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Material Flow Analysis for Lithium in the EU

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Affidavit

I, **MAG. NIKOLAS SIMON, B.SC.**, hereby declare

1. that I am the sole author of the present Master's Thesis, "MATERIAL FLOW ANALYSIS FOR LITHIUM IN THE EU", 64 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
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Abstract

The increasing use of raw materials due to economic growth around the world is having an impact on our environment. Lithium in particular is gaining in importance as an industrial mineral due to the increased use of lithium-ion batteries and accumulators. However, it is being used in a wide array of application, like in glass and ceramics, batteries, cement production, lubricating greases and others.

Hence, this thesis set out to develop a material flow analysis for the applications and quantities of lithium in the EU for the year 2014. As a result, conclusions about the potential for recycling and a circular economy for lithium will be drawn.

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List of Abbreviations

Al	Aluminum
BEV	Battery electric vehicles
BGS	British Geological Service
BIO	Bio Intelligence Service (by Deloitte)
CAGR	Compound annual growth rate
CRM	Critical raw materials
DOJ	Department of Justice of the U.S.
EC	European Commission
EOL	End of life
EU	European Union
GDP	Gross Domestic Product
HEV	Hybrid electric vehicles
HHI	Herfindahl-Hirschmann-Index
Li	Lithium
LiB	Lithium-ion-batteries
MFA	Material flow analysis
Mt	Million tonnes
PGM	Platinum group metals
PHEV	Plug-in hybrid electric vehicles
REE	Rare earth elements
RR	Recycling rate
USGS	U.S. Geological Service

1 Introduction

1.1 Background

> "*Because of the key role that minerals and fuels play in economic growth and in economic and military security, the extent of their resources is a matter of great importance to government, and questions concerning the magnitude of resources arise in conjunction with many public problems."* (McKelvey, 1972)

The motivation for writing this thesis originated in a discussion about the impact of widespread usage of Li-ion batteries and accumulators concerning availability of necessary raw materials.

Availability of natural resources has long been an issue of strategic importance to countries. Over time the importance of various materials changed from a focus on food towards a focus on industrial materials like metals. For modern man the material consumption rate is about a factor of 10 or 20 times greater than for prehistoric man (Brunner & Rechberger, 2004). Exponential growth in resource use has led to increased exploration for natural resources. The result was economic prosperity and inventions as well as conquest and destruction. One only needs to think about the enslavement of people across Africa, South America and Asia.

Lithium is expected to be of specific interest in the future due to its application in Li-ion batteries and accumulators. In fact, the compound annual growth rate (CAGR) for lithium is estimated to be an average of 7.8 percent between 2003 and 2013 (Christmann et al., 2015). This represents one of the highest growth rates among all industrial metals. After researching the literature, it was found that the focus concerning Li-ion batteries lies in other components but that lithium was not of specific interest. In fact, the European Commission did not view it as a critical raw material in the most recent assessment of critical raw materials in the EU (EC, 2017c).

Hence, it was decided to get a better picture about the situation of lithium supply and demand in the EU. Information was available in the form of other studies that followed a material flow analysis approach. For example, Ziemann et al. (2012) presented a global material flow model for lithium. However, no information was found concerning the situation for the EU.

Furthermore, in order to lessen the environmental impact of increased mining operations it would be interesting to know how recycling could balance some of the future lithium demand in order to protect natural resources. According to Graedel et al. (2011) the picture for the recycling of metals is a poor one. Of 60 metals only 18 reached end-of-life recycling rates above 50 percent and for many metals the recycling rates are below 11 percent. In the case of lithium this number goes down to less than 1 percent. An overview is given in Figure 1. Consequently, it is clear that there is potential for increased lithium recycling. In the course of this thesis we will see whether secondary lithium is a realistic competition for the primary supply of lithium.

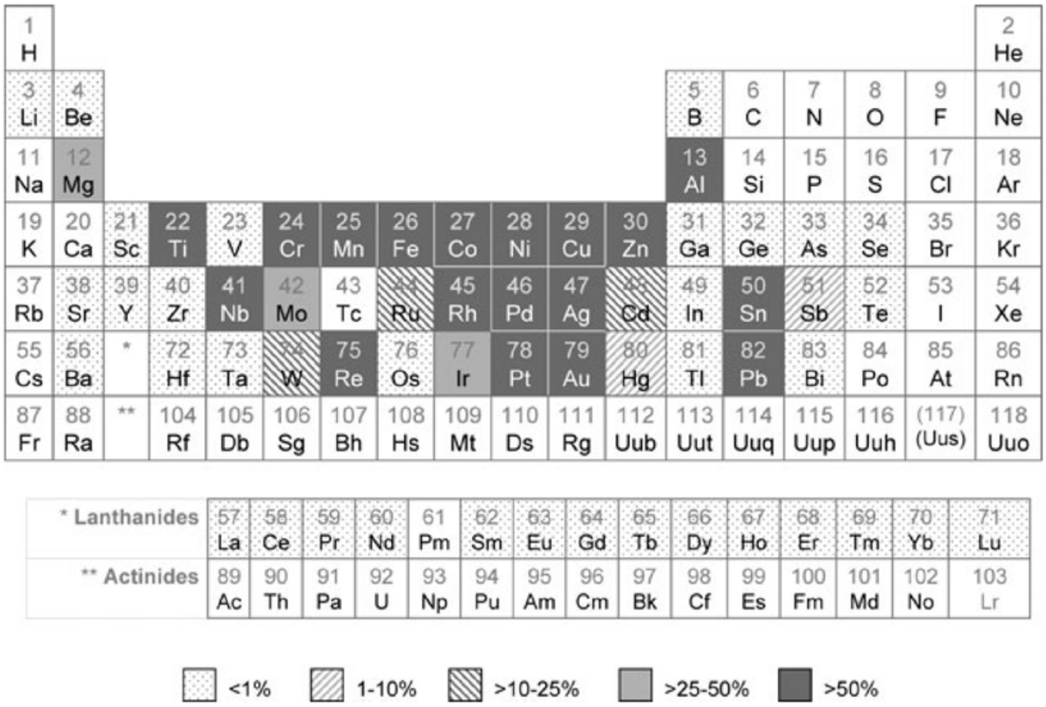

Figure 1: Overview of EOL RR for 60 Metals (Graedel et al., 2011)

In the rest of Section 1 the goals and the guiding questions will be outlined to set the direction for the thesis. Next, in Section 2 a theoretical overview over the field of resource management will be presented as far as it concerns the evaluation of the criticality of raw materials. Issues that are covered concern geological availability, technological developments, economic factors and supply risks. The materials and methods of this thesis are written down in Section 3. This chapter consists of a short presentation of the concept of a material flow analysis, followed by a detailed outline of the methodology used to assess the various elements of the MFA for lithium in the EU for the year 2014. Finally, in

Section 4 the results will be presented before the thesis is concluded with a detailed discussion of the weaknesses of the approach used and a conclusion.

1.2 Goals

The goal of this thesis is to identify and quantify the flow of lithium in the EU in 2014. In order to do so a material flow analysis (MFA) will be conducted via the software tool STAN. The main uses of lithium in production and consumption processes as well as the after-treatment of lithium in waste processes will form the basis for estimating the flows of lithium in the spatial system boundary Europe. Furthermore, the question of whether lithium is a scarce resource will be discussed over the course of the thesis. However, the evaluation of criticality is not a core part. In the end results, an optimal scenario for the recycling of lithium in the EU will be presented and thus, build the basis to evaluate whether a circular economy is possible in the case of lithium.

1.3 Guiding Questions

The thesis should answer the following questions:

- How is the criticality of raw materials assessed?
- Why is lithium important for modern production processes?
- What are the uses of lithium in production processes?
- What are the main processes and flows of lithium and lithium-containing compounds in Europe? Is the necessary data available?
- Is it possible to reduce the import dependency of Europe in the case of lithium via recycling or other measures?

2 Resource Management – Theoretical Overview

2.1 Critical Raw Materials (CRM) in the EU

The EU is set to achieve a manufacturing share of 20 percent of total GDP by the year 2020 (EC, 2017f). Hereby, the EU is reintroducing industry as a cornerstone of its economic future in a region where the service sector has taken over the major role of economic growth, especially in the more developed countries. At the time of writing this thesis, the share of industry (except construction) in percent of GDP, indicated by gross value added, stands at 17.5 percent for the EU (Eurostat, 2018). This means that still a considerable effort needs to be put into growing the industrial share in the EU.

Crucially, there will be an increased need for the supply with raw materials to enable the planned increase in production rate. Therefore, it makes sense that the EU has developed a strategy for raw materials that is intended to ensure the availability of CRM in the European markets at high volumes and for reasonable prices. This raw materials initiative was the first step in building a common framework for a coherent policy approach and was supposed to build a basis for international forums on the discussion of raw materials. It is built on three pillars (EC, 2008):

1. Ensuring that access to raw materials in international markets is guaranteed under the same conditions as for other countries,
2. Setting the framework conditions for a sustainable supply with raw materials from European sources,
3. And boosting resource efficiency, promoting recycling and decreasing import dependency.

Pursuant to the first pillar, it should be mentioned that it is estimated that there are more than 450 export restrictions concerning 400 different raw materials worldwide (BDI, 2010). This shows the huge importance of raw materials for the economic strategy and competitiveness of countries in the international markets.

The above-mentioned three goals of the Raw Materials Initiative have not changed significantly over the course of the last 10 years. However, in general, the EU was a late mover concerning the development of a raw material strategy, with other countries like the US, the BRIC countries (Brazil, Russia, India, China), Japan, Korea and some countries in Southern America having developed their strategies earlier (Tiess, 2010).

Another dimension to consider for policy makers and industry is being able to gauge whether there will be any *future* risks concerning the supply with raw materials. Consequently, the EC regularly publishes and updates its report on the criticality of raw materials. The first assessment on the criticality of raw materials on EU-level was published in 2011 (EC, 2011). After that a second report on CRM was presented in 2014 (EC, 2014), and a third one in 2017 (EC, 2017e). All of them included a list on CRMs.

The regularly updated list of CRM is intended to achieve various goals. First, it should make Europe's industry more competitive. Second, through an increase in mining activities as well as more efficient usage and higher recycling rates the supply with CRM should be ensured. Third, public and private stakeholders can assess potential CRM supply risks or opportunities in advance. Finally, the CRM list provides the basis for negotiating trade agreements, e.g. with a country that is a big supplier of a CRM, as well as lifting barriers in trade and to foster R&D.

In the following section the possible dimension to assess criticality will be discussed, especially as far as they are relevant for the latest CRM assessment.

2.2 Possible Dimensions for a CRM Assessment

The following sub sections will provide an overview over general resource management considerations that apply to assessing the criticality of raw materials. They will focus especially on such considerations that played a role in the latest assessment of CRM by the EC in 2017.

2.2.1 Geological Availability

A first important point to mention is that the factor of geological availability did not play a role in assessing whether a raw material can be seen as critical in case of the EC's assessment. It is worth to explore this issue in more depth and to discuss the different perspectives that play a role concerning the depletion of natural resources. First, it is necessary to define what a *resource* and what a *reserve* is. In everyday life these two terms are often used synonymously although there is a clear distinction between them. The issue of the distinction between the two has a long history and the developments in this area are closely intertwined with the oil and gas industry.

The American Petroleum Institute, in 1926, defined what constitutes a reserve in contrast to a resource (Wildavsky et al., 1981). It was stated that a resource constitutes all known deposits of raw material while reserves were only the part of the resources that could be extracted economically, meaning with profit. The raison d'etre was the ongoing discussion among industry as well as researchers whether supplies of crude oil (or other raw materials) were finite or not. Consequently, the term of *peak oil* was coined and developed by Marion King Hubbert who is also its most famous representative (Hall, 2016). Hubbert's (1949) idea was that production of oil can only happen once a deposit is found and that a peak and a consequent decline in oil production is inevitable due to the limited physical availability of the resource. One can imagine the opposition that the idea of limited oil reserves faced from oil companies but also other academics set out to oust Hubbert's proposal.

In 1972, the then-director of the U.S. Geological Service (USGS) and critic of Hubbert's theories, Vincent McKelvey proposed a method for a graphical representation of resources and reserves. In his chart the abscissa represents the *degree of certainty* with which deposits of raw materials (in his case oil) existed, while the ordinate represents the *feasibility of economic recovery* (McKelvey, 1972). The resulting graph was consequently updated and a revised version by the USGS (1980) can be seen in Figure 2 below.

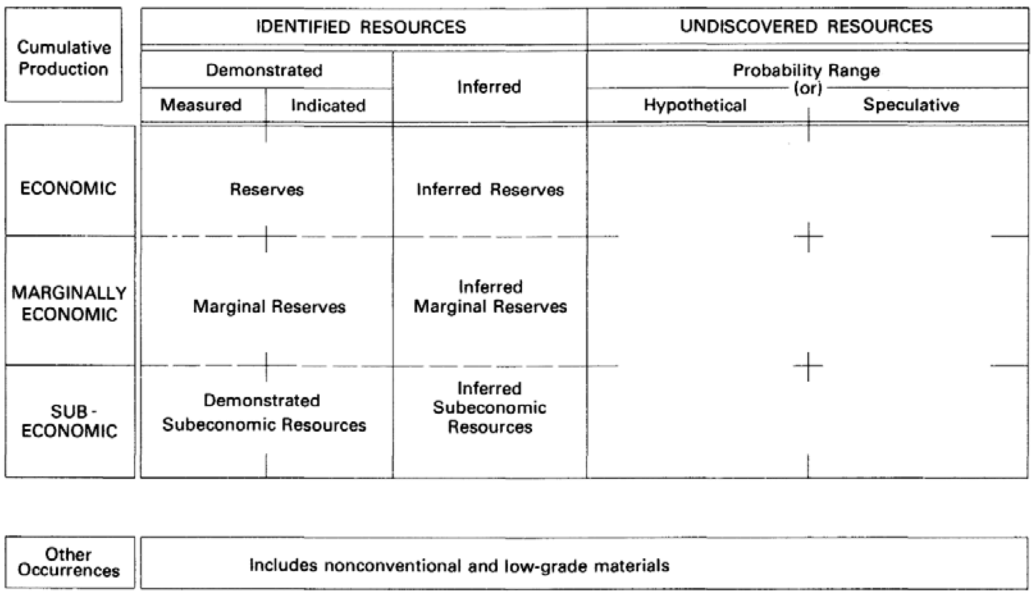

Figure 2: Classification of mineral deposits (USGS, 1980)

The first main differentiation that is apparent is that between identified resources and unidentified, or undiscovered, resources. According to the USGS (1976) a resource in general is a "concentration of naturally occurring solid, liquid, or gaseous materials in or on the Earth's crust in such form that economic extraction of a commodity is currently or potentially feasible." The crucial part here is the *potentially* economic, meaning that the raw material does not need to be economic in extraction right now but that there is at least a potential for making a profit in the future with better technology and methods. While identified resources are determined in their volume, quality and location “supported by geological evidence (...) [and] by engineering measurements”, the existence of unidentified resources is based on “broad geological knowledge and theory” (USGS, 1976).

Identified resources can be further separated into *economic, marginally economic and sub economic* deposits. Additionally, they are divided into *measured, indicated* and *inferred* resources according to the degree of geological certainty. More information about the exact differences can be found in USGS (1980) but is not relevant for this thesis.

The other important distinction is that of the *reserve.* According to the USGS (1980) the reserve is “that part of the reserve base which could be economically extracted or produced at the time of determination.” The *reserve base* includes reserves that are only inferred or not yet economic to extract. In contrast to a reserve base a reserve can thus be extracted economically, technologically as well as legally with a profit at the current time. Consequently, reserves are the smallest total value in the McKelvey Chart. They constitute what is attractive to mining companies and their exploration divisions.

Now with all the essential classifications in place, let us have a look at why geological availability is not the best indicator of resource scarcity in the short to medium term. Let us take the example of Copper, where a total of 2.1 billion tonnes of identified resources versus 3.5 billion tonnes of undiscovered resources are estimated to exist globally (Johnson et al., 2014). In comparison the production of Copper in the year 2015 amounted to 19.1 million tonnes. At this rate, without considering growth of production due to increased consumption, it would take approximately 110 years to mine the identified resources alone (the number of identified resources divided by the production rate).

While there are cases where the geological availability may be a factor, like in the case of Antimony where resources may be exhausted in 2040 already, in most cases there are still more than 100 years of resources left (Henckens et al., 2016). Of 60 different elements that were considered only one was found to be very scarce (Antimony) and four were considered scarce (gold, molybdenium, rhenium and zinc).

In the literature there is no clear consensus on whether geological scarcity will present problems in the near future or not. There are two main positions to consider which can be summarized in two distinct paradigms. First, the so-called *fixed stock paradigm*. According to Bleischwitz et al (2009) “for various commodities, the peak of extraction has already been reached or is currently about to be reached.” This refers to energy products, like oil and gas, as well as to non-energy products like metals. Because of this depletion it could be concluded that import dependency of the European Union will rise and there will be increased competition for raw materials on the world markets.

Giurco et al. (2010) conclude that while there are key differences between peak oil and peak mineral assumptions, due to the recyclability of minerals, there is a point where the processing of these minerals bears such high economic, social and environmental costs that it is useful to consider the metals stock to be fixed. This line of argument refers to the *mineralogical barrier*. It is the threshold where concentrations of a mineral drop significantly in extracted material due to atomic substitution (Skinner, 1976). Instead of the minerals being present as separate ores in the extracted material their concentration is small and they are mixed with many different trace minerals. Hereby, more sophisticated technological processes are needed for extraction and at the same time the energy costs rise due to the higher difficulty of separating the various compounds. This leads to a less economic extraction process overall which results in higher environmental costs because of an increased use of energy and extraction methods like the use of chemicals (Henckens et al., 2016). Gordon et al. (2006) also stress that while it is true that there is a continuous discovery of resources in the case of copper, the cumulative extraction is rising faster than the discovery and that cumulative extraction is approaching cumulative discovery.

In contrast, the *opportunity cost paradigm* takes a different standpoint. It postulates that “the total stock of mineral resources on earth far exceeds human needs” (Köhler, 2013). Through technological improvements it will be possible to extract increasingly low-grade minerals and still make profits. Consequently, this position assumes an opportunistic standpoint about technological progress. According to Tilton and Lagos (2007) “copper resources change over time as new technology and other developments increase the portion of the resource base considered potentially feasible for future exploitation.”

Fuel for the discussion about the opportunity cost paradigm is provided by the fact that long-term trends of past world market commodity prices do not show significant increases in prices as should be the case for the fixed stock paradigm (Bretschger et al., 2010). Because the argument is that if in fact reserves are already being depleted we should see increases in world prices due to declining supply while at the same time raw materials use is increasing due to economic growth.

Giurco et al. (2010) draw the conclusion that no matter what paradigm you agree with, whether you are optimistic about technological progress or not, it is not likely that most metals or minerals will become geologically scarce in the near-term. As the timeframe of the EU CRM assessment is 10 years it makes sense that the EU did not include geological scarcity as a main factor despite its importance in resource management discussions today.

Nevertheless, there are more other issues that affect scarcity of raw materials, namely technological developments as well as considerations of economic importance and supply risks. These will be discussed in the following three sub sections.

2.2.2 Technological Developments

In the CRM assessment methodology, a similar position to the opportunity cost paradigm is apparently followed. It states that the “key driver that has enabled us to keep up with demand in the past, has actually been the technological progress in exploring, mining and processing mineral raw materials” (EC, 2014). Especially, yet underdeveloped remote exploration areas like the desert, the bottom of the sea or the Arctic might hold significant and currently untouched reserves.

Examples that are listed include epithermal precious and base metal deposits that are contributing to global reserves despite being unknown prior to 1970. In addition, over the course of the 20th century world copper mines experienced a production increase from 0.3 to 2.2 kg per person, which is more than a seven-fold increase (Tilton & Lagos, 2007). Most mining operations average a drilling depth of about 200 m even though this number can go up to 500m for established mining operations and some special cases where open-pit mines go down almost 1000 m or 4000 m in the case of underground mines (EC, 2014). When considering that the continental crust is on average around 30-40 km deep it is evident that there is still substantial potential for improved exploration techniques that might open up new reserves (Fyfe & Selverstone, 2016).

Moreover, technological developments can extend to other parts of the value chain of mineral processing. For example, raw materials that are being dug up and are then used in production do not simply vanish. Instead they are contained in the growing anthropogenic stock of resources from where they can be reused, recycled or reprocessed. Improvements of recycling technologies have been achieved in the past and will continue to improve, thus opening up new potential secondary supplies of raw materials that might offset the need to explore primary resources (Köhler, 2013).

However, one must at the same consider the second law of thermodynamics which states that “in an isolated system available matter-energy is continuously and irrevocably degraded into the unavailable state” and thus there are limits to the potential for recycling (Georgescu-Roegen, 1977). In essence, if a raw material like lithium is taken from its pure form and then transformed to compounds that are used in the glass making industry its entropy will increase, meaning the order of its energy state will become more chaotic. Consequently, considerable energy input is required to convert the end product back to the elementary lithium.

Georgescu-Roegen (1977) even goes as far as postulating a fourth (thermodynamic) law which states that “[I]n a closed system, the material entropy must ultimately reach a maximum”. A closed system is defined as a system that does not receive external input in the form of energy. Other authors like Ayres (1999), however, have contested the existence of limits to full recycling and the fourth law postulated by Georgescu-Roegen (1977). Instead, if the stockpile of secondary resources is large enough and due to the external input of energy into the Earth system the possibility of 100 percent recycling is theoretically existent. However, this discussion is on-going and cannot be resolved in the course of this paper.

Other areas for technological improvements cover better processing methods that result in less by-products and thus greater efficiencies in raw materials use. Furthermore, the possibility to substitute critical raw materials with other less scarce materials can also reduce production bottlenecks (EC, 2014).

2.2.3 Economic importance

In the above section we have discussed criticality considerations according to physical scarcity and technological developments. Both of the two factors represent a timeframe of arguably decades, even though technological improvements are on a much shorter timescale than geological processes. Nevertheless, a more short-term effect and arguably one of the biggest influences on shortages in raw materials is caused by economic variables. Supply and demand are both essential factors that determine world markets.

Henckens et al. (2016) list a few possible causes for high/low demand/supply. First, increased demand can be caused by an increased use of innovative appliances that use a mix of various elements of the Periodic System. So-called *technology metals* like rare earth elements (REE) are increasingly important for modern appliances like clean-carbon technologies, e.g. in thin-film solar cells, wind turbines, or fuel cells and accumulators (Köhler, 2013). Second, due to economic growth of developing countries it follows logically that their consumptions of raw materials will also increase. Third, due to innovations in production processes it might be possible to substitute certain materials with others which would decrease demand in one resource and increase demand in the other (this factor also has a clear technological component). Fourth, increased efficiency can result in lower raw material demand but might also lead to the opposite because of higher production growth. Fifth, governments can artificially influence supply and demand via import/export restrictions/subsidies.

The EC (2017d) calculated the criticality of raw materials according to a formula that is shown below, where:

- *EI* is the economic importance,
- A_s is the end use share of a raw material in a NACE Rev. 2 (2-digit level) sector,
- Q_s is the value added of the respective sector,
- SI_{EI} denotes a substitution index of a raw material in relation to its economic importance,
- and *s* denotes sector.

$$EI = \sum\nolimits_{s} (A_s * Q_s) * SI_{EI}$$

There were some changes compared to previous assessments. First, unlike in the past the so-called mega sector approach was not used. A mega sector represents an aggregation of several different single sectors. This resulted in a high level of aggregation that was abandoned in the latest assessment for higher detail. Second, the possibility for substitution concerning the use of raw materials was formerly included in the supply risk dimension (see Section 2.2.4 below) but is now also incorporated via the substitution index SI_{EI} in economic importance.

The reason is that substitutability is more an economic variable than a supply variable because it influences economic decisions in the EU market, i.e. decrease of production costs. The calculation of the substitution index relies on so-called substitution cost parameters that intend to capture costs, technical performance as well as functionality of substitute materials.

2.2.4 Supply risk

The second dimension used to assess CRM is the supply risk dimension. It is supposed to account for "concentration of primary supply from countries exhibiting poor governance" as well as recycling rates and substitution possibilities (EC, 2017a). The formula for this calculation incorporates various elements like the World Governance Indicator (WGI), which is used to assess bad governance in a country. Additionally, variables are included for trade issues, dependency on imports, the mix of domestic production plus imports as well as substitution and recycling as counter-measures to reduce supply risks.

To measure the stability and the concentration of production in specific countries the so-called Herfindahl-Hirschmann-Index (HHI) is applied. It is for example used by the Department of Justice in the US for merger guidelines (DOJ, 2015). The index ranges from zero, meaning many different firms are having small market shares, to a maximum of 10'000 points, which means that one firm controls the market as a monopolist.

In total the calculation of the supply risks covers eight steps and includes more variables than the calculation of the economic importance. In the following section, the results from the above-described approach concerning CRM will be presented.

2.3 Assessment of the Criticality of Raw Materials in the EU

The latest CRM assessment by the EU was conducted in 2017 (EC, 2017c). It resulted in a list of critical raw materials that are presented in Figure 3 below. Compared to previous assessments there were several changes made (EC, 2017d). First, for calculations a data average of 5 years is used and not the last available year. Second, a screening for bottlenecks in the value chain for supply risks was incorporated. Third, the substitution index was updated and made transparent and got introduced to the economic importance calculation. Fourth, the mega sector approach has been abandoned for a more detailed assessment. Fifth, data has been prioritised according to its quality, the best being official EU data and the worst being trade association's data and expert judgement. Finally, parameters for import reliance as well as trade aspects were introduced.

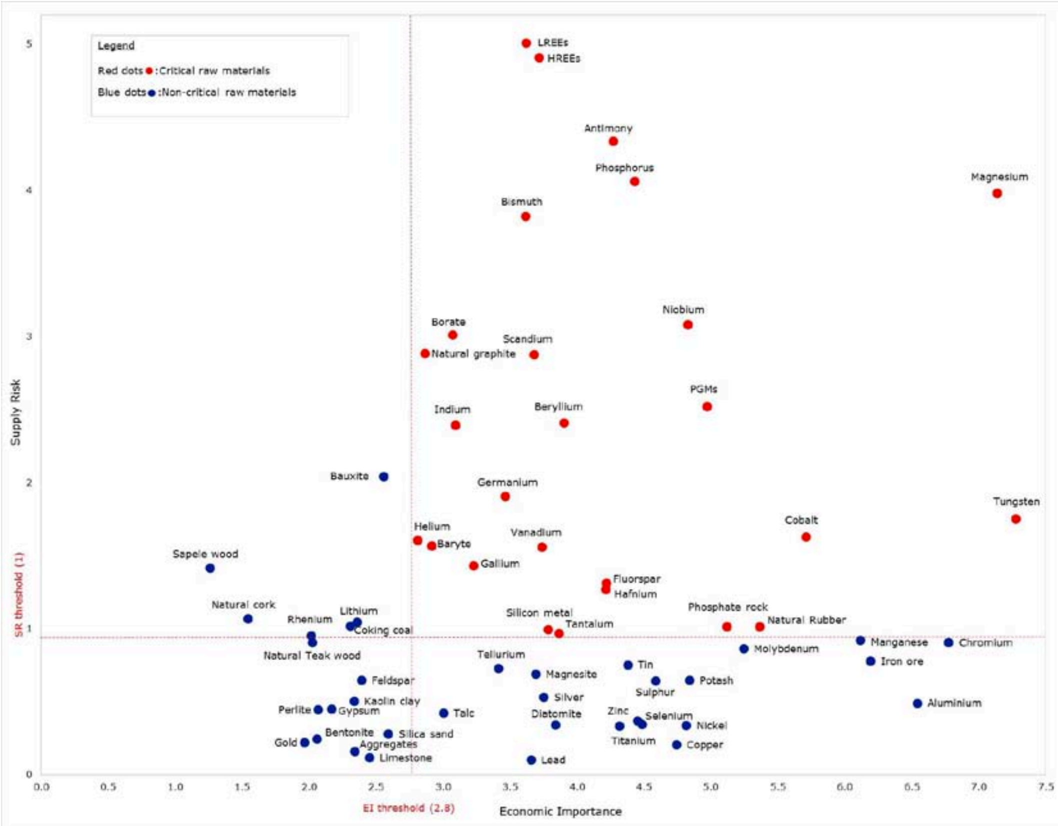

Figure 3: EU List of CRM for the Year 2017 (EC, 2017c)

In 2017 the assessment was carried out for 61 materials, 58 of which represented individual materials and three of them represented groups, i.e. light and heavy REE and platinum group metals (EC, 2017c). Of these materials 26 were found to be critical. A list of the names of all the critical materials is given in Table 1 below.

Table 1: List of CRMs in the EU in 2017 (EC, 2017c)

Antimony	Gallium	Magnesium	Scandium
Barite	Germanium	Natural rubber	Tungsten
Beryllium	Hafnium	Niobium	Vanadium
Bismuth	Helium	PGMs	
Borate	REEs (light & heavy)	Phosphate rock	
Cobalt	Indium	Silicon metal	
Fluorspar	Natural graphite	Tantalum	

What is apparent is the fact that lithium is not on the list of critical raw materials. Instead it is classified as a non-critical raw material. More about the production and demand of lithium and their effect on criticality will be discussed in the following section.

2.4 Lithium

Lithium is a chemical element with the symbol Li and the atomic number 3. It is part of the alkali metals, the first group in the periodic system, and it is a very light element with one valence electron and a core that consists of one proton and one neutron. Its name is derived from the ancient Greek word *lithos* which means *stone* (Pfeiler, 2016). The discovery of the element lithium is credited to Johan August Arfwedson from Sweden, who realized that there is a novel element present in petalite and spodumene – both are members of the group of silicates – as well as in lepidolite – a rare solid solution (Figurovskij, 1982).

The physical appearance of lithium is that of a silvery-white and soft, light metal. Lithium is soft enough to be cut with a knife. At room temperature it is the lightest of all solid elements with a density of 0.534 g/cm^3 (Holleman, Wiberg, & Wiberg, 1985). Among the alkali metals it has the highest melting and boiling point, with 453.69 K (180.54 °C) and 1'603 K (1'330 °C) respectively. Chemically, it is a highly unstable substance that will react heavily when encountering oxygen or water. This is due to the high energy density of the Li-ion and the lowest standard potential of all elements with -3,04 V (Binnewies, 2011). The electron configuration of lithium is [He] $2s^1$ and since lithium only has one valence electron in its *2s* shell it readily donates its free electron to other elements. Therefore, lithium in nature is only available in the form of compounds. Additionally, the high electronegativity is a reason why lithium is so attractive for the production of batteries and accumulators.

2.4.1 Primary Production of Lithium

According to the USGS (2016) the total lithium production in 2014 amounted to approximately 31'500 tonnes and annual production increased by six percent, on average, between 2004 and 2014. Compared to that, the world lithium consumption was estimated to be at 31'000 tonnes in 2014 with an average growth rate of 8 percent between 2004 and 2014. This comparison could draw the conclusion that production is only able to cover demand by a small margin. However, the potential for increasing output is significantly higher than it would seem.

Chile was the world's largest producer in 2014, with an estimated 44 per cent of the total world output, which was entirely from brine extraction. The second largest was Australia (32 percent, entirely from minerals), followed by Argentina (11 percent, from brine), and China (five percent, from both minerals and brine).

The shares in world lithium production are shown in Figure 4. Interestingly, the only EU producing country, Portugal, only represents one percent of the world lithium output. This explains the high import dependency of the EU concerning lithium compounds (BGS, 2016). In case of lithium carbonates 84 percent of the imports came from Chile.

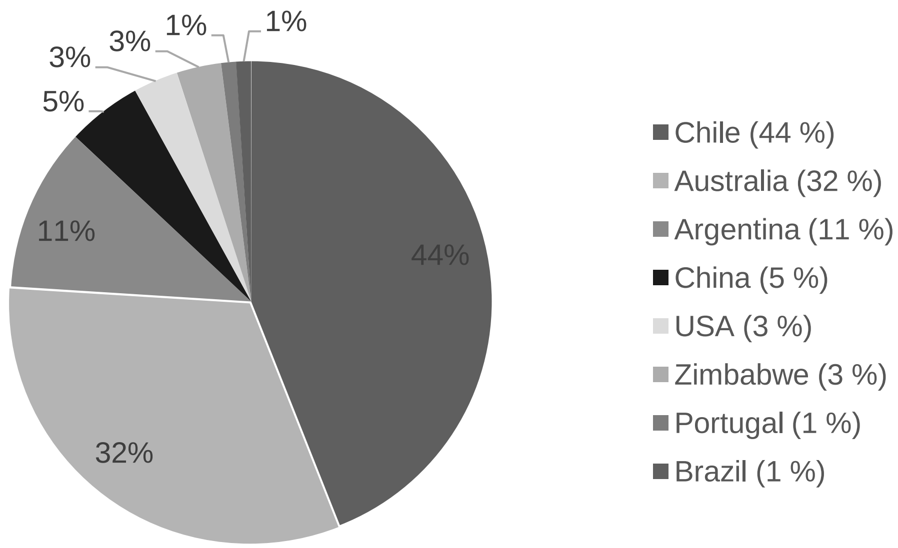

Figure 4: World production shares for Lithium (BGS, 2016)

Deposits that have become increasingly important for global lithium supply, due to the low extraction costs, are brines: continental, geothermal or oilfield deposits. Continental brines hereby refer to brines where surface or sub-surface waters have resulted in small amounts of lithium being leached from volcanic rock (Ide & Kunasz, 1989). The Salar de Atacama deposit in Chile is one example for a continental brine deposit. In total, Li-containing brines from two operations each in Argentina and Chile as well as three Spodumene operations in Australia account for the majority of worldwide lithium production (USGS, 2018). Geothermal and oilfield brines are more recent and there is no current exploration in this area (Evans, 2014). Estimated resources exist in California for geothermal brines with approximately 1 million tonnes of Li-content and potentially additional resources in the form of oilfield brines in the U.S.

In general, there are some factors that are consistent among different Li-rich continental brines (Munk et al., 2016). First, an arid climate like in the subtropical or the mid-latitudes is a major component due to the higher evaporation rate and the resulting increase of lithium concentration in the brine. This goes hand in hand with a higher share of evaporation than precipitation. At the same time, a substantial source of new inflow water is necessary to enrich the brines to begin with. Additionally, a suitable source for lithium is necessary in order to be leached out by inflowing water. Finally, the right hydrogeological conditions as well as a large enough timeframe for the Li concentration to occur play a role.

As a next point, an overview over estimations for total resources and reserves will be outlined in order to clarify why it makes sense that the EC (2017c) did not classify lithium as a CRM. Lithium is not a rare element and makes up about 0,006 percent of the Earth's crust (Breuer & Breuer, 2006). Its relative abundance can also be quantified by expressing it in parts per million. The ranges for lithium's occurrence in Earth's crust go from 20 to 60 parts per million (ppm) of lithium and to around 18 ppm in the sea water (Angerer et al., 2009). Consequently, geologically speaking, it is less rare than elements like copper or zinc but scarcer than tin or lead.

According to the classification in Section 2.2.1, we differentiated between resources and reserves. While reserves are the part of the total identified resources that are economic to extract, resources cannot be extracted yet due to economic considerations. However, they will be available for future production due to efficiency gains via technological development. In Table 2 different estimates for lithium deposits by various authors are summarised.

Table 2: Estimations of Global Resources and Reserves of Li

Resources	Reserves	Source
39 Mt	Not available	Gruber et al. (2011)
40 Mt	Not available	Evans (2014)
64 Mt	29.4 Mt	Yaksic and Tilton (2009)
25.5 Mt	9.9 Mt	USGS (2010)
39.5 Mt	13 Mt	USGS (2014)
53 Mt	16 Mt	USGS (2018a)

There are a couple of interesting points to discuss from Table 2. First, even with the lowest estimations total resources and reserves are assessed to range at 39.5 Mt and 13 Mt respectively. Considering that world production in 2014 was 31'000 tonnes the reserves alone would last for approximately 314 years, at current demand rates. And the reserves are the part of the resources that are already identified and economic to extract (see Section 2.2.1). Even if the demand increases by a factor of 10 reserves could still cover lithium demand for 30 years (9.9 Mt) or even for another 95 years (29.4 Mt). In addition, the different numbers by the USGS show the changing nature of the estimated resources and reserves of Li. Over the course of eight years resources increased by 208 percent and reserves by 162 percent.

What is more, Gruber et al. (2011) project that the world demand for lithium between 2010 and 2100 will range between 12 and 20 Mt. In the case of lower demand the reserves estimated by USGS (2018b) would be enough to cover it. In case of the upper limit of 20Mt reserves would not be enough. However, considering the increase in estimated reserves over time, the fact that resources from all sources in Table 2 are still higher than 20 Mt and that resources might become more and more economic to extract it seems evident that lithium supply will not be an issue for the future.

3 Material and Methods

3.1 Material Flow Analysis (MFA)

3.1.1 Introduction - (Brunner & Rechberger, 2004)

The method used to gauge the flows of lithium in the EU for this thesis is based on a material flow analysis (MFA). It is a “systematic assessment of the flows and stocks of materials within a system defined in space and time” (Brunner & Rechberger, 2004). A material can be both a substance and a good. The difference between them is that a substance is a uniform type of matter, like elements such as lithium. A good, on the other hand, is a mixture of a substance that has an assigned economic value, like fuel, food, cars or sewage sludge. However, unlike in economics a good in the MFA terminology does not include immaterial goods like energy or information.

The main principle enabling a MFA is the law of the conservation of matter. The Greek philosophers already postulated that nothing can be created from nothing and the French chemist Antoine Lavoisier (1743-1794) provided experimental evidence for the law of mass conservation in relation with chemical reactions. The latter showed that in a closed system without external inputs all the inputs of a reaction – even after transformation of the material – equal the outputs of the reaction. This means that no new matter is created or lost during the reaction. Hence, we know that all the lithium that enters a system and does not leave its spatial and temporary boundaries is conserved in the system due to the law of conservation of mass.

A *system* in the sense of the MFA consists of flows, stocks and processes within a certain boundary, like geographical borders or virtual limits (e.g households). The time boundary of the system could for example be one year, the summer months, one day, etc. The smallest possible system may only comprise a single process. Examples for systems are: a market economy like the EU, cities, factories, households, agricultural areas, etc.

A *process* can be the transport, transformation or storage of materials. They can be natural (flow of a river, decomposition, sedimentation) or man-made (waste collection, chemical treatment, landfilling). Processes are linked to each other via *flows* (mass per time) or *fluxes* (mass per time and area). Flows that come into the system from outside are called imports (or inputs) and those that originate in the system and leave it are called exports (or outputs).

Stocks can be defined as the storage component of the system that are contained in processes. They represent the difference in mass amount between input and output flows of a process. Due to the law of mass conservation we know that if the output flows are smaller than the input flows the system has some kind of storage (provided that all flows have been recorded appropriately). Hence, the respective process in the system is building up stock, e.g. due to sedimentation in a waste treatment system or due to landfilling.

The MFA can be a useful tool to analyse (environmental) systems according to their efficiency in material use and hence have wide possible applications in resource management. It helps in analysing and designing more efficient and thus more environmentally friendly systems.

3.1.2 STAN – (Brunner & Rechberger, 2017)

Due to the structured approach of the MFA the method is suitable for software support. One of these software tools is STAN, short for subSTance flow ANalysis. With 13’000 users between 2006 and 2016 it is the most widely used software tool for performing MFAs. It provides the interface to conduct an MFA according to the Austrian standard ÖNORM S 2096. Benefits of the use of STAN include: predefined components for graphical representation, data can be entered manually or be imported, predefined units can be chosen for dimensions like mass or volume, the results of the MFA can be displayed as a Sankey-style diagram, etc. In this thesis STAN was mainly used for the graphical representation of the MFA.

3.2 Material Flow Analysis - Lithium

The MFA model detailed in Figure 5 below was compiled according to Brunner and Rechberger (2004). A geographic spatial system boundary was chosen, namely the EU, and the time boundary is the year 2014. Due to the low resources and reserves of lithium in the EU it was decided to look at this geographic area to gauge the potential for supplying the lithium needs in the EU with secondary lithium from recycling. The choice of the year 2014 is due to the latest available Eurostat data from this year and was supplemented with data from 2012. Since these two years are close together it was assumed that assumptions that hold true for 2012 would also be valid in 2014.

In total, we have 29 flows, for seven processes. Three of these processes contain stocks, namely extraction, end-use and other waste management. First, the extraction process has a stock because there is some storage of extracted material that can be used to supplement the normal production if needed. Second, in the case of the end-use process the stock is due to the fact that products have different lifetimes and thus they would enter their end-of-life stages, meaning the recycling or other waste management processes, at different times in the future. However, in this thesis the lifetimes are not considered due to the lack of availability of proper data and thus we assume that products enter their end-of-life directly after production. This way we can assess the potential for lithium recycling in our chosen system. Consequently, the outlined MFA represents a best-case scenario for lithium recycling and is not an actual representation of secondary lithium resources in the year 2014. Third, the process of other waste management has a stock because the lithium waste that enters this process does not disappear but is stored, e.g. in landfills.

In the next sections, we will discuss the different processes and flows according to their relevance for the flow of lithium in the EU.

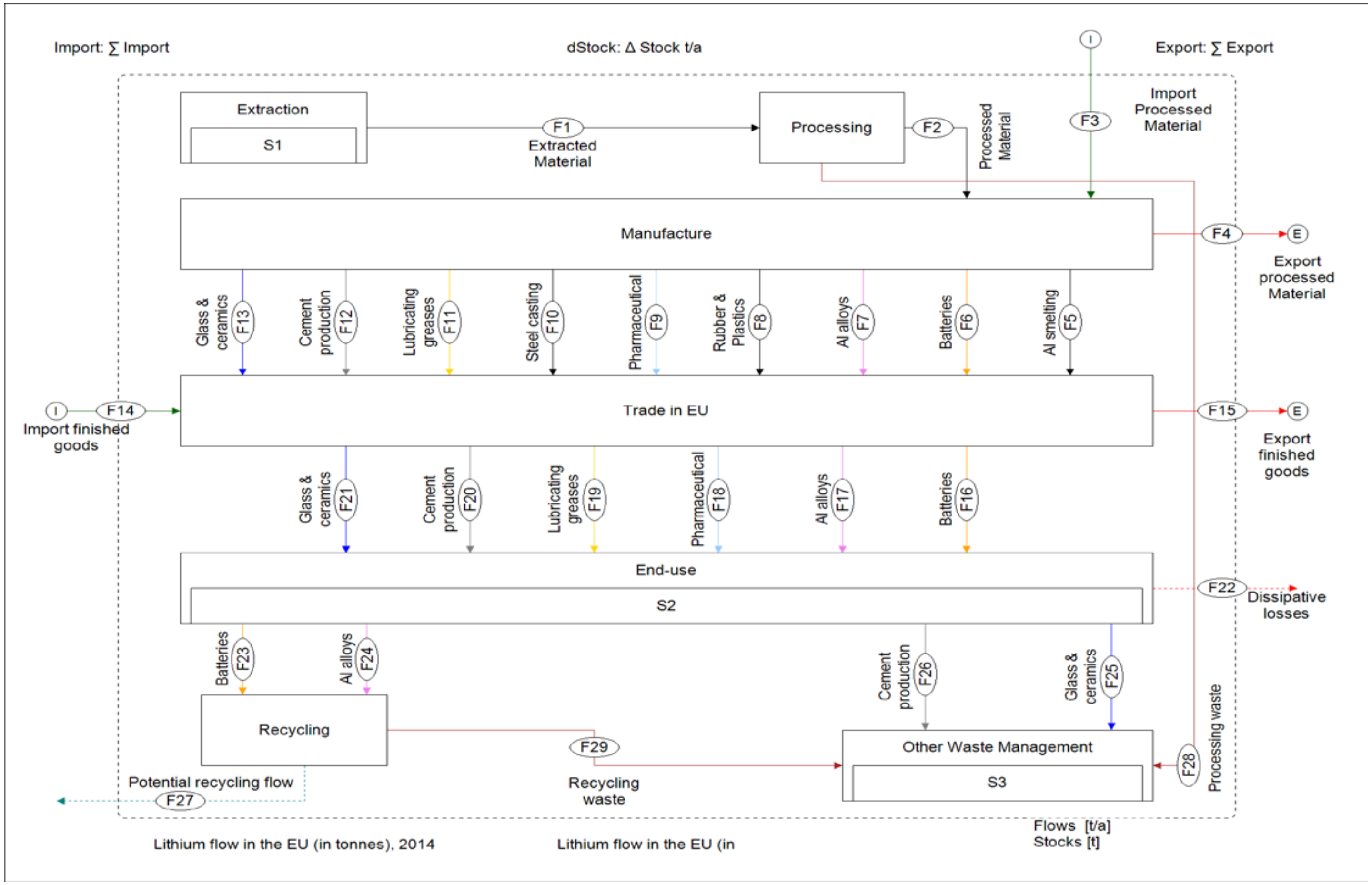

Figure 5: Lithium flow in the EU, 2014

3.2.1 Process 1 – Exploration

For the process of exploration, it is necessary to identify all relevant mining operations that produce lithium on an industrial scale. In a first step, it is therefore essential to know what kind of minerals, rocks or other materials contain lithium. They are summarized in Table 3 below, where also the average lithium-content of the respective minerals is given. The latter information is needed to convert mined material to Li-content in tonnes. The only significant domestic exploration of lithium minerals in the EU occurs in Portugal, where lepidolite is mined (Brown et al., 2016).

Some of the minerals from Table 3 appear in so-called pegmatites which are “coarse-grained rocks formed by the crystallisation of late magmatic fluids” (Evans, 2014). The most widely available Li-bearing mineral is Spodumene, a prismatic crystal that often occurs in granites and pegmatites where it is usually intermixed with quartz. Lepidolite, which has a rather complex and varying structure, is found in pegmatites with book-type crystalline structures. Petalite often occurs with lepidolite together and it can also transform to spodumene. Both lepidolite and petalite are rather rare and the latter one is only produced in the Bikita mining operation in Zimbabwe (Evans, 2014).

Table 3: Most common lithium-containing minerals (BGS, 2016), (Christmann et al. 2015)

Mineral Name	Chemical Formula	Li content	Appearance (colour and lustre)
Spodumene	$LiAlSi_2O_6$	3.73%	White, colourless, grey, pink, lilac, yellow or green; vitreous
Lepidolite	$KLi_2AlSI_3O_{10}(OH,F)_2$	~ 1.92%	Colourless, grey/white, lilac, yellow or white; vitreous to pearly
Petalite	$LiAlSi_4O_{10}$	2.27%	Colourless, grey, yellow or white; vitreous to pearly
Eucryptite	$LiAlSiO_4$	2.1-5-53%	Brown, colourless or white; vitreous
Amblygonite	$LiAl[PO_4][F,OH]$	3.4-4.7%	White, yellow or grey; vitreous to pearly
Hectorite	$Na_{0.3}(Mg,Li)_3Si_4O_{10}(OH)_2$	0.54%	White, opaque; earthy

Jadarite	$LiNaSiB_3O_7(OH)$	7.3%	White; porcellanous

Finally, this process is also represented with a stock. This is due to the fact that lithium exploration has a storage component, meaning that some of the extracted material is stored temporarily to be delivered at a point in the future. Consequently, at the beginning of the year 2014 there would be lithium contained in this extracted material and hence, the process would start with a stock.

3.2.2 Process 2 – Processing

As has been said above, lithium compounds are mainly produced from pegmatites – Li-containing rocks – and continental brine sources. For the two different sources two very different extraction processes exist. An extensive overview over different processing methodologies and their respective chemistries for different Lithium minerals and brines can be found in Tran & Luong (2015). In this section we will only briefly discuss the available processing methods for the major Li minerals spodumene and lepidolite as well as brines. Spodumene and brines make up the majority of world Li production, while lepidolite is the only Li-containing material being mined in the EU.

According to Evans (2014) the majority of spodumene extracting operations (like in Australia) use an acid leach process that produces lithium carbonate (Li_2CO_3). There are different steps to be followed: first, crushing and grounding of the ore; second, spodumene and gangue are separated by flotation; third, the produced concentrate is converted to its chemical beta form through heat treatment and then sulfuric acid is added; finally, the resulting lithium sulphate is concentrated, purified and reacts with sodium carbonate to produce lithium carbonate.

For lithium brines the picture looks different and is presented in Munk et al. (2016). The first step here is solar evaporation after the brines have been pumped to the surface. The ideal case would be that the material has a low Mg/Li ratio (optimally less than 10) because the Mg ions behave very similar to the Li ions and hence separating the two can be energy intensive because the brine needs to be heat-treated. After being led through various evaporation ponds a Li concentrate is produced. This may take between a few months and two years, depending on the climate. As has been described above an arid climate with a higher rate of evaporation than precipitation is preferable and speeds up the process substantially. Extraction from geothermal and oilfield brines cannot always be done by solar evaporation and processing methods are not yet clear.

In the case of lepidolite a two-step leaching process is applied, similarly to spodumene (Tran & Luong, 2015). First, the lepidolite is treated through sulphate roasting before it is leached with water to extract the lithium. However, numerous different extraction methods exist here, both in operation in mining companies and some that are currently being researched. All of them result in the production of lithium carbonate (Li_2CO_3). The efficiencies that are achieved during this process vary between 80 percent and 99 percent. The average efficiency of the thirteen extraction methods listed in Tran and Luong (2015) is 91.42 percent. This number was chosen as a basis to calculate the amount of lithium that is generated as well as lost during the processing step.

As a next step, we need to know what kind of lithium compounds are being produced by processing methods. Some of them have already been named in the sections above and in Table 4 they are summarized. Their uses vary between different sectors. Lithium oxide, also known as lithia, is formed when Li reacts with oxygen in the air (BGS, 2016). Through reaction with water and steam it forms lithium hydroxide. Lithium oxide is used in the glass and ceramics industry as a flux since it reduces the melting point as well as the viscosity of silica compounds. Lithium hydroxide is used for the production of lubricating greases, for air treatment and CO_2 scrubbing technology, aluminium smelting and for continuous steel casting as well as for the production of primary (non-rechargeable) and secondary (rechargeable) batteries (Christmann et al., 2015).

Lithium carbonate is used in the glass and ceramics industry as well as for aluminium smelting and the continuous casting of steel, for pharmaceutical products as well as to produce secondary batteries. Furthermore, it is the basis for the production of other lithium compounds like lithium bromide, lithium salts, lithium hydroxide, etc. The purity of lithium carbonate ranges between 99 percent for industrial use and 99.5 percent for battery production (Evans, 2014).

Lithium bromide is used exclusively in air treatment, while butyllithium is used for polymer production and lithium metal in the production of primary batteries and to make Al-Li alloys (Christmann et al., 2015). Lithium chloride finds applications as a flux in the process of welding aluminium and as a solution in pharmaceutical applications and hospitals where it is used due to its sanitising effect (Evans, 2014). Often lithium carbonate is the starting material to produce lithium chloride, bromide or hydroxide. More about the specific uses in the industries that are relevant for this thesis will be discussed in the next section.

Table 4: Conversion Factors to convert Lithium Compounds to Lithium Content (Christmann et al., 2015), (BGS, 2016)

Name of Compound	Formula	Li Content
Lithium metal	Li	100 %
Lithium carbonate	Li_2CO_3	18.79 %
Lithium oxide	Li_2O	46.46 %
Lithium hydroxide	LiOH	28.98 %
Lithium chloride	LiCl	16.37 %
Lithium bromide	LiBr	7.99 %
Butyllithium	C_4H_9Li	10.84 %
Lithium hydroxide monohydrate	C_4HgLi	10.8%

3.2.3 Process 3 – Manufacture

In order to assess the flows of lithium in this process it is necessary to take into account the flow of lithium compounds that comes into the EU via imports. Similarly, one must account for the exports of lithium compounds. Lithium compounds like the ones described in Section 3.2.2 above are used in the manufacturing of finished products. Data about imports and exports were available from the BGS via Brown et al. (2016) as well as from the ComExt database of Eurostat. However, in the case of both data sets there is no separation between lithium oxide Li_2O and lithium hydroxide *LiOH*. As can be seen in Table 4 above, the two lithium compounds have different stoichiometric ratios and different molecular compositions (lithium hydroxide having an additional hydrogen atom).

This poses a problem for the following reasons. First, in order to follow the MFA methodology it is necessary to calculate the mass of elementary lithium contained in the material that is produced or traded in the EU market. Second, to properly calculate the mass of imported or exported Li we would need to know the relation between lithium oxide and -hydroxide. This would allow us to separate the total according to relative shares and estimate the lithium content.

One way to work around this is to find data on the usage of both compounds in the respective sectors in a specific year available and then to use or extrapolate this number to the year chosen for the MFA, i.e. 2014. However, it needs to be stated that the assumption that market shares of lithium compounds stay the same is only valid when looking at a short time frame, maybe a few years. After this point, new production processes or structural changes will change the composition of lithium compounds used in manufacturing.

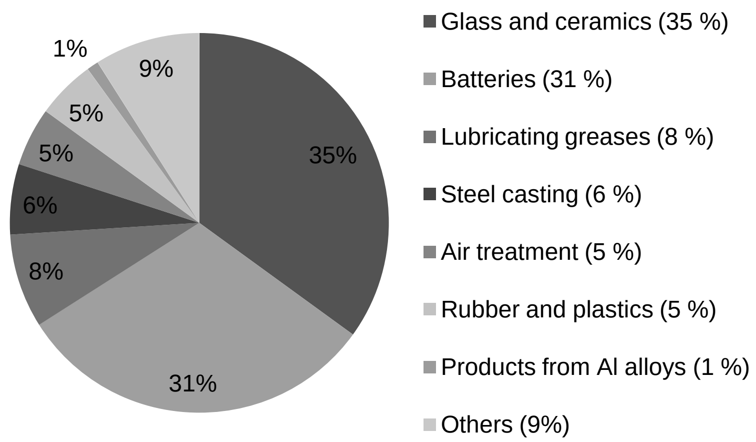

Figure 6: Global Lithium Use in Manufacturing (USGS, 2016)

Another reason the above-described approach is not appropriate is the different structure of the manufacturing market for lithium in Europe compared to the rest of the world (see Figure 6 versus Figure 7) and the lack of available data for market shares of lithium compounds in the EU. Especially, the higher share of the glass and ceramics industry in the EU would distort the results of the MFA (32 percent globally in 2014 versus 66 percent on average between 2010 and 2014 in the EU).

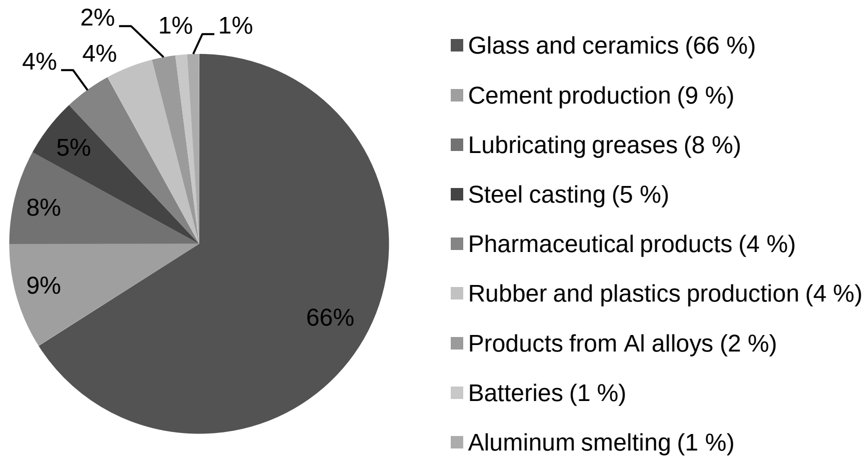

Figure 7: EU Lithium Use in Manufacturing (USGS, 2016)

A better approach to separate lithium oxide from hydroxide import numbers is to find information what compounds are used in which sectors. In a next step, this information will be used to split up the combined Li-oxide and Li-hydroxide numbers according to the use of each compound in the different sectors (see

Figure 7). Due to the low domestic production rate of lithium (see above in Section 2.4.1) it is reasonable to assume that the import data for lithium compounds will reflect the production needs of European firms, meaning each sector will import the lithium compounds they use in production. Hence, glass and ceramics will have a 66 percent share in lithium imports, the cement industry 9 percent, the manufacturing of lubricating greases 8 percent and so on (see Figure 7).

As it turns out, lithium oxide is almost exclusively used by the glass and ceramics industry to improve the durability of their products (see more information below). In addition, lithium oxide is used in steel casting as well. In total this would represent 71 percent of the total lithium use in manufacturing assuming that both sectors use lithium oxide exclusively. In case of the steel casting sector this assumption is problematic because Li-metal is also used. However, since no data about importance of the two compounds could be found and due to the low influence of this sector (only 5 percent of total lithium use) it was decided to assume a complete use of lithium oxide. In conclusion, of the combined Li-oxide and –hydroxide 71 percent will be imported as lithium oxide and 29 percent as –hydroxide thus allowing us to split them up and appropriately calculate the Li-content in imports.

Furthermore, the export numbers will be deducted from the imports to reflect the amount of material that stayed in the EU. In order to do so we must find data that separates trade data concerning intra and extra EU trade. This is necessary because we want to know the amount of lithium that stays in the EU. If we would take the accumulated data by the BGS in their Minerals Yearbooks we would have the combined intra- and extra-EU trade data. Subtracting the exports from the imports would distort our results because we would not know whether the exports are to another EU country (thus staying in our spatial system border) or to a partner outside the EU (thus leaving our spatial system border). Since data on intra- and extra-EU trade is available through the Eurostat ComExt database we decided to use this data set, even though there are some discrepancies between the BGS and Eurostat data sets about the total traded volume.

Finally, we take this number of Li-content in net processed material that is staying in the EU and apportion it according to the shares of the respective sectors using lithium (see Figure 7). Unfortunately, not the complete picture concerning lithium use is captured this way. Since we only have data about imports and export of Li-oxide –hydroxide and –carbonates we can only apportion these flows. No data on Li metal or other Li compounds was available. In the following list we will briefly discuss the nine manufacturing sectors in the EU that use lithium compounds.

i. **Glass and ceramics**

In the glass and ceramics industry as well as in continuous steel casting (see below) lithium minerals can be used directly for the production process which is specific to these industries (Christmann et al., 2015). For other industries the lithium minerals have to be processed before they can be used. Lithium oxide is used in the glass and ceramics industry as a flux since it reduces the melting point as well as the viscosity of silica compounds (BGS, 2016). Thus, it leads to energy and cost savings. The resulting glass or ceramic glaze is more resistant to stress like high temperatures and chemical attacks and has better hardness and shine. Furthermore, when using lithium oxide in glass ceramics applications, like cooktops, cookware or large telescopic lenses, the thermal expansion is reduced to almost zero (Evans, 2014).

ii. **Cements production**

Due to the so-called Alkali-silica reaction Lithium compounds can enable control of the thermal expansion of concrete to prevent its deterioration (Micheal et al., 2007). In this sector, different lithium compounds may be used.

iii. **Lubricating greases**

Per definition a lubricating grease is “a type of lubricating fluid that has been combined with a thickening agent which ensures the lubricant is more readily retained where it is needed” (BGS, 2016). In order to produce high-quality and cost-effective lubricating greases lithium hydroxide is used. This results in a product that has excellent water resistance and can endure wide temperature ranges (Evans, 2014). Approximately 90 percent of the worldwide demand for lithium hydroxide is being accounted for by this sector (Angerer et al., 2009). The produced lubricating greases are mainly used in cars, airplanes and ships as well as in machines.

iv. **Steel casting**

In steel casting lithium in the form of lithium oxide is added to the process (Evans, 2014). In addition, the BGS (2016) states that metallic lithium “is used as a flux in welding or soldering because it promotes the fusing of other metals and at the same time absorbs any impurities.” This application is similar to the production of Al-Li alloys. The process of continuous steel casting represents 90 percent of modern steel production (Christmann et al., 2015).

v. Pharmaceutical products

There are applications for Lithium compounds, especially lithium carbonate, in the pharmaceutical sector as drugs that can stabilise the mood as well as in the treatment of bipolar disorder (BGS, 2016). Furthermore, it can be used in dermatological applications, for weight loss drugs as well as AIDS and cancer treatment (Christmann et al., 2015). Another lithium compound that is used on a much smaller scale in pharmaceuticals is lithium chloride which can be used for humidity control in the food industry or in hospitals for sterilizing (Evans, 2014).

vi. Rubber and plastics production

In the manufacture of synthetic rubber so-called organolithium compounds are being used, especially butyllithium is an important one (Evans, 2014). It acts as a catalyst in the production of synthetic rubbers that are needed for car tire manufacturing or in the production of pipes, kitchen ware and acrylic paint (Christmann et al., 2015). Additionally, lithium hydroxide and lithium acetate are used in some polymers as additives for the dying process.

vii. Products from aluminium alloys

Alloys of aluminium and lithium are being developed for the aeronautics sector due to their low weight and high durability compared to other materials (Christmann et al., 2015). The percentage share of products from aluminium alloys is only 2 percent (see Figure 7). However, the development of these lightweight alloys is only in its infancy and will likely have a bigger impact in the coming decades. For the production of Al-Li alloys Li metal is used (Evans, 2014).

viii. Batteries

This application is clearly one of the most important future uses for lithium due to the benefits that arise from the characteristics of Lithium. Nishi (2014) has summarized underlying reasons for the development of the first Li-ion batteries.

First, lithium has a high operating voltage with 3.7 V on average. Second, lithium ion batteries (LiB) have high gravimetric and volumetric energy densities. While gravimetric energy density or specific energy means the energy per mass (Wh/kg) volumetric energy density is about the energy per volume (e.g. Wh/cm^3 or Wh/l). Often there is limited volume available for a battery, like in a smartphone, and thus volumetric energy density is especially important. Third, there is no memory effect, meaning that the battery does not have to be fully charged or discharged to not lose some of its capacity. Instead, it can be charged at any level and still keep its full capacity. Finally, the self-discharge rate is low compared to other batteries, i.e. less than 20 percent per year.

However, the efficiency of LiB is more easily affected by varying temperatures (BGS, 2016) . Mostly, LiB are used in electronic applications where a long lifetime as well as low weight are important, e.g. phones, laptops, calculators, electrical vehicles, power tools, pacemakers for the heart, watches, clocks, etc. (Wendl et al., 2009).

Since 2005, the battery production sector has overtaken the glass and ceramics sector as the biggest consumer of lithium compounds (Christmann et al., 2015). It is also the fastest growing sector for lithium use worldwide with a compound annual growth rate (CAGR) of 22.8 percent between 2003 and 2013 alone. Secondary (rechargeable) batteries accounted for 90 percent of the market (Christmann et al., 2015). Primary (non-rechargeable) batteries only make up 10 percent of LiB in use.

In the non-rechargeable form Lithium metal is used (EC, 2017b). In contrast, for the production of secondary batteries, or accumulators, lithium carbonate as well as lithium hydroxide and chloride are being used (Christmann et al., 2015). The rechargeable batteries function through the use of electrochemical reactions. In fact they are actually accumulators and not batteries in the strict sense of the word because batteries are not rechargeable. However, if not clearly stated otherwise batteries and accumulators will be used synonymously.

Normally, these accumulators consist of a positive electrode and a negative electrode as well as an electrolyte. The ions move from the negative electrode (also called anode) to the positive electrode (also called cathode) via the electrolyte. This creates voltage, which can then be used to generate electricity. Usually, the anode consists of graphite while lithium is present in the electrolyte as well as the cathode (BGS, 2016).

Information on the material used in the cathodes can be found in Christmann et al (2015). The materials used for the positive electrode according to decreasing order of importance for the year 2013 are: lithium cobalt oxide ($LiCoO_2$); lithium nickel, manganese, cobalt oxide ($Li[Ni_{0.33}Mn_{0.33}Co_{0.33}]O_2$); lithium manganese spinel ($LiMn_2O_4$); and finally, lithium iron phosphate ($LiFePO_4$). Lithium cobalt oxide was the first cathode material used in the industrial production of LiBs that were produced by Sony and Asahi and today still have the highest production rates. However, their expected growth rates up to 2025 are much lower than for the other cathode materials. The other lithium cathode materials are being used for the production of accumulators for electric vehicles. Especially lithium manganese, nickel, cobalt oxide and lithium iron phosphate cathodes have a high projected CAGR until 2025 with 12.6 percent and 20 percent respectively.

This brings us to the most important future sector for the application of Li-ion accumulators: the electric vehicle industry. Three different types of electric vehicles have to be differentiated, namely battery electric vehicles (BEVs), hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) (Angerer et al., 2009). In the case of BEVs only electricity is used for propulsion, for HEVs a mix of an electrical and a combustion motor is used and for PHEV the built-in accumulator can be charged via a plug. It is important to differentiate between these three types because all of these have different kinds of accumulators and consequently will contain different amounts of Lithium. Which one of these technologies will dominate the market cannot be projected safely. One also should consider that competing technologies like fuel cells are being developed as well, thus lowering the market share of the above-mentioned electric vehicles. However, it is expected that the CAGR for the electrical vehivle sector could reach almost 20 percent between 2012 and 2025 alone (Christmann et al., 2015).

A challenge that was encountered in this section was trying to estimate correctly how much lithium is contained in Li-ion batteries and accumulators. In literature, there is a wide range available with authors reaching different conclusion. An overview over such estimates can be found in Table 5 below. As a consequence, no calculations were performed concerning Li-content in manufactured or traded batteries.

Table 5: Estimation of the Li (Metal and Carbonate) Content in Grams per kWh of Battery Capacity

Source	Tahil, 2010	Miedema & Moll, 2013	Kushnir & Sandén, 2012	Gruber et al., 2011	Speirs et al., 2014	Evans, 2014
Li per kWh	320	178	200	114	190-280	113-176
Li_2CO_3 per kWh	1703	949	1064	607	1011-2022	600-938

ix. Aluminium smelting

In this use-case lithium carbonate as well as lithium chloride are used (Angerer et al., 2009). In order to produce aluminium, one must electrolyse aluminium oxide also called alumina (Al_2O_3). This process is known as Hall-Heroult process and requires significant amounts of electricity due to the high melting point of alumina at 2072°C (Christmann et al., 2015). Thus, the process is energy- and cost-intensive. Lithium carbonate and chloride react with fluoride in the melt to produce lithium fluoride which then reacts with the aluminium oxide and CO_2 (Wendl et al., 2009). The advantages are the following: it is possible to reduce process temperature by 12-18°C; reduction of electrical consumption by 2-4 percent; reduction of cathode consumption between 1 percent to 2 percent and reduction of harmful Fluor emissions by 40-50 percent (Christmann et al., 2015).

3.2.4 Process 4 – Trade

As a next step, we have to assess how many finished products are being traded in the EU. This means that the Li-content in imports and exports has to be estimated. One way to do so would be to identify all industries that use lithium and to calculate the Li-content in the finished products, very similar to the process of manufacturing above.

Since data in ComExt from Eurostat is only available for specific sectors it is a challenge to follow this bottom-up approach. This is due to the fact that we would need to know what percentage of products in this sector contains lithium and additionally to what extent. Via this information it would be possible to estimate the amount of lithium being traded. However, this data is hard to obtain not least because there are nine different sectors that are using lithium compounds in manufacturing in the EU.

Additionally, it could be the case that the imports do not readily reflect the same picture as the manufacturing process since we already discussed above that the manufacturing sector in the EU is different to the rest of the world concerning lithium (higher share of glass and ceramics, very low share of battery production; see Section 3.2.3).

Another way to estimate the amounts of lithium contained in this process would be a top-down approach. In order to follow this method, we need data on the total use of lithium in a given period or on the amount of lithium being imported to and exported from the EU via finished products. Next, we would take the net number (imports – exports) to assess the amount of lithium staying in our spatial border. Finally, the flows from the process of manufacturing also come into this process since some of the manufactured products will also be exported outside of the EU and additionally be traded within the EU. The component that exits the EU of course needs to be subtracted from the rest.

From Figure 8 we can already see that a large amount of finished products containing Li-ion batteries and accumulators are being imported, since there is little domestic manufacturing of batteries (one percent; see Figure 7). One way to estimate the export ratio for finished products would be to look at another year of which we know how much lithium has been imported or exported in the form of finished products. Then, we build a relation between the amounts of imported processed materials to the amount of imported finished products. From the study done by BIO by Deloitte (2015) we know that in 2012 a total of 8’430 tonnes of lithium in finished products and a total of 14’200 tonnes of processed lithium had been imported. This gives a ratio between finished products and processed materials of approximately 59 percent. Since the lithium market in the EU will not have changed significantly in the two years between 2012 and 2014 this assumption is fairly robust. Next, the number of imported processed materials in 2014 will be multiplied by 59 percent to get a result for the total number of imported finished products.

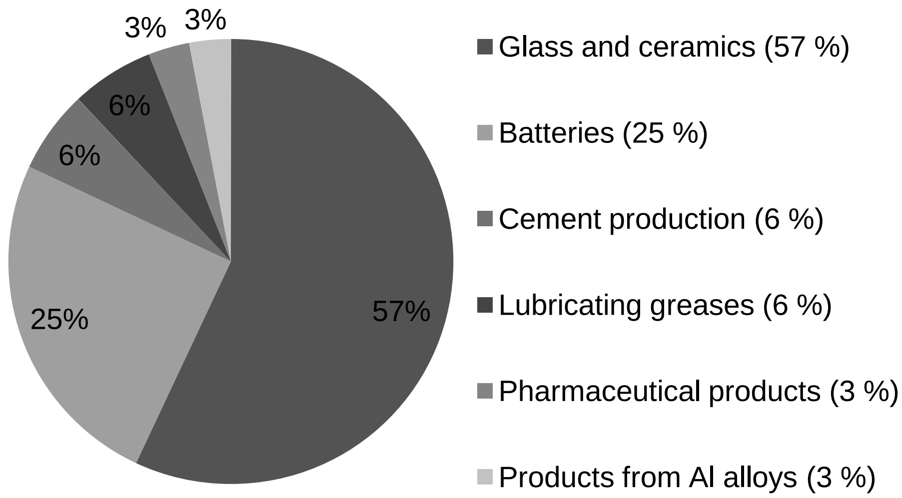

Figure 8: Shares of Li in End-use in the EU (BIO by Deloitte, 2015)

In order to arrive at a number for total exported finished products a similar approach was followed. This time we built a ratio between total exports of finished products and total imported finished products plus addition to in-use stock, i.e. the manufacturing component, in 2012. Again, the study done by BIO by Deloitte (2015) was used for this data. In 2012, 5’180 tonnes of finished products were exported, 8’430 tonnes imported and 8’200 tonnes added to the in-use stock. The resulting ratio is approximately 31 percent. Now, to get a number for 2014 we add the total lithium contained in manufactured products, that are assumed to all enter the in-use life cycle immediately, and the total imports from 2014 (according to the estimation above). This number is multiplied by 31 percent to get a result for exported finished products.

Finally, we arrive at a total number for lithium being traded in the EU as well as flows of lithium according to the specific sectors, like glass and ceramics, batteries, lubricating greases, etc. The resulting amounts are apportioned according to the percentages of the share of lithium in the end-use. Again, we know the share of lithium according to end-use through the work that was done by BIO by Deloitte (2015). The respective numbers are shown in Figure 8.

3.2.5 Process 5 – End-use

The flows coming into this process are represented by the percentage shares in end-uses as shown in Figure 8. Interestingly, the picture looks considerably different form the uses of lithium in manufacturing. Most importantly, batteries represent a significantly higher share in end-use (25 percent) compared to manufacturing use (1 percent). Consequently, from this information we can derive that while there is no significant production of batteries happening in the EU (in contrast to the rest of the world: see Figure 6) there are still a lot of batteries being used here in the EU. This also means that most of these products are being imported in the form of finished products from outside the EU.

One of the major problems that were encountered during this process was the fact that in order to assess stocks here we would need to know the lifetime of products. What this means is that when products containing lithium are being manufactured or imported they will be used for different timespans. For example, a phone will be used for a shorter time than an electric car, glass and ceramics products or cement. Additionally, Al-Li alloys used in aeronautics will probably have a lifetime of 30-40 years, which is the average lifetime of a modern jet aircraft (Christmann et al., 2015). In effect, when such alloys are being produced in 2014 they would only enter the recycling step in 2044 or even in 2054. Similarly, if you build a road with Li-containing cement it will be used for some years before it gets renewed. In general, this would mean that all the finished products produced in the year 2014, and from then on until they are being decommissioned, are building up stock of lithium in the process end-use.

However, it is difficult to find data on the lifetime of all the different products that are being produced in the above-mentioned sectors. Additionally, to then draw a conclusion on the average lifetime for the end-use sectors from Figure 8 would require a much more complex approach and thus is out of the scope of this thesis. Therefore, we assume that all the products that enter the end-use in 2014 also enter either the process of recycling or other waste management in the same year. Of course, this assumption is not correct, however, it enables us to assess how much lithium could *potentially* be retrieved in the EU.

3.2.6 Process 6 –Recycling

The process step of recycling is of specific interest in this thesis. The combination of comparably cheap extraction costs of international mining companies and high environmental costs that are associated with mining operations should be viewed critically. Economic incentives often lead to the focus on primary supply. This will likely have major impacts on our environment.

If it were possible to retrieve significant amounts of materials from end-of life products in Europe and to use this supply of secondary material for manufacturing, we would achieve multiple benefits. First, the environmental impact of primary resource extraction would be lowered. Second, high collection and recycling rates mean that less waste will be landfilled. This would in turn have a positive feedback loop on reducing the emissions from landfills in Europe, and so on.

However, an increasing problem is the growing complexity of modern technology products. The reason being that, especially in the manufacturing of finished products the entropy is usually increased. Additional components or reactions are sources for potential disorder in the system. High entropy of finished products requires higher amounts of exergy in the recycling process. Modern products require a large variety of different special metals or alloys that improve product usage. Different physical and chemical characteristics pose additional problems for the recycling process. Mobile phones for example use more than 40 different elements of the periodic system (Hagelüken, 2014).

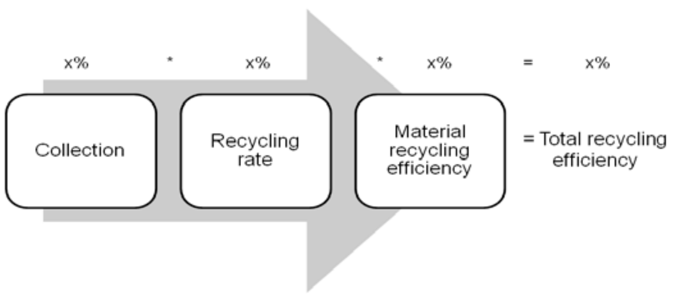

Figure 9: Components of a Recycling Value Chain (Hagelüken, 2014)

After the end of the lifetime of the products they have to be collected and recycled to arrive at secondary materials that can be used as inputs into a new production cycle. This poses challenges due to the different physical and chemical extraction methods needed for the numerous components. For example, different battery chemistries may require tailored recycling methods (Christmann et al., 2015). A common value chain for recycling can be seen in Figure 9.

From Figure 9 we also see why it is important to assess the efficiencies of the different processes along the value chain. In order to arrive at a total recycling efficiency one has to multiply the efficiency of each single step. The starting point being the collection rate of products containing lithium. This would include all the different applications outlined in the manufacturing process (see Section 3.2.3).

However, some of the uses of lithium are of dissipative nature like the manufacturing of lubricating greases via lithium hydroxide (Wendl et al., 2009) or the lithium carbonate used in the pharmaceutical sector, among other Li-compounds (BGS, 2016). This means that the Li-content cannot be recovered from these end products due to their dispersion into the environment. Thus, these flows are leaving our system boundary.

Furthermore, lithium contained in finished products like cement or glass and ceramics also cannot be recycled with current technologies (Christmann et al., 2015). For example, it would prove difficult to separate the lithium from the sand and the cement powder or to recover it from a glass matrix. Additionally, the lithium amount in these products is too small and the energy content needed too high for the process to be economic in a foreseeable future. These flows are, however, not leaving our system boundary since theoretically there might be a possibility to recover the lithium in the distant future with respective technological progress or increased lithium prices. Thus, these flows are "stored" in our system. But they are also not stocks in the sense of secondary lithium due to the lack of recycling technologies.

As a matter of fact, lithium can currently only be recycled from batteries and accumulators as well as from Al-Li alloys and from air treatment. However, the recycling from lithium from air treatment technologies is on such a small scale that it can be discarded (Wendl et al., 2009). Furthermore, there is no end-use share of this application in the EU (see Figure 8). As a result, recycling will be limited to flows of batteries and Al-Li alloys coming from the process of end-use.

The recycling rate of end-of-life products, meaning products that are no longer in use, containing lithium is estimated to be below 1 percent in total (Graedel et al., 2011). This number includes Li-ion batteries and accumulators and reflects low incentives that currently exist for the recycling of lithium. For example, in September 2014 the price for cobalt on the London Metal Exchange stood at 33

$/kg while the price for lithium carbonate averaged 6.39 $/kg (Christmann et al., 2015). Consequently, it is five times more valuable to recover cobalt than lithium.

Nevertheless, there exist quite a few recycling technologies for recovering lithium from batteries. An overview over their material recycling efficiencies is given in Table 6 below. In this thesis the values given by Shin et al. (2005) and Georgi-Maschler et al. (2012) were used to represent the theoretically possible recycling efficiencies that could be achieved. The authors have apparently achieved a material recycling efficiency of 100 percent via hydrometallurgical methods. Consequently, since there is proof of concept we assumed a material recycling efficiency of 100 percent in this MFA. This way we get the *recycling potential* for lithium batteries in the EU in contrast to what is actually being recycled. The reasoning behind this approach is to show how much lithium could theoretically be recovered with optimal processes. Additional overviews over recycling methods for Li-ion batteries is given by Ekberg and Petranikova (2015), in Kwade and Diekmann (2018) and by Vezzini (2014).

Table 6: Material Recycling Efficiencies of Different Processes

Recycling Process	**Recycling Efficiency**	**Commercial Operation**
VAL'EAS-Process (Umicore)	80 %	Yes
By RWTH Aachen	80-90 %	Planned
By Shin et al. (2005)	Up to 100 %	No
By Paulino et al. (2008)	90 %	No
By Georgi-Maschler et al. (2012)	Up to 100 %	Planned

Going back to Figure 9, we must also find efficiencies for collection rates and the recycling rate, i.e. the percentage of collected batteries that are suitable for recycling. To represent the collection rate for Li-ion batteries we can compare it with the collection rate for lead-acid batteries, despite differences between the two technologies. According to the International Lead Association (ILA) the collection rates for lead-acid batteries in Europe and North America are 99 percent (ILA, 2015). One has to consider that this number comes from an association that is supposed to promote the benefits of these batteries but also the U.S. EPA (2015) concluded that this number is realistic. Therefore, we set the collection rate at 99 percent.

Next, we need to find a value for the rate of collected batteries that are suitable for recycling. Meaning what percentage of the batteries and accumulators that are collected are also suitable for recycling. In Germany, the recycling rate of collected batteries in 2008 was 99 percent (Angerer et al., 2009). Again, this numbers was used as a proof of concept and theoretical assumption in the MFA. Consequently, we get a total recycling efficiency of 98 percent.

Since there was no data available on efficiencies for Al-alloy recycling we assumed that the picture would be similar to batteries. The reasoning is that both batteries and Al-alloys contain low amounts of lithium and both can theoretically be collected with high efficiencies. As was outlined above, a large share of Al-Li alloys is used for the aeronautics industry and have lifetimes of 30 to 40 years. After this time, it should be easy to collect the metals from the decommissioned airplanes. And if trace amounts of metals can be retrieved from batteries with efficiencies of up to 100 percent then the same should hold true for Al-Li alloys.

3.2.7 Process 7 – Other Waste Management

Finally, we arrive at the process of Other Waste Management. Here, all the lithium that is being discarded via efficiency losses in the processes of recycling and processing as well as the material that cannot be recovered with current technologies and under current economic conditions is collected. The latter concerns cement production as well as glass and ceramics. In contrast, lithium from lubricating greases and pharmaceuticals is not entering this process, due to the dissipative nature of its use (as was discussed above in Section 3.2.6).

As one of three processes, there is a stock component for waste management. Products containing lithium that entered their end-of-life stage in previous years and could not be recycled will be stored in landfills. Consequently, all the lithium contained in this material from previous years would represent the stock for the year 2014.

4 Results

In this section, the results from the MFA that was conducted according to the methodology outlined in Section 3 will be presented. Figure 10 shows the MFA for lithium in the EU for the year 2014 graphically. Unfortunately, it was not possible to estimate any of the stocks due to the lack of access to proper data. It would have extended the scope of this thesis too far and thus was discarded in this MFA. However, via the assumptions made in Section 3 it was possible to estimate all the identified flows of our modelled system. Consequently, the MFA represents a good approximation of the total lithium flows in the EU for 2014.

Nevertheless, it has to be stated that the only secondary data that was collected without making assumptions stems from the amounts of imported and exported processed materials provided by the ComExt database of Eurostat. In addition, estimations for efficiencies for the processes of Processing and Recycling were taken from literature (see Section 3 above). All other results had to be based on available data from the year 2012 which was accessible via the study done by BIO by Deloitte (2015). The numbers in Figure 10 have been rounded for easier reading.

4.1 Process 1 - Exploration

In 2014, and also at the time of writing this thesis, the only significant exploration operation in Europe is taking place in Portugal (BGS, 2016). In 2014, a total of 17’459 tonnes of Lepidolite have been produced by mining operations in Portugal. According to the conversion factors provided in Table 4 above, this amounts to a total of 335 tonnes of lithium.

No data was available on how much is put into storage and how much is being transferred to processing. Therefore, it was assumed that all the material goes to processing. Furthermore, we could not find any data on whether some of the Lithium minerals were used directly in the glass and ceramics industry (as is possible; see Section 3.2.3 above). In literature only the direct use of spodumene and petalite are mentioned concerning the glass and ceramics industry (Evans, 2014). In Portugal, however, lepidolite is extracted. Consequently, the above assumption that all the extracted material is sent to processing (due to it being Lepidolite) should be fairly robust in the case of the EU.

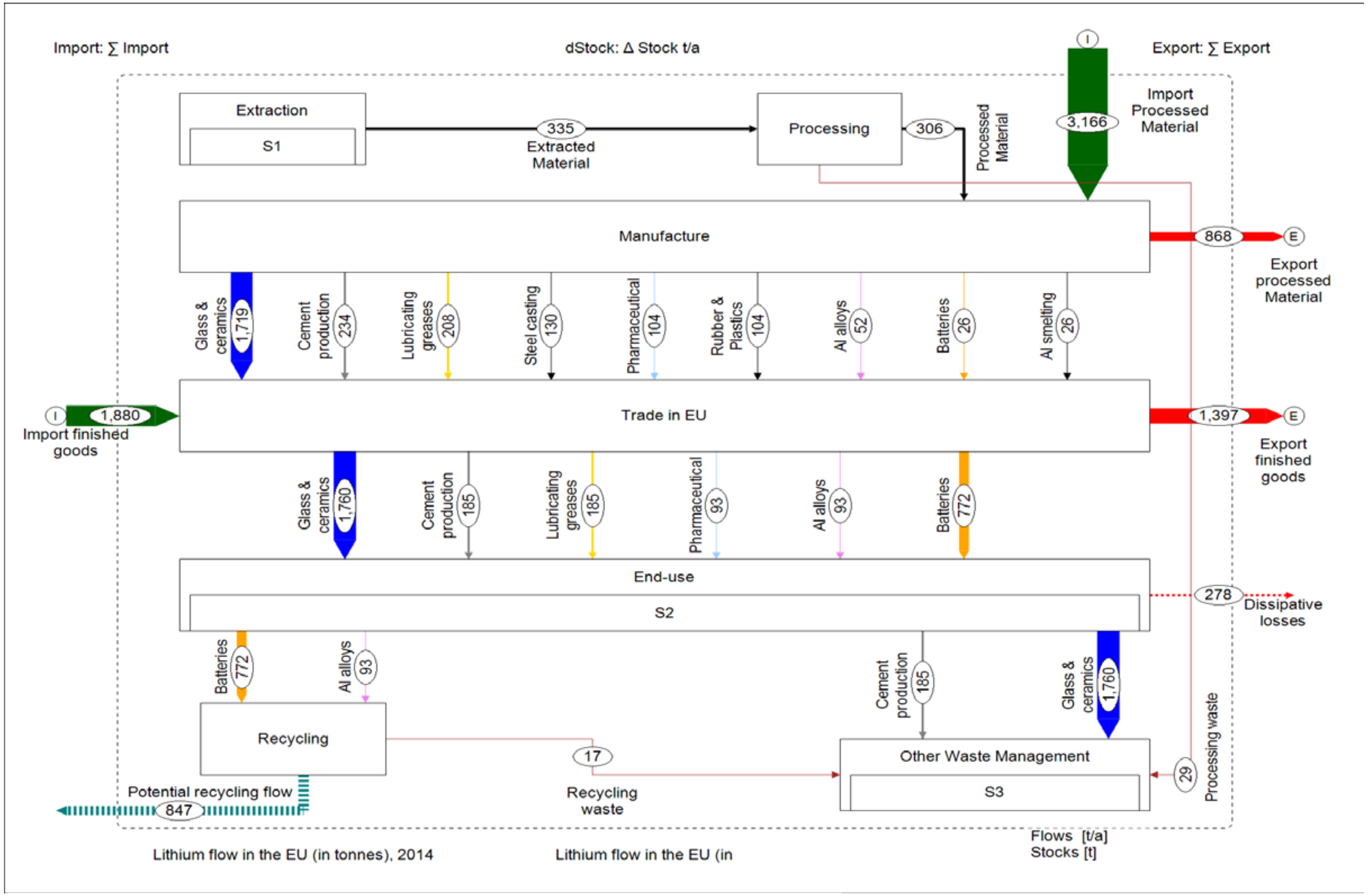

Figure 10: Estimated Lithium flow in the EU (in tonnes), in 2014

4.2 Process 2 – Processing

Since a total of 335 tonnes is being extracted in Portugal and assuming an average processing efficiency of 91.42 percent (see Section 3.2.2 above) we get a total of 306 tonnes of lithium in the form of processed material flowing out of this process into manufacturing. The remaining 29 tonnes represent processing waste and they go directly to other waste management.

4.3 Process 3 – Manufacture

In this process, we have two inflowing sources of lithium. First, there are the 306 tonnes of Li that come from processing. Second, a total of 3'166 tonnes of lithium were imported into the EU in the form of processed materials like lithium carbonate, oxide and hydroxide in 2014. This data was collected from the ComExt database of Eurostat and represents secondary data. The lithium oxide and hydroxide fraction was split up according to the methodology outlined in Section 3.2.3 above.

Some of the processed material is being exported from the EU. This amounts to a total of 868 tonnes of lithium. It is not clear whether this material is being imported and then directly exported or if some of this is from domestic processing operations in the EU. It could be that some of it is from the stock of extracted material, which is further processed and then exported. However, it is not important to know the exact origin since we know that all the lithium in exports exits our system.

There are several different lithium applications in manufacturing in the EU. The biggest fraction is used for glass and ceramics with a total of 1'719 tonnes of lithium. Second, cement production uses 234 tonnes of lithium. Third, lubricating greases manufactured in the EU contain approximately 208 tonnes of lithium. There is a big difference between the number one application, glass and ceramics, and the other top three ones. Additionally, the numbers again drop for pharmaceuticals (104 t), rubber and plastic production (104 t), Al alloys (52 t), Batteries (26 t) and Al smelting (26 t).

What is interesting is the low amount of battery production in the EU compared to the rest of the world (see Figure 6 versus Figure 7). Furthermore, the very high share of the glass and ceramics industry is significantly different from the rest of the world. In total 3'472 tonnes of lithium enter the Manufacturing process and a total of 3'471 tonnes leave the process. The difference is due to rounding.

4.4 Process 4 – Trade

In this process, there is the highest total number of inflows of lithium with ten. They make up 4’483 tonnes of lithium. Imported finished products constitute 1’880 tonnes of lithium while exports of finished products contain 1’397 tonnes of lithium. There are a few interesting points to mention here.

As we see from Figure 10, flows from Al smelting, from steel casting as well as from rubber and plastics production enter the trade process but they do not leave the process towards end-use. This would mean that the lithium contained in these products is not being used in the EU but instead is being exported. Consequently, it could be argued that the exported finished products contain 130 tonnes from steel casting 104 tonnes from rubber and plastics production and 26 tonnes from Al smelting.

First, in the rubber and plastics industry lithium acts as a catalyst in the production of synthetic rubbers and is used in some polymers as additives for the dying process (see Section 3.2.3 above). Second, to make the process of Al smelting more efficient Lithium fluoride reacts with aluminium oxide and CO_2 to reduce the melting point of Al (see Section 3.2.3 above). Third, Li metal is used as a flux in welding or soldering to fuse other metals and to absorb any impurities (see Section 3.2.3 above). It is not clear whether the lithium from these manufacturing uses is contained in the finished products or if it is contained in the waste produced by the process. In this MFA, it was assumed that it is contained in the finished products.

Another interesting observation that has already been introduced above is the fact that many Li-ion batteries and accumulators are being imported into the EU compared to the very low number of domestic production. The battery flow increased from 26 tonnes of lithium to 772 tonnes of lithium during the trade process. This is a difference of 746 tonnes. However, the largest lithium flow is still from glass and ceramics with 1’760 tonnes of lithium. Nevertheless, this flow only increased by a mere 41 tonnes.

In summary, 4’483 tonnes of lithium come into the trade process while a total of 4’485 tonnes of lithium leave this process. The difference is again due to rounding.

4.5 Process 5 – End use

In 2014, 3’088 tonnes of lithium entered the end-use stage via finished products, either imported or produced domestically. Most of this stems from the glass and ceramics production. In contrast to manufacturing the second most important use of lithium in the end-use process comes from Li-ion batteries and accumulators with 772 tonnes. Next is cement production and on par with it lubricating greases, each representing 185 tonnes of lithium. Unfortunately, we could not provide data on the amount of stock that is contained in the end-use sector.

Additionally, it was assumed that all the products that enter the end-use in 2014 leave the process in the same year. This of course is an assumption that is not true due to the different lifetimes of products containing lithium. Li-ion batteries would stay in the end-use process for a shorter time than for example Al-Li alloys used in aeronautics. The latter ones having a lifetime of 30-40 years (see Section 3.2.5 above) while batteries have varying lifetimes, a Li-ion battery in a watch having a shorter one than a Li-ion accumulator in an electric vehicle.

Lithium from lubricating greases and from pharmaceutical applications leaves the end-use sector as dissipative losses. The lithium from these flows cannot be recovered because it is dispersed into the environment. For example, lithium contained in medication will be excreted in the form of urine and faeces and is thus not available for recovery. In total, dissipative losses make up 278 tonnes of lithium in the year 2014.

In summary, 3’088 tonnes of lithium enter this process and the same amount leaves the end-use sector. In the next two sections, we will discuss the two final stages for lithium in the EU, namely recycling and other waste management.

4.6 Process 6 – Recycling

The process of recycling was a main area of interest in this thesis concerning the MFA. It is supposed to showcase what an ideal recycling situation could achieve in the EU. However, what is immediately apparent is the low number of lithium that enters this process. Only lithium from batteries and accumulators as well as Al alloys can currently be recycled. Hence, only 865 tonnes of lithium are available for recycling.

Additionally, to represent an ideal recycling scenario for 2014 it was assumed that all the lithium from the end-use sector becomes available for recycling and other waste management in the same year. Still, after accounting for a total recycling efficiency of 98 percent (see Section 3.2.6 above) we see that only 847 tonnes of lithium are available in the form of secondary lithium (potential recycling flow), which can be used for manufacturing. In relation to the total amount of imported material in 2014 this represents a mere 27 percent. And this already considers the recoverable lithium under optimal conditions, which are not currently achieved in the EU.

Additionally, no economic aspects are represented, meaning the relation of recycling costs to the costs of primary lithium resources. However, as was discussed above, the primary resources are much cheaper than secondary resources (see Section 3.2.6). Since we do not know whether this lithium will be used domestically or will be exported the outflowing arrow leaves our system boundary. Nevertheless, in theory it could all be used as an input into the manufacturing process. The lithium that is wasted in the recycling process due to the 98 percent efficiency goes to other waste management and amounts to 17 tonnes.

4.7 Process 7 – Other Waste Management

Finally, all the lithium that cannot be recycled and that is not lost due to dissipative use goes to other waste management. Especially, the large amount of lithium from glass and ceramics (1’760 t) goes to this process. In total, 1’991 tonnes of lithium are contained in other waste management. Unfortunately, it was also not possible to estimate the amount of stocks in this process. However, it is safe to assume that it is significant considering the large input from the glass and ceramics industry, which has been important in the EU for many years.

5 Discussion and Conclusion

First of all, as the possibility to supply the EU's lithium needs with secondary supply was one of the main issues in this thesis the discussion starts with this point. Looking at the MFA in Figure 10 it is rather obvious that the high import dependency of the EU concerning primary lithium (see Section 2.4.1 above) cannot be tackled through proper recycling channels. Even when channelling the full *theoretical* potential of Li in the EU concerning collection rates of 99 percent, recycling rates of 99 percent and a material recycling efficiency of 100 percent only 27 percent of the import needs concerning processed materials can be satisfied. And an overall recycling efficiency of 98 percent is of course an incredibly optimistic scenario. It is unlikely that a collection rate of 99 percent and a material recycling efficiency of 100 percent on an industrial scale will be achieved in the next few decades.

Even if the manufacturing of batteries in the EU would multiply by a factor of ten it would only raise the total amount of lithium flowing into the recycling process to 1’006 tonnes (from 772 tonnes). Hence, 986 tonnes of lithium would be available as potential recycling flow. If we would assume that the amount of imported material would stay the same only 31 percent of lithium demand in manufacturing would be met. This is an increase of four percentage points through a ten-fold increase in battery production in the EU. Of course, the assumption that the amount of imported processed lithium compounds staying the same is highly unlikely since additional manufacturing of batteries needs additional input of processed material (which would have to be imported due to the low domestic production of primary lithium). Furthermore, as long as the glass and ceramics industry makes up a large portion of the used lithium a lot of material is made unavailable for recycling due to the lack of technological possibilities to recycle lithium from glass and ceramics.

Nevertheless, a possible route to decrease import dependency of the EU concerning lithium could be the widespread recycling of batteries and accumulators that are currently being imported. Compared to the domestic production this flow is much higher (26 t versus 746 t). Doubling the amount of imported batteries would raise the imported lithium flow to 1’492 and the potential recycled lithium flow from these imports to 1’462 t. This would represent 46 percent of the imported processed lithium in 2014 (3’166 t).

On another issue, the conversion factors from Table 4 about the Li-content in Lepidolite are only average values. Thus, they are not necessarily relevant for Lepidolite in Portugal but are rather rough estimates. Therefore, it should be taken with a grain of salt. Due to the low production rate and supply from Portugal this does not prove to be of high importance.

Finally, we would arrive at the question of whether lithium will become a scarce resource in the future. In Table 2 the lithium resources and reserves were summarized. When we compare these numbers to estimated lithium demand given by Gruber et al (2011) with 12 to 20 million tonnes between 2010 and 2100 or Angerer et al (2009) with a maximum of 0.5 million tonnes in the year 2050 it can be concluded that there is no threat for shortages in lithium supply. This point has already been mentioned in Section 2.4.1. Additionally, the EU does not currently view lithium as a critical resource nor has it viewed it as critical in any of its three critical raw material assessments. In the next section we will discuss the weaknesses of the MFA in relation to the data that was available.

5.1 Data issues

In order to conduct the MFA for lithium in the EU it was necessary to make a lot of assumptions. The problems that arise from these will be discussed here.

To begin with, the data on the shares of lithium uses in the EU for manufacturing and for end-use were only available as an average over the years from 2010 to 2014. Yet, they were used as representative for the year 2014. This is problematic since it is unlikely that these shares will stay the same over the course of four years. Nevertheless, in the case of manufacturing in the EU it is not as problematic as for the rest of the world due to the low share of Li-ion battery production, which is the fastest growing sector for lithium use worldwide (Evans, 2014). In the case of end-uses it is likely that the share of batteries in 2010 was lower than in 2014 thus lowering the share of Li-ion batteries in 2014 and making the results less accurate.

As a next point, a lot of the data needed to conduct an MFA for lithium, or any other industry metal for that matter, is not readily available. Often it concerns industry data, like production efficiencies or amount of wastes and by-product, Li-content of the wide variety of products available, level of substitution by other raw materials, etc. In fact, the only data that was available via Eurostat was the amount of imported processed lithium compounds. However, there we only found information about lithium carbonate, hydroxide and oxide. Information about other compounds like butyllithium or Li metal was not recorded. This is problematic because it is not known for how much lithium these materials account for.

Furthermore, lithium hydroxide and oxide were not separated but instead share the same Eurostat code. As a consequence, assumptions had to be made about the relative share of lithium oxide to hydroxide use since both compounds have very different Li-conversion factors (see Table 4). This in turn affects the estimated amount of lithium in the system boundary.

Especially data concerning the distribution of lithium use according to manufacturing and end-use sectors were an essential tool to conduct the above MFA. Without them it would have been close to impossible to estimate which sector uses how much lithium. Therefore, the work done by BIO by Deloitte (2015) was a great resource to estimate ratios like imports and exports of finished products and was readily used in this MFA. Consequently, the MFA in this thesis relies on the accuracy of the assumptions undertaken by the above-mentioned study. The methodology also laid the groundwork for the EC's publication of the CRM factsheets.

Another very important issue in collecting the data was to estimate the amount of lithium that is being imported to and exported from the EU in finished products. Often only aggregated information for the whole sector is available, e.g. glass and ceramics, or rubber and plastics production. In addition, data about the amount of waste produced from processing, manufacturing and recycling needs to be assumed. Data on imports of secondary material for reprocessing, export and imports of end-of-life products, export of recycled material, as well as stocks in the exploration, end-use and waste management processes could not be obtained.

If the EU would make the information about the methodology provided to them by Bio by Deloitte (2015) available for the use of the academic sector it would make data collection significantly easier. It involves information about the metal content in various end-use products, information about their lifetime and use, about waste management strategies, among many other things. Once all necessary material to construct a framework for conducting an MFA has been collected it can be used for the following years without much additional effort. This of course only, if no major structural changes happen in the involved industries (like introduction of completely new raw materials or production processes).

Making the methodology and tools publicly available would enable scholars to test the assumptions of the methodology of the Bio by Deloitte (2015) study for various metals across different timelines and construct a more robust approach by trimming the model to accommodate past phenomena. Similar things are being done with climate models that are tuned according to inconsistencies with past projections versus real climate data.

5.2 Conclusion

In general, secondary lithium supply (from recycling) will most probably be far less important than primary lithium supply (from mining and exploration) in the next century or more. It is unlikely that the price of lithium will increase so drastically that it will become economically interesting to ramp up recycling efforts. However, the collection and recycling of Li-ion accumulators in electric vehicles and other batteries will definitely be a valid approach for supplying at least some of the lithium demand of the EU via secondary lithium.

Gruber et al (2011) for example estimate that PHEVs, HEVs and BEVs will make up more than 50 percent of the lithium demand in 2100. Furthermore, the accumulators contained in BEVs may contain up to 3.85 kg of lithium. Consequently, collecting and recycling these accumulators could be worthwhile, economically and from a sustainability standpoint. Nevertheless, they also forecast that the share of recycled lithium to primary lithium would be less than 5 percent. Angerer et al. (2009) arrive at a maximum recycling rate of one third for the year 2050 in a scenario where electro mobility dominates the future automobile market. This is similar to what was estimated in this thesis as an optimal situation for a potential recycled lithium flow (27 percent). Due to the large resources of lithium still available and the low costs of extraction, primary lithium will dominate the market for a long time. Additionally, production is being ramped up around the world to meet the increasing demand for lithium in the automotive sector (Evans, 2014).

In conclusion, the current recycling efficiencies of less than 1 percent (see Graedel et al., 2011) for products containing lithium are due to economic and political structures that incentivise high primary production and growth rates. In turn, environmental aspects are taking a secondary role compared to economic ones. Cheap primary production rates of course do not appropriately reflect the environmental costs that stem from increased mining operations. One of the results of the low recycling and high primary production rates would be that it will be highly unlikely to achieve a circular economy concerning lithium supply.

Concerning recycling rates of critical metals in general there is a lot to be done before a circular economy is realistic with only four critical metals having end-of-life recycling-input-rates of above 20 percent: vanadium, tungsten, cobalt and antimony (Mathieux et al., 2017). And lithium is not even seen as a critical raw material, hence its priority level is even lower (EC, 2017c).

The competition for land use between environmental goals like preservation of biodiversity and economic goals like availability of cheap raw materials will continue to pose a significant challenge in the future of the EU. Through the MFA of industrial metals scholars can definitely have a positive impact on future resource management by finding appropriate potentials for creating circular economies. An interesting potential area for future research would be a methodology to capture the *real* costs of industrial raw materials by incorporating environmental and social costs. This way we would get a better idea on what it costs society as a whole to focus heavily on cheap primary production.

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