrate per annum (Mineral Resources 2020b).

Outlook

As the overview above shows, on top of Greenbushes a large variety of other Australian lithium mines started production in the past years. Moreover, the vast majority of the producers are concentrating the ore to ca. 4-6 % Li₂O which is then shipped mainly to China. Many of the mines have expansion plans scheduled even further increasing Australian production. The currently displayed

reserves point to secured mine life's in the mid-term which can of course change in the course of further exploration. The overview only included mines that are already producing or have produced until recently, therefore they only represent the most mature and operating projects. On top of them further exploration is ongoing and promising projects in Australia are in the pipeline (see e.g. Lithium Australia 2020). As the example of Tianqi and Albemarle at Greenbushes shows there is a trend to include more steps of the value chain in Australia by further processing the spodumene concentrate to produce lithium hydroxide. Also, Mineral Resources who own the Wodgina mine are holding interest via a joint venture in the Kemerton chemical plant (Mineral Resources 2020b, Champion 2019).

Environmental impacts of spodumene mining

The environmental impacts of a mine can be very manifold. A detailed analysis e.g. an environmental impact assessment is always required on a case to case basis. This following overview aims at summarizing some key issues of spodumene mining in Australia. The overview is not exhaustive and represents topics that should be further studied to mitigate the impact of lithium extraction.

Tailings Storage Facilities

The processing of spodumene ore to a concentrate and the extraction of lithium from it result in wet residues that are stored in tailings storage facilities (TSF). TSFs are large structures that contain the wet residues and can vary in form size and height. This kind of storage can result in variety of issues that can impact the environment.

In a worst-case scenario, a dam of a tailing's storage facility can break releasing the contained mining residues (Dolega et. al 2016). The devastating consequences have been recently widely displayed in the media following the dam break of an iron ore mine in Brazil in 2019 (e.g. Raman & Liu 2019).

At Wodgina seepage of tailings to the groundwater has been reported. The groundwater levels under the tailings storage facility are increasing rapidly. The process waters stored in the pond are also of concern since they contain elevated levels of lithium, tungsten and uranium which can have negative impacts on area near Wodgina (DWER 2019, S&P Global 2019).

At Greenbushes each year ca. 8 Mt of processed spodumene residue will be stored in the TSFs after the expansion. Therefore, currently another TSF is built at Greenbushes resulting in a total of four TSFs that contain the processing residues (Talison Lithium 2018). GHD (2019) used a model assessing the new TSF regarding the consequences of a dam breach for Talion Lithium. In the case of an accident the population at risk would be between 10 and 100 persons. The assessment of severity of damages concludes that infrastructure costs, business costs, health and societal impacts and environmental impacts are affected to a major degree. This overview is not intended to imply that the TSF is at a risk of failure. It does however show the severity of a failure and underlines the necessity to regularly check and monitor the structures.

All of the mines presented before producing spodumene concentrates are using at least one TSF.

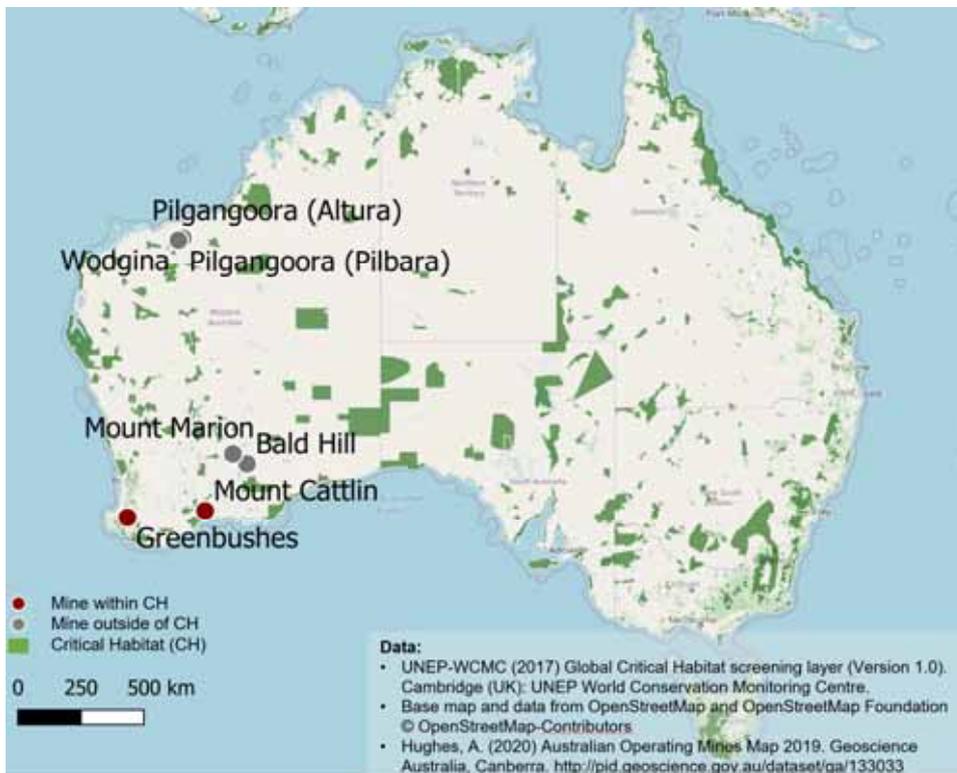
Biodiversity

The location of mine sites is connected to significant impacts on biodiversity. Mine located in desert areas with particularly low biodiversity have a low probability of greatly impacting flora and fauna. Operations on the other hand that are located in densely vegetated tropical forests will potentially affect it to a much larger degree.

Brauneder et al. (2018) compiled a Geographic Information Systems (GIS) dataset representing areas of high biodiversity. The "Global Critical Habitat Screening Layer" represents a global screening

layer of Critical Habitat, based on global spatial datasets covering information on biodiversity features. The authors define critical habitat as areas with high biodiversity value covering e.g. areas with significant importance for critically endangered species or endemic species, habitats supporting globally significant migratory species, areas representing threatened and unique ecosystems, areas associated with key evolutionary processes, nationally and or internationally recognized high biodiversity areas etc. (Brauneder et al. 2018, UNEP-WCMC 2017).

This information has been combined with the mines' locations to see whether they are located in sensitive areas in terms of biodiversity. This analysis is a very high-level investigation that cannot replace on-site assessment to confirm the existence of critical habitat. However, it is suitable to give an indicative picture describing the likelihood of an impact. The area of the mines has been buffered to 10 km from the centre point of the mine, covering pretty much all mine infrastructure and the pits. The GIS analysis shows that all Australian lithium mines except for Greenbushes and Mount Cattlin are located outside of critical habitat (compare Figure 3-4). Australia's rather strict regulations regarding environmental protection are reflected in the analysis, given the fact that most mines are located outside of critical habitat. The Yale Center for Environmental Law & Policy publishes the Environmental Performance Index (EPI) annually which "provides a data-driven summary of the state of sustainability" on a country to country basis. Australia ranks on place thirteen among the 180 countries analysed representing an overall score of 74.9 of 100 (Wending et al. 2020). The analysis consists of 32 performance indicators and 11 issue categories. Among others biodiversity is analysed. One of the indicators is the Protected Areas Representativeness Index (PARI) that measures how well protected areas (on land) represent a countries ecological diversity. Australia only scores 40.4 out of 100 on the indicator. This indicates a lack of protected areas (EPI 2020).

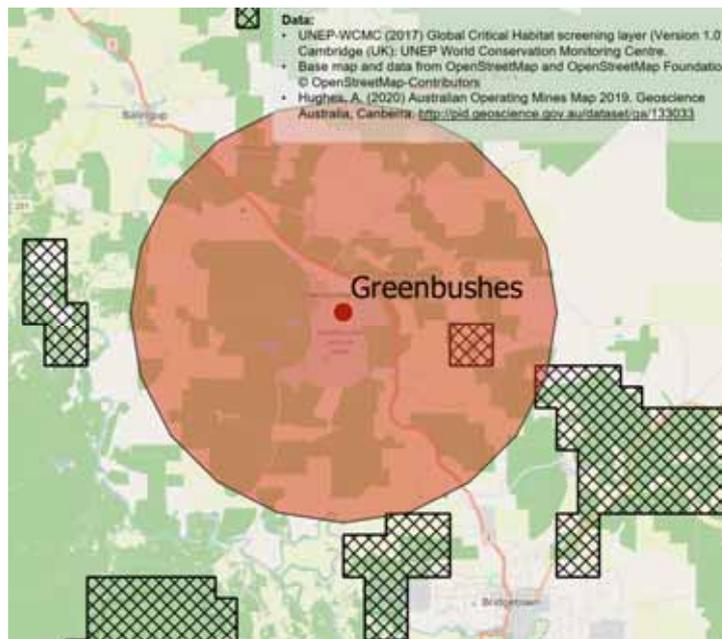


map based on UNEP-WCMC 2017, OpenStreetMap 2020, Hughes 2020

Figure 3-4: Location of Australian lithium mines in areas of critical habitat

Particularly Greenbushes which is by far the largest operation is located in critical habitat. If the situation is analysed further in more detail it becomes clear, that the classification is also related to

the applied buffer zone. Selecting a rather large buffer zone of 10 km leads to the borders of the polygon to intersect areas of critical habitat. Also, a smaller area east of the mine is included. The pit itself is not located in critical habitat (compare Figure 3-5). Nonetheless mining activity can have an impact on the surroundings such as noise pollution, mining infrastructure etc. Again, this only gives a very rough estimate to the situation and cannot replace detailed assessments on the ground. Moreover, it has to be pointed out, that the mine has been in operation since 1888, therefore in all likelihood no assessment regarding biodiversity issues has been conducted when the mine was opened (which should not be a justification for not looking into biodiversity related issues today!).



map based on UNEP-WCMC 2017, OpenStreetMap 2020, Hughes 2020

Figure 3-5: Greenbushes and critical habitat in the surroundings

Revegetation

It should be noted that historic mining also significantly disturbed the areas since the mine has opened in 1888. The Environmental Protection Authority points out that a comparison of aerial photos from the 1970s and 2019 shows that a lot of areas of historical disturbance have been revegetated (EPA WA 2019).

Social impact

Social impacts of mining are a widely studied field. However, in Australia problems relating to negative social impacts are somewhat different than in other countries. There are very high work safety standards and salaries in the sector are above average. Issues such as child labour or artisanal and small-scale mining are not taking place.

There are reports of issues related to mining on Aboriginal sites (see e.g. Albeck-Ripka 2020). On the other hand, the mining industry is one of the most important employers for aboriginal people. E.g. Pilabara Minerals Limited, the owner of Pilangoora (described above) offer preferential employment and procurement for Indigenous workforce and businesses (NAIF 2018).

Another important aspect that poses a social impact on Australian miners is the fly-in fly-out concept, where people working in remote areas are not permanently staying at the place of work. Often mines in Australia are located in desert areas without big cities nearby and workers fly in for longer periods of time being absent from their families. This situation can lead to psychological effects on worker’s

mental health and their families. Issues e.g. such as substance abuse can occur (e.g. Langdon et al. 2016).

This short overview only gives a very rough summary of the main social issues related to lithium mining in Australia. However, this paper focuses on the environmental aspects of lithium and included this short overview to paint a more complete picture of the situation.

4. The future of battery supply chains

Battery and EV manufactures are scrutinized by the public even more than other industries. The sector fuels the shift towards a greener mobility and therefore needs to achieve this with minimal adverse effects on the environment. Attaining a clean mobility at the cost of causing avoidable environmental impacts is at least very questionable. Therefore, the current discussions circulating around supply chain transparency will continue to be more important. Downstream actors need to be aware of issues in the upstream. This paper pointed out some of the issues related to lithium mining and the production of graphite. The impacts of production of battery raw materials need to be studied further in order take the right decisions when trying to mitigate environmental and socioeconomic impacts.

A large number of companies, enterprises and initiatives have committed to responsible sourcing of minerals. As cell manufacturing is very likely to become more important in Europe, it will be key to face issues along the whole battery supply chain.

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