Tampere University of Applied Sciences

Life cycle assessment for lithium hydroxide production

Preoperational study of carbon footprint for Keliber's lithium hydroxide production in Central Ostrobothnia

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Risk Management and Circular Economy

ABSTRACT

Tampere University of Applied Sciences
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Life cycle assessment for lithium hydroxide production
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The aim of this thesis was to identify the hotspots of the environmental footprint for a Finnish mining and chemical company Keliber Technology Oy, and to assess the challenges related to the implementation of LCA methodology in the mining industry. The practical part of this study was carried out as a preoperational cradle-to-gate assessment on the environmental impacts of a battery-grade lithium hydroxide production. The data collection used in this study was based on one year of fictional operation (with an estimated annual operation hours 7500 h and a production capacity of 15 000 t) and plans and data available by September 2021. The theoretical part of the study on the challenges of LCA in the mining industry was carried out as a literature review.

The total carbon footprint calculated in this preoperational study for 1 tonne of lithium hydroxide monohydrate from Keliber's process is 9,4 t CO2 eq. Majority of the emissions (77%) derives from the operations at the chemical plant which use most of the energy and chemicals. According to the results, energy use accounts for the biggest source of CO2-emissions together with the use of calcium oxide as a process reagent at the chemical plant. Energy use was assessed to cover 61% of the total CO2-emissions whereas transportation in its entirety, proved to be a minor contributor to the carbon footprint with just 3% share of the emissions. In addition to the greenhouse gas emissions, the production process was identified to generate significant amounts of extractive waste and contribute to the depletion of fossil resources through the use of non-renewable energy sources. Based on the results, decarbonizing fuels and energy would offer the most efficient tool for emission mitigation.

In terms of challenges of LCA methodology in the mining industry, several needs for customization and harmonization have been identified in order to realize the full potential of life cycle methodology for the sector. Further development is required, for example, to increase the suitability of impact categories to meet the specificities of the mining industry. Fundamental differences in methodological issues like units and practices, characterization models and allocation approaches are likely to introduce unacceptable variation into the results. Full implementation of life-cycle methodology in the mining industry is particularly important because the assessment of the environmental impacts of other products depends directly or indirectly on the information provided by the mining industry.

Key words: life cycle assessment (LCA), battery-grade lithium hydroxide monohydrate (LHM), mineral extraction, global warming potential (GWP)

CONTENTS

ABBREVIATIONS AND TERMS

CO2 – eq.	Carbon dioxide equivalent
EPD	Environmental Product Declaration
GWP	Global warming potential
ISO	International Organization for Standardization
KIP	Kokkola Industrial Park
LCA	Life cycle assessment (or life cycle analysis)
LCE	Lithium carbonate equivalent
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LHM ($LiOH \cdot H_2O$)	Lithium hydroxide monohydrate
LIB	Lithium-ion battery

1 INTRODUCTION

The European Union intends to fight global warming by achieving carbon neutrality by 2050 (European Commission, 2021). In Finland, Sanna Marin's Government Programme (2019) aims at making Finland the first fossil-free welfare society by setting the goal already for the year 2035 (Ministry of the Environment, 2021).

Reaching carbon neutrality means economy with net-zero greenhouse gas emissions. The emerging challenges to meet the emission reductions needed to achieve these objectives have increased the pressure to find efficient low-emission energy solutions. Renewable energy sources, like wind power and solar energy, together with a rising trend of electrical vehicles rely on rechargeable batteries as energy storages. This, combined with an increasing population and demand for portable electric devices, is about to radically increase the demand for suitable battery raw materials in future. (Tabelin et al. 2021, 1-2.)

Lithium's suitability for clean energy storage technologies and electric transport has roughly doubled its demand in battery industry during the last five years and the increase is projected to continue as global efforts to achieve carbon neutrality intensify (Tabelin et al. 2021, 17). According to a Finnish mining and chemical company Keliber Technology Oy, the lithium demand is expected to grow almost 18 % per year until 2032. The demand growth will be particularly strong for battery grade lithium hydroxide with an expected increase of 44,3% per year between 2017 and 2027. (Keliber Oy, 2019.)

Although lithium batteries allow for a significant reduction in emissions during usage phase, the environmental impact from their production remains of concern and has increased the level of scrutiny on the sustainability of lithium as raw material (Wells 2020, 1).

This Master thesis aims at using Life Cycle Analysis methodology to carry out a preoperational study on the environmental impacts of Keliber's lithium hydroxide production in Central Ostrobothnian area of Finland. The research questions this study seeks to answer are as follows:

- What are the hotspots in Keliber’s environmental footprint?
- What are the main challenges of LCA in the mining industry?

The main drivers of Keliber’s environmental impacts are assessed in a practical LCA study. Challenges of LCA methodology are examined in a theoretical section at the end of the study.

2 LIFE CYCLE ASSESSMENT

Life cycle assessment (or analysis) refers to the study of the environmental impact of a product, service or process throughout its life cycle: from the raw material acquisition to the final disposal of the product. However, the depth and the level of detail is always study-specific and can vary significantly as it depends on the intended use of the assessment (SFS-EN ISO 14044 2006).

Life cycle assessment was originally developed to make the differences between products visible from an environmental point of view. The beginning of LCA methodology goes back to 1960's when it was first developed to assess packaging options. However, it was not until 1990's when the methodological development really took off and in 2002 the World Summit on Sustainable Development identified it as a promising future approach to guide policies that aim at improving products and services and their environmental impact assessment. The comprehensiveness of LCA methodology allows the exposure of the whole production chain, which helps to avoid shifting adverse impacts from one stage or location to another. (Lesage et al. 2008, 3.)

LCA can be used for various purposes such as informing stakeholders and promoting marketing (SFS-EN ISO 14044 2006). However, one of the most useful reasons for performing an LCA is that it helps operators to identify the key resources and processes that account for the biggest environmental impacts. This can help to improve operational planning and target mitigation measures correctly.

LCA study consists of four main phases which are:

- goal and scope definition
- inventory analysis (LCI)
- impact assessment (LCIA)
- interpretation of results

After determining the goal and scope for the assessment, all the input and output data related to the studied system is collected in the inventory analysis phase to meet the goals set for the study. In the LCIA phase characterization models are applied to convert the data from LCI into concrete impacts like ozone depletion or eutrophication to better understand their environmental significance. The final phase consists of interpreting and discussing the results, giving recommendations and evaluating whether the goals set for the study were met. (SFS-EN ISO 14044 2006.)

One of the most well-known indicators applied in LCA –studies is a global warming potential (GWP). It is defined as the integrated radiative forcing of a gas on a given timeline, relative to that of CO2 (meaning each gas's ability to trap heat in the atmosphere compared to CO2). GWP is expressed as CO2-equivalents. The metric was first introduced in an IPCC-report during the 1990's and although it involves a high degree of complexity and ambiguity, GWP has become a widely used universal measure of environmental performance. (UNEP 2016, 59.)

In terms of benchmarking, the leading standards for Life Cycle Assessment, ISO 14040 and ISO 14044, state that direct comparison between different LCA results is only possible for studies for which the assumptions and context are equivalent. This means that, according to ISO 14044 chapter 4.2.3.7, for a comparative study the equivalence between systems needs to be evaluated in terms of scope, units and methodological considerations like system boundaries, allocation approaches and data quality etc.. The standards aim to ensure the transparency on these issues by demanding identification and reporting of any differences related to the studied systems. (SFS-EN ISO 14040 2006, 10; SFS-EN ISO 14044 2006.)

3 LITHIUM AND ITS AVAILABILITY IN BATTERY INDUSTRY

Lithium is a relatively abundant element with an estimated abundance of 17-60 mg/kg in the Earth's crust. Lithium occurs in various rock-forming minerals as well as in desert basin lake brines, where lithium salts have concentrated over time. (Tabelin et al. 2021, 2.) Lithium concentrations can also be found in less common resources like lithium-bearing clays and borosilicate minerals but the extraction of these is currently lacking economic feasibility (Wells 2020, 2).

Estimates on the availability of lithium vary significantly due to the differences in the deposits included, measures and metrics applied and the changes that take place in the current information and technology. United States Geological Survey has published in 2020 an estimate of approximately 80 Mt for global identified lithium resources (as lithium metal content). (Tabelin et al. 2021, 5.) While lithium is not a rare element, the global distribution of resources is uneven especially in terms of brine deposits. Mineral deposits are relatively widespread but most of the mineral (hard rock) extraction is currently concentrated in Australia due to the favourable geology and reasonable geographical distance to Chinese refineries (Wells 2020, 1).

The superiority of lithium as a battery material is based on its suitability for light weight rechargeable batteries with a high energy density. Lithium-ion batteries (LIBs) can thus store more energy per unit mass/size compared to other type of batteries. (Tabelin et al. 2021, 2.)

The extraction of lithium is mainly done using either of the most common deposit types; mineral (hard rock) or brine. These two methods differ widely in terms of fuel use and environmental profile because of the technical and geographical differences in their application (Wells 2020, 1). Mineral extraction refers to the extraction of lithium in its mineral form from hard-rock granitic pegmatites (hard rock types). Hard-rock mineral extraction is carried out using conventional mining techniques such as blasting and excavating. The majority of lithium from mineral deposits is exploited using open-pit mines even though also underground mines exists. (Wells 2020, 2.) An alternative and historically more common way of extraction from brines is not addressed in this study.

There is a range of lithium compounds on the markets. Until recently lithium carbonate has been the most demanded form of lithium raw material in EV (electrical vehicle) battery industry. This is projected to change in the coming years due to the advantages of lithium hydroxide in cathode manufacturing and the demand for lithium hydroxide is predicted to outstrip lithium carbonate by the year 2024. (Wells 2020, 17.)

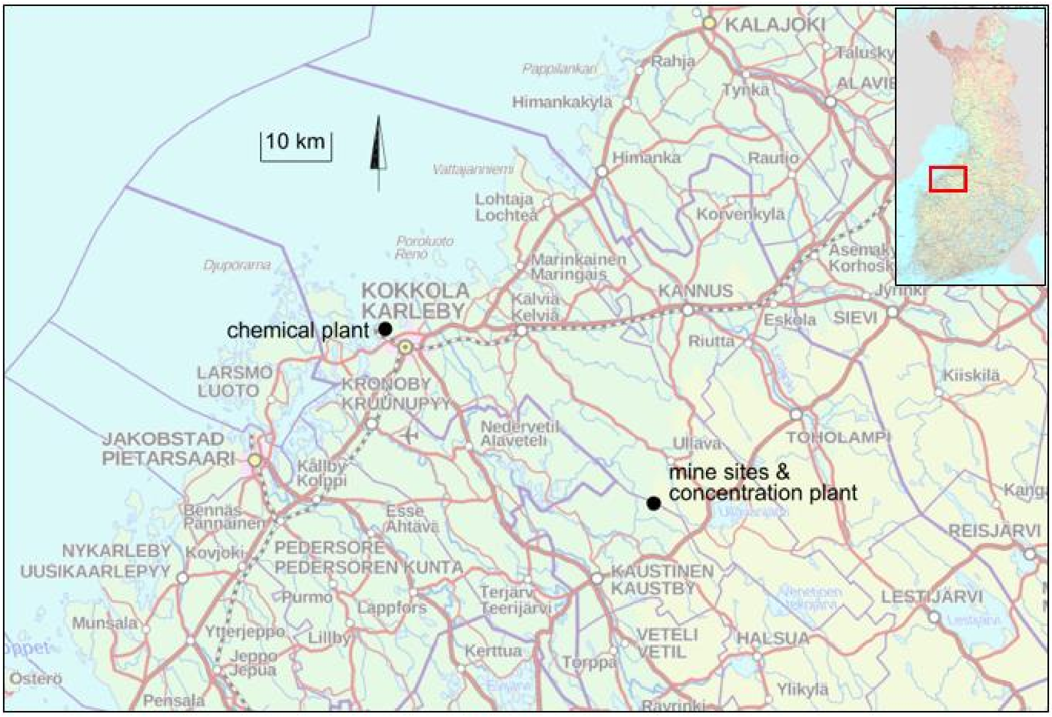
4 LCA STUDY ON KELIBER'S LITHIUM HYDROXIDE PRODUCTION

4.1 Background and objectives

Keliber Technology Oy *(later Keliber)* is a Finnish mining and chemical company aiming to become the first vertically-integrated producer of battery grade lithium hydroxide in Europe. This means producing high-purity lithium hydroxide from own ore reserves in a production chain that consists of mine(s), a concentration plant, and a lithium chemical plant all located in Central Ostrobothnia.

This study was commissioned by Keliber with Environmental Manager Kari Wiikinkoski as a contact person. The purpose of the study was to examine the environmental impacts of battery-grade lithium hydroxide monohydrate (LHM) production and to identify the key factors affecting the environmental performance. LHM is the final, commercial form of lithium hydroxide.

The assessment was carried out as a preoperational study. Lithium chemical plant operations are planned to be located in the Kokkola Industrial Park (KIP) where energy and other supplies are easily available. Concentration plant will be located in Kaustinen and the mine sites in Kokkola (Syväjärvi) and Kaustinen (Rapasaari). The operations are shown on the map in Picture 1.



PICTURE 1: Operations on the map (© National Land Survey Open data).

The methodology of the study is in accordance with the ISO 14040:2006 and 14044:2006 standards. The target group of the study comprises various stakeholders interested in the product's environmental impacts and the results of the study can be used for both business-to-business (B2B) and business-to-consumer (B2C) communication.

5 PROJECT SCOPE

According to the standards ISO 14040 and 14044 the scope of the study determines the depth in relation to the aim (goal) of the study. Scope of the study was chosen to cover cradle-to-gate because the applications of lithium, and thus the end-of-life scenarios, vary significantly. The assessment is based on the following annual volumes and production capacity shown in Table 1:

TABLE 1: Annual volumes and production capacity.

	Amount per year
Mined ore (Syväjärvi or Rapasaari open-pit mine)	650 000 t
Spodumene concentrate	165 000 t
Battery-grade lithium hydroxide monohydrate (LHM)	15 000 t
Operating time	7500 h

5.1 Product description

Battery-grade lithium hydroxide monohydrate (LHM) refers to a white crystalline powder type of a lithium chemical generated as an end product of the production process. LHM is especially suitable for the latest batteries that have a low cobalt content. Battery grade product is a superior purity grade product involved in making critical battery materials. (Keliber, 2020.)

In general the extraction of lithium is currently done using either mineral (hard rock) or brine deposits. The methods differ widely in terms of fuel use and environmental profile because of the technical and geographical differences in their application. (Wells 2020, 2.) Keliber's operations are based on the exploitation of hard rock deposit.

5.2 Manufacturing process description

The production at Keliber includes mineral processing stage and conversion stage. Mineral processing stage refers to the activities at the mine site and concentration plant whereas conversion stage takes place at the lithium chemical plant.

5.2.1 Mineral processing

Mineral processing takes place in Kaustinen and Kokkola and involves mining the ore (spodumene) and processing it at the concentration plant to form spodumene concentrate. In the model prepared for this study, mining is assumed to take place at the Syväjärvi open-pit mine. In reality, the mining will be done alternately at the Syväjärvi and Rapasaari mines. The geographical distance between the mine sites is < 2 km. According to Keliber, the activities at mine include stone blasting, earthmoving work and transportation of the ore to the concentration plant in Päiväneva. Rain and groundwater are pumped to keep the open-pit dry. Mining requires the use of explosives, electricity and fuels and generates waste rock and waste waters. In Rapasaari the operations will, at some point, include also underground mining but this is not considered in the assessment.

At the concentration phase the spodumene ore is crushed and sorted before grinding and processing it with flotation. After flotation the concentrate is fed to pressure filtration to form spodumene concentrate cakes that are ready to be stored and taken to the chemical plant for further processing. Activities at the concentration plant involve the use of chemicals, electricity and fuels. Waste is mainly sludge-like refuse or tailings from the process. (Keliber Oy, 2020.)

5.2.2 Lithium chemical plant

In the last phase of production lithium concentrate is processed into the final product (LHM) at the lithium chemical plant located in Kokkola. Operations at the plant require the use of chemicals, electricity and fuels. The process starts with receiving the concentrate from the concentration plant in Päiväneva. In order to extract lithium from spodumene concentrate by leaching, the crystal structure of spodumene is first converted from α-form to β-form. This is done in a high temperature conversion phase that takes place in a rotary kiln running on natural gas. The conversion is followed by a hydrometallurgical process in which lithium is recovered from the concentrate using pressure leaching with soda. In the pressure leaching, the concentrate reacts to form lithium carbonate and analcime. After this, the lithium carbonate is added with milk of lime in a conversion leaching stage. Lithium carbonate reacts with lime to form the final product lithium hydroxide. The slurry is further passed to filtration to separate analcime sand as a residue. Final steps include ion exchange purification to remove the residual calcium and crystallization and centrifugation to separate the final product. Finished product is dried and packed for transportation. (Keliber Oy, 2020.) A simplified process flowchart is show in Figure 1.

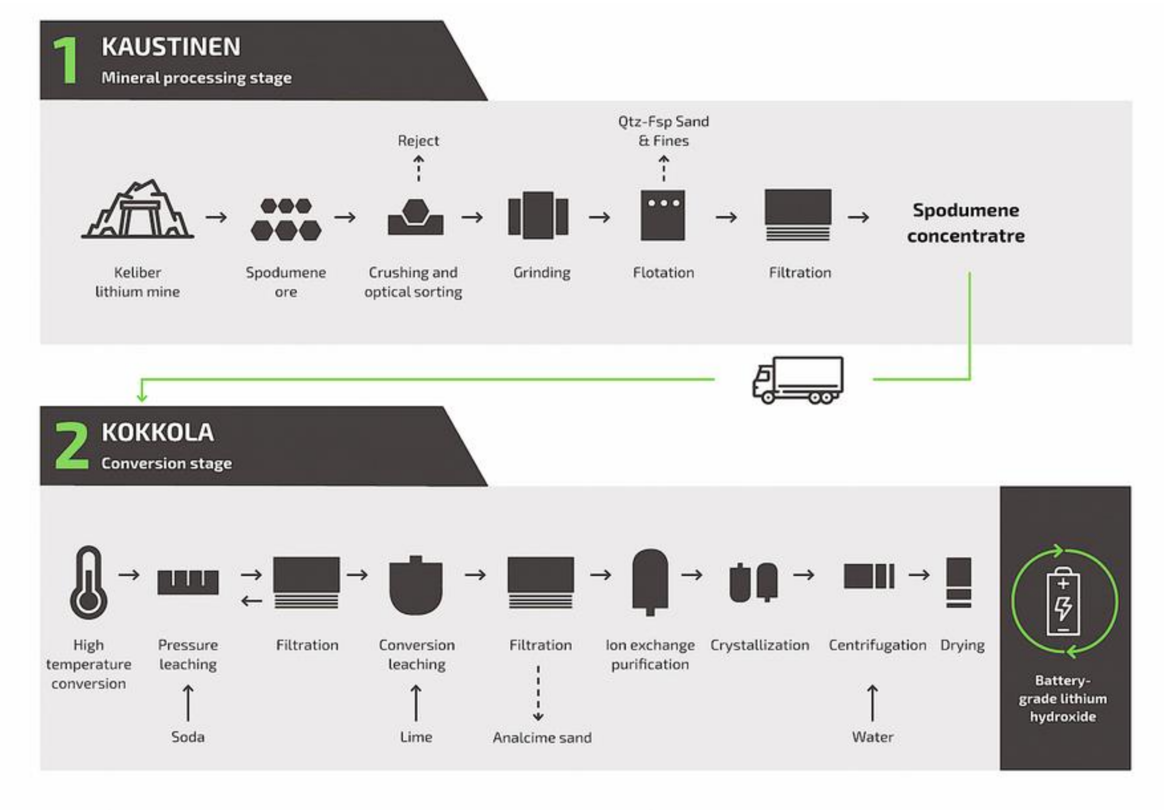


FIGURE 1: Simplified process flowchart (© Keliber 2021)

5.3 Declared unit

When carrying out a life cycle assessment, it is essential to determine the unit for which the results are expressed. According to the standard ISO 14044, a *functional* unit “defines the quantification of the identified functions (performance characteristics) of the product”. In case the precise function of the product is not known, or if the study does not cover a full life cycle, a *declared* unit can be used instead (Hendry 2014, 16). The declared unit in this study is one tonne (1 t) of battery-grade lithium hydroxide monohydrate (LHM). The functional unit has not been declared as the use phase has not been included in the study.

5.4 System boundaries

The standard ISO14044 defines system boundary as the determination of the unit processes that shall be included in the LCA. Determining system boundaries requires case-specific consideration and shall be consistent with the goal of the study (EN ISO 14044 2006).

This study is a cradle-to-gate assessment. It covers the production phases from raw material acquisition and extraction to a finished product leaving the factory gate. The study includes energy and material consumption and waste handling. Stages included in the study are marked in Figure 2.

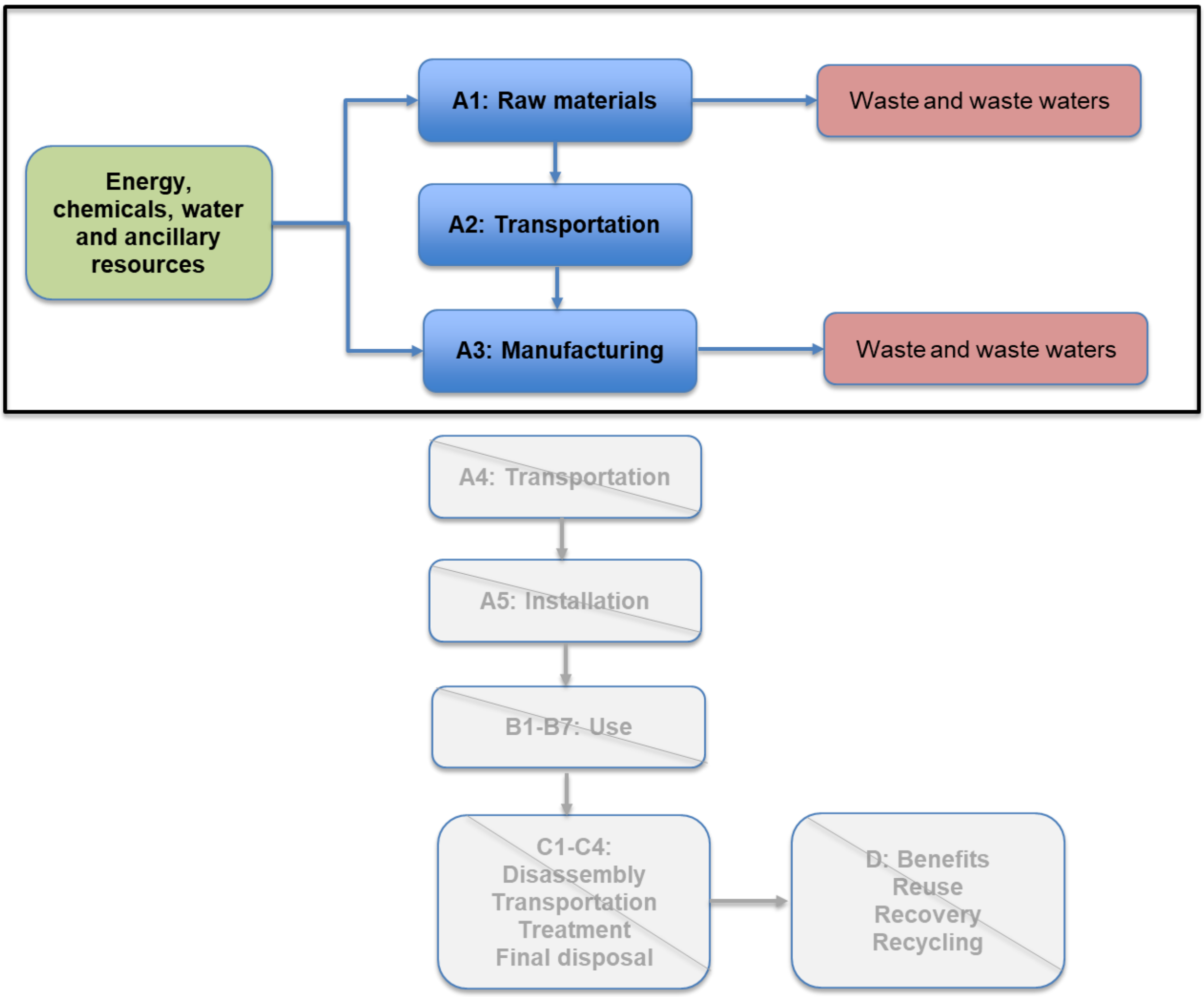


FIGURE 2: System boundary.

Technology coverage

Technological coverage of the study covers mineral extraction from an open-pit mining. This refers to the extraction of lithium in its mineral form from hard-rock granitic pegmatites (hard rock types) using conventional mining techniques such as blasting and excavation.

Geographic coverage

Geographic coverage of the study covers the mineral processing stage activities in Kokkola and Kaustinen (mining in Syväjärvi and concentration plant in Päivä-neva) and conversion stage activities (chemical plant) in Kokkola.

Time coverage

The study is preoperational so data collection is based on one year of fictional operation (with an estimated annual production capacity of 15 000 t of LHM) and plans and data available by September 2021.

5.5 Cut-off criteria

According to guidelines determined in the standard ISO 14044 (section 4.2.3.3.3.), the cut-off criteria applied in LCA practice can be based on mass, energy or environmental significance (SFS-EN ISO 14044 2006).

The study includes all major raw material and energy consumption. All the relevant inputs and outputs of the unit processes for which data was available are included in the calculation. There is no neglected unit process more than 1% of total mass and energy flows. Included processes and resources are described in the following chapters and listed in the Appendix 1.

The production and maintenance of capital equipment, construction activities and infrastructure as well as activities related to R&D, sales, administration or personnel (commuting etc.) are excluded. Further exclusion by process stage and the related cut-off criteria is provided in Table 2.

TABLE 2: Processes excluded from the study and the related cut-off criteria.

Process excluded from the study	Cut-off criteria
Mine	
A2: Tap water (tank water used and treated at site)	Insignificant in material and energy flows
A2: Chemicals related to work machines (oils, lubricants etc.)	Insignificant in material and energy flows
A3: Mixed municipal and hazardous waste	Insignificant in material and energy flows / Challenging to determine the flow
A3: Heating of social facilities	Insignificant in material and energy flows
Concentration plant	
A2: Sulfuric acid, emulsifier and flocculant	Insignificant in material and energy flows
A2: Chemicals related to work machines (oils, lubricants etc.), absorbents and anti-slip / anti-dust agents ($CaCl_2$)	Insignificant in material and energy flows / Challenging to determine the flow
A3: Machinery fuel (light fuel oil / electricity)	Insignificant in material and energy flows / Challenging to determine the flow
A3: Water treatment chemicals	Insignificant in material and energy flows
A3: Process water (purified raw water that circulates in the process)	Insignificant in material and energy flows / Challenging to determine the flow
A3: Household- and sanitary waters	Insignificant in material and energy flows / Challenging to determine the flow
A3: Drainable waters	Insignificant in material and energy flows / Challenging to determine the flow
A3: Sludge from water management (circulating water basin and nitrogen removal), reject from raw water treatment	Insignificant in material and energy flows / Challenging to determine the flow
A3: Mixed municipal and hazardous waste	Insignificant in material and energy flows / Challenging to determine the flow

Chemical plant	
A2: Coagulant, corrosion inhibitor, ion exchange resin	Insignificant in material and energy flows
A2: CO2 (a by-product from KIP-area, delivered via pipe in a gaseous form)	Insignificant in material and energy flows, a by-product from another operator
A2: Packaging materials (nitrogen gas, chemical bags etc.)	Insignificant in material and energy flows
A3: Direct process vapour emissions into the air (CO_2)	Insignificant in mass / environmental significance
A3: The transport of analcime sand from the plant to the storage at concentration plant (the need for transport is currently unclear)	Challenging to determine the flow
A3: Light fuel oil or diesel used in machinery (e.g. reserve generator)	Insignificant in material and energy flows
A3: Consumption of district heating (social facilities)	Insignificant in energy flows
A3: Stormwater and cooling water discharge	Insignificant in energy flows
A3: Mixed municipal and hazardous waste	Insignificant in material and energy flows / Challenging to determine the flow

6 LIFE CYCLE INVENTORY (LCI)

Life cycle inventory involves data collection and calculation procedures that are applied to identify and quantify the resources used to produce the product. LCI is an iterative process that may highlight the need to readjust procedures or even change the objectives or scope of the study. (SFS-EN ISO 14040 2006, 33.)

6.1 Data sources and data collection methods

The LCI model was created in One Click LCA which is a cloud-based LCA software. The source data in the software is Ecoinvent 3.6 or verified Environmental Product Declarations (EPDs). Ecoinvent is widely recognized as the leading database for studies and assessments based on ISO 14040 and 14044 (SimaPro 2021). The database contains international life cycle inventory data on various processes and resources. Environmental Product Declarations in turn are voluntary product-specific studies that apply LCA methodology in a standardised way to present the environmental impact of a product's life cycle (RTS 2021).

Inventory data of the product stage (A1-A3) was collected via personal contact with a representative of the manufacturer. Data was collected about the (intended) annual quantities of raw and supplementary materials as well as about material suppliers, transportation distances and types. Also, an estimate of annual energy and water consumption and waste generation was collected.

6.2 Data gaps and key assumptions

Whenever necessary, the missing data gaps were covered by making conservative and relevant assumptions. Estimations and assumptions made are reported in the dedicated module’s description in the following chapters.

6.3 Validation of data

The quality requirements for the life cycle assessment were set according to the EN ISO 14044 standard (4.2.3.6) as far as possible.

The data was examined carefully and clarification requested from the manufacturer when necessary. All gathered data was used without excluding categories following the system boundaries set in the earlier chapters.

The resource data was primarily searched from available EPDs but, as they were poorly available, Ecoinvent database was the main source of data in this study. To ensure the suitability for modelling the countries studied in this assessment the data collected from Ecoinvent was primarily chosen to represent Europe. In case European data was not available, the data representing world was selected. The generic data used in modelling the input and output flows can be considered to be of good quality (in other words geographically, technically and temporally representative).

The Ecoinvent 3.6 (2019) version of resources was chosen for calculations. In terms of considering temporal relevance it is worth noting, that Ecoinvent does not provide year specific data, but the data represents a period of time.

6.4 Allocation

According to the standard EN ISO 14044 (section 4.3.4.2) an LCA study “shall identify the processes shared with other product systems” and deal with them according to the procedure described in the standard. The main principle is to avoid allocation whenever possible. In case allocation cannot be avoided it should be carried out in a way that reflects the physical relationships between inputs and outputs. This refers to identifying the changes that occur if there are quantitative changes in the products or functions in the system. If physical relationship cannot be used, the allocation should rely on, for example, on the economic value of the products. In terms of allocation the separation of co-products and waste is important since the allocation should be applied to co-products only. (EN ISO 14044 2006.)

All the data collected from the manufacturer represents the intended production of lithium hydroxide monohydrate. The data does not include resources related to co-products or R&D activities, so no allocation was needed in the calculations.

6.5 Description of unit processes

6.5.1 Raw materials (A1)

At the mineral processing stage the raw material for mining is the ore in the earth's crust. At the concentration plant the raw material is the mined ore and at the conversion stage (chemical plant) the raw material is the spodumene concentrate.

Since the assessed final product is LHM (lithium hydroxide monohydrate, LiOH·H2O), the only raw material it contains can be considered to be the lithium from the mined ore and oxygen and hydrogen from the process. The ore or the concentrate as raw materials are not taken into account as inputs, as their impacts are inherited from the resources considered in the previous process stage. Thus, all the materials used in the manufacturing are declared as ancillary materials (A3).

6.5.2 Transportation

The considered transportation impacts (A2) include exhaust emissions resulting from the transportation of raw materials from suppliers to manufacturing facilities as well as the environmental impacts of the production of the diesel used in transports. The manufacturing, maintenance and disposal of the vehicles as well as tyre and road wear during transportation have also been included. The transportation distances and methods were mainly provided by the manufacturer or estimated on the basis of the best available knowledge. For confidentiality reasons, exact delivery points are not reported but are referred to at a more general level, such as by continent. Occupancy rate of 100% is assumed for professional logistics companies unless otherwise stated.

Mining

Bulk emulsion explosive is transported from Central Finland. Internal transports at the mine site and the transportation of the ore to the concentration plant are included in the consumption of diesel in the module A3.

Concentration plant

Flotation chemical (fatty acid) is assumed to be transported from a potential wholesaler in South-East Finland as the actual distance cannot be estimated at the current preoperational stage. Sodium hydroxide is assumed to be transported from Western Europe. Grinding balls and rods are presumably transported from Asia according to which the distance is estimated. Spodumene concentrate is transported from the concentration plant to the chemical plant in Kokkola. Occupancy rate 50% is assumed as return trips are done with an empty load.

Chemical plant

Soda is transported from the eastern part of Central Europe and quicklime from Western Europe. Sulphuric acid is acquired from KIP-area along a pipeline. Trisodium phosphate is assumed to be transported from Asia and sodium hydroxide from Western Europe. Hydrochlorid acid and flocculant (polyacrylamide) are assumed to be domestic raw materials. List of processes included in A2 is shown in Table 3 (Appendix 1).

6.5.3 Manufacturing

The environmental impacts considered for the production stage (A3) cover the manufacturing of materials used in the production but not included in the final product such as packaging materials and other ancillary materials. Also, fuels used by machines, energy consumption (heat & electricity) as well as handling of waste generated in the production processes at the manufacturing facilities are included in this stage. The assumed amount of ancillary materials and consumption of energy in each process stage is provided by the manufacturer or estimated on the basis of the best available knowledge. The assumed material and energy losses are included in the data and relate to the loss of energy or ancillary materials during manufacturing and to the share of lithium residues in waste rock or process waters.

Mining

In the mining area, energy is used to fuel machines and transport equipment and provide electricity. Machinery includes e.g. excavators, wheel loaders, and crushers. Transport equipment mainly operate between the mine and warehouse or crushing area. The use of internal combustion machinery is a major consumer of energy in the mining phase. The estimated fuel consumption at the mine site is about 3150 tonnes per year. The machinery is mainly fueled by light fuel oil / diesel. (Keliber Oy, 2020.)

According to the manufacturer, the electricity use at the mine site (2,0 MW/h) includes electricity required for water pumping, lighting and social facilities. Electricity can also be used as an alternative energy source for crushing the waste rock or fueling the vehicles. Since Syväjärvi is an open-pit mine, the energy needs of an underground mine (ventilation, drilling rigs and lighting etc.) are not considered. Electricity for the mine site is assumed to be conducted from the concentration plant.

Mining activities involve the use of explosives. The amount used in the assessment is based on the volumes estimated in the environmental impact assessment report. Waste generated in mining mainly consists of waste rock. Waste rock is dumped at site and does not involve external transports. Activities also generate small amounts of municipal and hazardous waste (e.g. lubricants) but the amounts are insignificant and have not been estimated.

Concentration plant

At the concentration plant energy is used for electricity, heating and fuels. The estimated electricity consumption (4,0 MW/h) includes lighting and process steps like sorting, crushing and concentration process, as well as pumping of waters and process waste. (Keliber Oy, 2020.)

The heat used at the concentration plant is mainly produced by a thermal power plant (< 10 MW) to be built in the area. The heating plant uses wood pellets as fuel. The use of liquefied natural gas as an alternative fuel is also considered.

Machinery at the plant are either electric or use light fuel oil but data on machine fuel consumption was not available.

Activities at the concentration plant require the use of various process chemicals. Quantitatively significant chemicals are sodium hydroxide (lye) used in pH adjusting and fatty acid (rapeseed) coagulant used in flotation. Noticeably factors in the concentration process include also the grinding media, in other words the use of grinding balls and rods.

Waste generated at the concentration plant is, for the most part, sorter reject (waste rock), magnetic and prefloat fractions, tailings and sludge. The final disposal in tailings ponds and waste rock piles is done at site. (Keliber Oy, 2020.) The amount of other process waste and municipal and hazardous waste is negligible in quantitative terms and excluded from the assessment.

Lithium chemical plant

At the chemical plant most of the energy is used for rotary kiln in high temperature conversion and in the subsequent hydrometallurgical process. The furnace is fueled with natural gas that is acquired from the local network or imported from outside. Hydrometallurgical process uses steam in pressure leaching, crystallization and drying. The steam is produced in the industrial park area and transferred via pipeline. Also the rest of the energy demand (electricity and district heating) is acquired from local suppliers. The estimated electricity consumption at the chemical plant is 8,1 MW/h, consisting of the electricity used in the process (including seawater pumping) and in the production facilities (lighting etc.) as well as the pumping of analcime sand to the port. According to the estimation the amount of energy taken from the district heating network in cold weather and the amount supplied to it in warm weather are close to equal, so the use of district heating has been excluded from the calculations. (Keliber Oy, 2020.) Light fuel oil or diesel is used to fuel machinery (such as reserve generator) but the amounts have not been estimated and are assessed insignificant.

The most significant chemicals used in the chemical plant are calcium oxide (quicklime) and sodium carbonate (soda) used as reagents. Other chemicals used in higher amounts include pH adjusting agents (sodium hydroxide, sulphuric acid and hydrochloric acid), precipitant (trisodium phosphate) and flocculant (anionic polyacrylamide).

The use of resources at the chemical plant also includes the use of water. Water is used, for example, for diluting chemicals, washing the product and gases and cooling heat exchangers. Requirements for the water quality differ between process stages. Demineralized water is required for washing the final product while seawater is used for cooling. Process water is tap water from the local water supply network. Cooling water is taken from the seawater supply network in the KIP-area and returned to the sea after use. Demineralized water is from the KIP industrial network. Most of the process waters are circulated in the process. Drainable water is generated from process effluents, cooling water discharge, storm waters and sanitary waters in the area. The waters are drained into the local sewer system. (Keliber Oy, 2020.) Storm waters and cooling water discharge are excluded from the assessment as their treatment does not require significant resources.

Waste generated at the chemical plant is mostly analcime sand. The composition of the sand is largely equivalent to the composition of the concentrate, excluding most of the lithium. The sand can be transported via pipeline and utilized as a fill material in the port of Kokkola as the port expands its area, so no waste treatment is required. Process water treatment produces sludge which is dried and taken to a waste treatment. (Keliber Oy, 2020.) Municipal and hazardous waste fractions generated at the chemical plant are excluded from the assessment as their amount is assessed as insignificant. A simplified description of mass balance is shown in Figure 3 and the total use of energy and distribution by source in Figure 4.

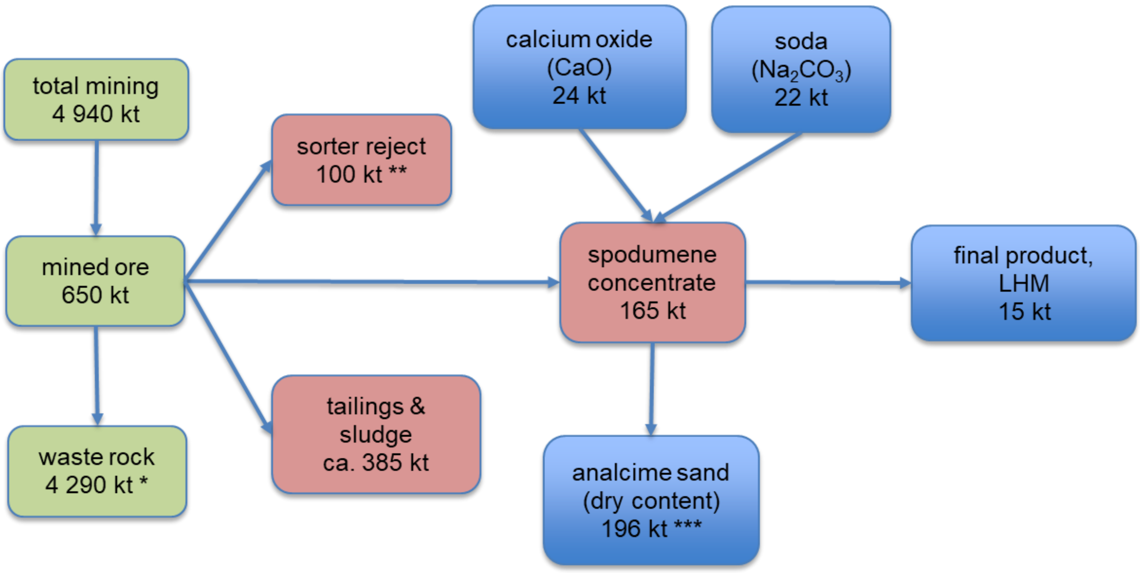


FIGURE 3: Indicative mass balance. Notes: * waste rock ratio 6.6, ** ca. 16 % of mined ore, *** water content varies.

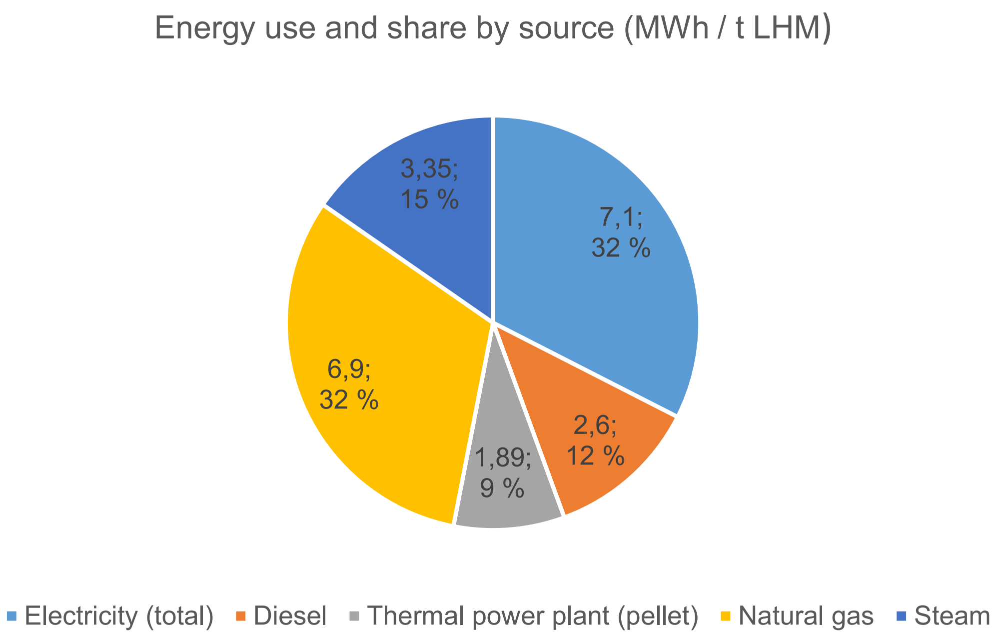


FIGURE 4: Total energy use (MWh / t LHM) and share (%) by source.

List of processes and resources in A3 are shown in Tables 4 and 5 (Appendix 1).

7 LIFE CYCLE IMPACT ASSESSMENT (LCIA)

7.1 Impact Assessment procedures, calculations and results of the study

The calculations were conducted using One Click LCA -tool and Ecoinvent 3.6 database or verified EPDs. The data collected from the manufacturer was entered into the software to cover input flows of materials used in the product or in the production process and their transportation distances and transportation methods. Also input flows of electricity, heat, and fuels used in the production and output flows of waste from the production were included. Delivery and installation as well as the use phase and end of life were excluded from the study.

The numeric inputs were multiplied in the software with the impact factors from the database. The impacts were calculated per studied stages. Numeric results per declared unit of the studied product are presented in Appendix 2.

7.2 Relationship of the LCIA results to the LCI

LCI data (Life Cycle Inventory data) is the list of all inputs and outputs from the studied process. LCIA data (Life Cycle Impact Assessment data) instead is the LCI data that is converted into environmental impacts by using a characterization model. (SFS-EN ISO 14040 2006, 35.) Characterization models relate to the way of calculating substance-specific characterization factors to quantify the potential impact of each elementary flow in the common unit of the impact category (indicator). The usefulness of the results thus depends on the accuracy, validity and characteristics of the characterization model and factors. (EN ISO 14044 2006.)

One Click LCA software tool is based on Ecoinvent database and verified EPD’s. It is originally developed for the building and construction industry, therefore the LCA calculation rules are compliant with the standard EN 15804. However, the tool is suitable for use also in other sectors because the database and LCA rules are based on the same characterization model regardless of the sector. The calculation in this study is based on the Ecoinvent database, the only exception being the explosive. Characterization factors used in the study are in accordance with CML-IA version 4.1. The resource for the explosive is an EPD (EN15804+A1) which is based on the CML -IA 2012 methodology as a characterization model. This may cause a small distortion in A2 results, but the effect is negligible as the share of explosive in the overall results is small (<1%).

8 REVIEW OF THE RESULTS

8.1 Interpretation of results

In terms of carbon footprint, the share of energy use stands out in the results as it accounts for 61% of the total global warming potential (GWP). The use of natural gas in the high conversion furnace at the chemical plant produces 20% of the total CO_2 -emissions. Electricity consumption covers 18% of total emissions and is at the forefront at all process stages.

The biggest single contributors to the carbon footprint are the use of natural gas as energy and quicklime as a process reagent at the chemical plant. These resources together account for 40% of the total GWP. The emission-intensity of quicklime derives from its manufacturing process in which calcium carbonate is heated at high temperature to form calcium oxide. Heating also causes the release of carbon dioxide. (Nordkalk, 2021.)

Steam used at chemical plant accounts for 13% and the diesel used at the mine site 9% of the total GWP. Soda used at chemical plant covers 7% of the CO_2 –emissions whereas the rest of the resources account for the remaining 13% of the total impacts. Based on this study, the total carbon footprint for 1 t of LHM from Keliber’s process is 9,4 t CO_2 eq. The distribution of the carbon footprint by resource is shown in Figure 5.

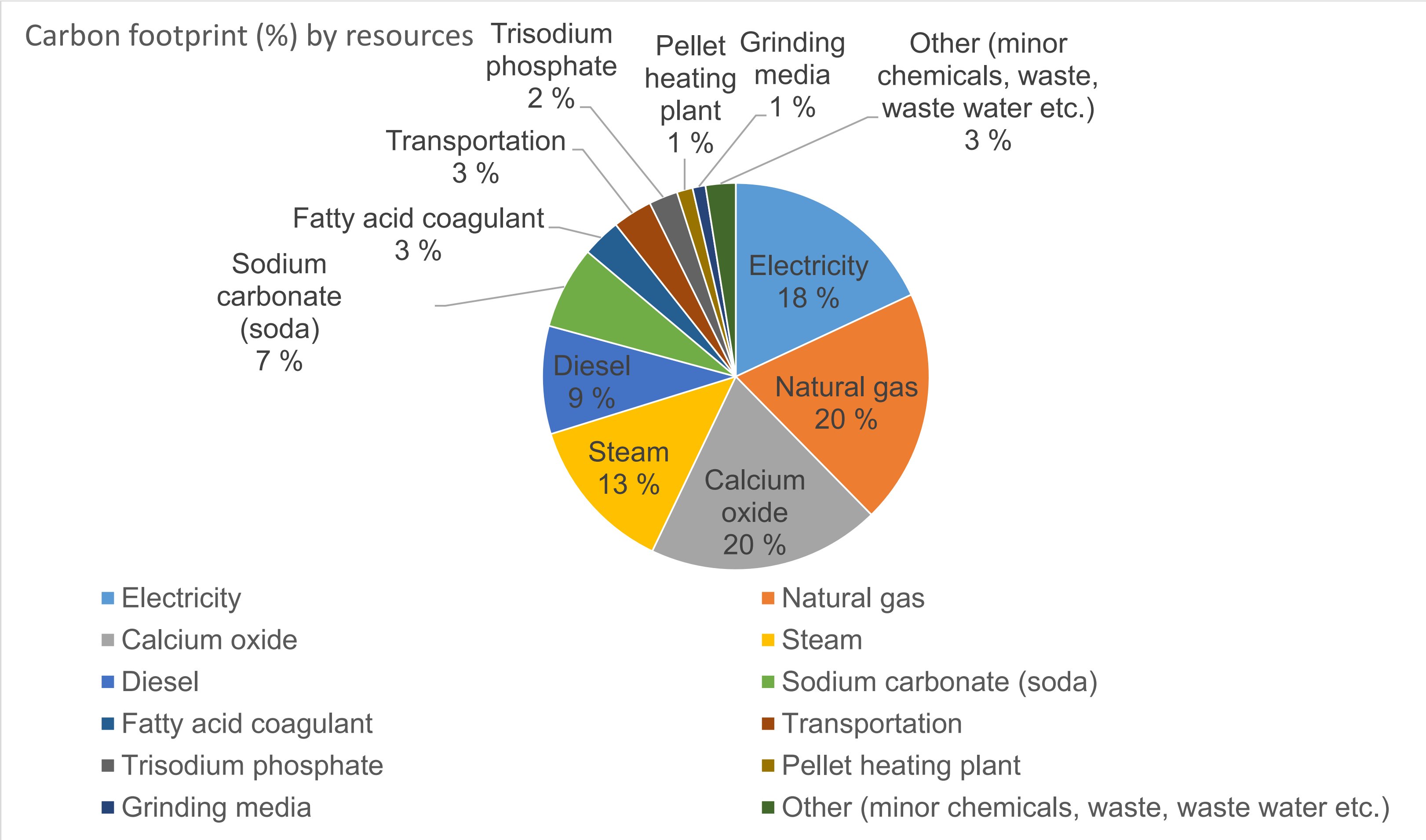


FIGURE 5: Percentage of total carbon footprint by resource. The graph includes both mineral processing stage and conversion stage (i.e. the whole production chain).

The distribution of emissions between production stages is shown in Figure 6.

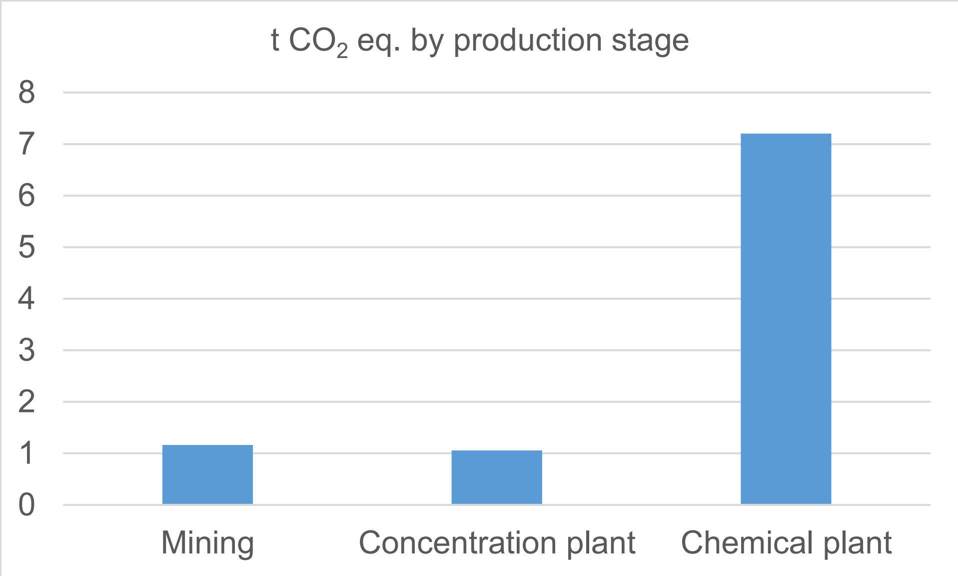


FIGURE 6: CO2-emissions by product stage.

The share of transportation is relatively small at all stages. Transports account for ca. 4% of the total CO2-emissions at chemical plant and < 2 % at the concentration plant. The transports during the mining phase are included in the total fuel use and therefore cannot be separated. Due to large volumes, the transportation of spodumene concentrate to the chemical plant accounts for a significant part of total emissions from transportation. However, the estimation of an actual percentage is challenging as the emissions from transports at mine are not separately available and some of the chemical transports are calculated only from the assumed wholesaler.

The production process has significant impacts on the generation of waste, which is largely due to the high volume of waste rock from mineral extraction (mining). Waste management (treatment of waste rock, tailings and waste water) is not reflected in the carbon footprint, but its affects are realized, for example, through land use impacts. Other relevant impacts include the effects on the depletion of abiotic (fossil) resources through the use of non - renewable energy resources.

At the mine site the use of diesel is the biggest contributor to CO2-emissions, which was expected as the activities consists mainly of the use of heavy machinery and the volume of transferred masses is large. Emissions at the mine site are shown in Figure 7.

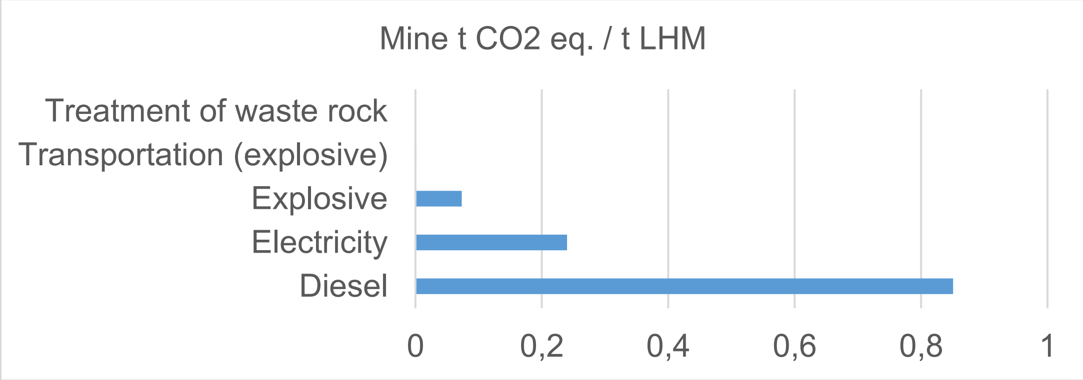


FIGURE 7: Global warming potential (GWP) of the mining by resource. Diesel use includes the transports at site and to the concentration plant.

At the concentration plant most of the impacts derive from the electricity use. The share of thermal power plant is relatively small due to the use of pellet as fuel. Emissions at concentration plant are shown in Figure 8.

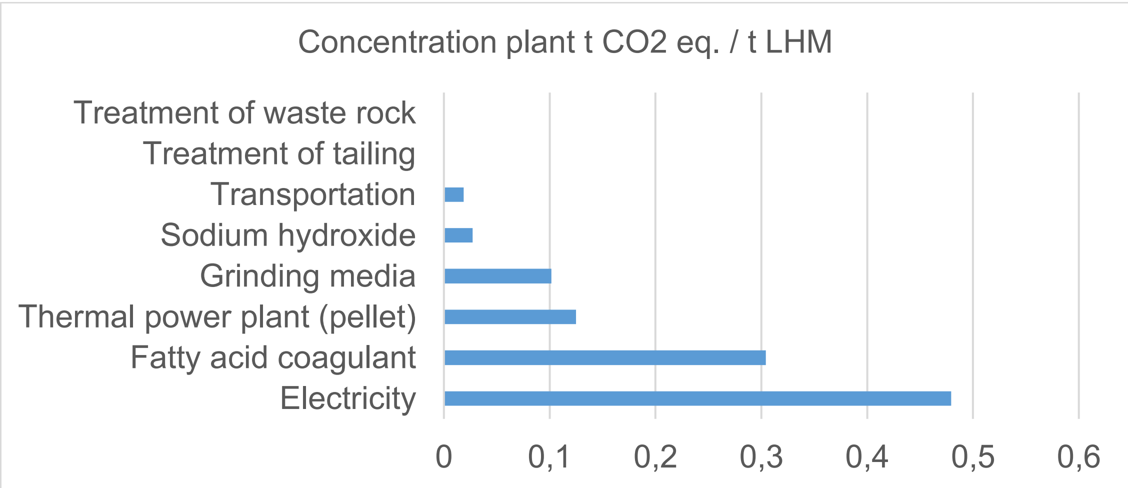


FIGURE 8: Global warming potential (GWP) of the concentration plant by resource.

At the chemical plant majority of the impacts are caused by energy consumption and the use of quicklime and soda. Emissions at the lithium chemical plant are shown in Figure 9.

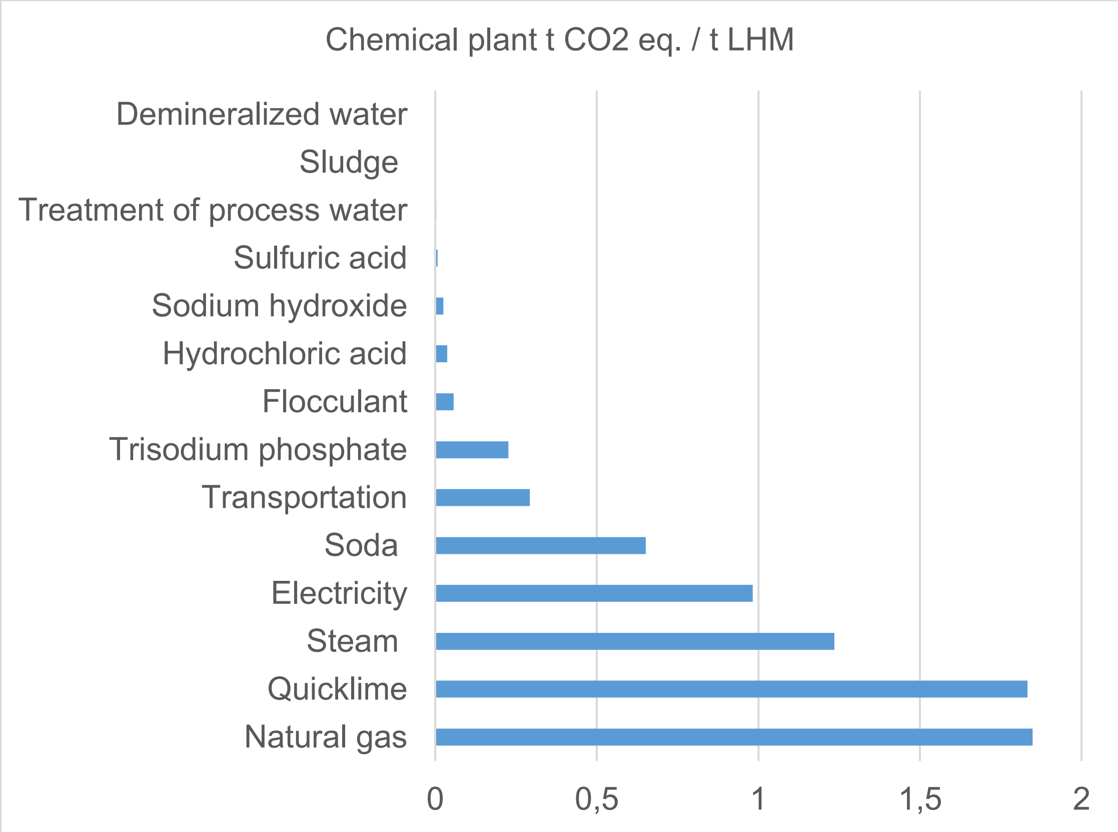


FIGURE 9: Global warming potential (GWP) of the chemical plant by resource.

8.2 Sensitivity analysis

Due to the preoperational nature of the study, there are considerable uncertainties related to the use of the results as a model of an actual, operational situation. The uncertainty mainly arises from the lack of precise data related to pending issues such as selection of suppliers (transportation distances etc.) and verification of environmental permit conditions. However, uncertainties are mainly related to resources that play minor role in the overall impact so the reliability of the assessment can be considered relatively good given the pre-operational situation. The figures used in the calculation have mostly been taken from environmental permit applications and environmental impact assessment reports, which means that they are estimated on the maximum and might, at some point, be excessively conservative.

Uncertainty in the results is also due to the difficulty of finding exactly the right kind of resources in the database. Except for the explosive used at the mine site, there were no product-specific EPDs available in the database. The uncertainty related to the selected resources is particularly pronounced in extractive and process waste (waste rock and overburdens) because of the high amounts generated. In terms of chemicals, the soda used at the chemical plant was modelled using a resource for *Market for soda ash, light, crystalline, heptahydrate*. However, according to the information subsequently received from the manufacturer, an anhydrous form of soda ash will be used in the production process. This is estimated to increase the total carbon footprint by approximately 6%.

The amount of waste rock generated at the mine site has been estimated on the basis of the coefficient (6.6) used for Syväjärvi mine in the environmental impact assessment report. However, in reality the coefficient varies. The extraction rate and strip ratio vary considerably from year to year. Factors affecting the ratio include, for example, the depth of the mine, ore concentration and deposit type. The ore grade at Rapasaari is expected to be 20% lower which significantly affects the strip ratio and increases emission-intensity. (Keliber Oy, 2020.)

There is also some level of uncertainty related to the recycling of process water and the need for additional water so determining the precise flow for water use and/or sewerage is challenging.

The assessment is prepared on the basis of activities in Syväjärvi mine site due to which the effects from underground mining and nitrogen removal for mining water needed at Rapasaari are not considered.

8.3 Conclusion and recommendations

Acknowledging that energy use accounts for the majority of the environmental impacts, the biggest improvements could be achieved by targeting the emission reduction measures accordingly (that is, boosting energy efficiency and the use of clean energy). Pellet appears to be a low-emission choice for the heating plant as, based on the emission factors; the CO2 -emissions from the heat production would be about fourfold in case the thermal power plant used liquefied natural gas instead of pellets.

The use of diesel at the mine site accounts for 9% of the total carbon footprint. Replacing the vehicles and machinery with electric ones would, according to the estimate, double the use of electricity (1 MW → 2 MW) but cut down the emissions from diesel use. Activities at Rapasaari will most likely increase the impact from mining phase as the strip ratio is expected to be higher and the underground mining will require the use of ventilators (approximately 3 * 500 kW). These would significantly increase the use of fuels and electricity at mining phase. To further evaluate the results obtained for the mining phase, an alternative calculation was done using the already available Ecoinvent resource for spodumene. Compared to the data from the manufacturer, the data from Ecoinvent resulted in 1,6 times higher value for GWP. In case the spodumene was acquired using an external supplier from Europe (Portugal was used for the evaluation), the transports required would increase the GWP for spodumene up to 3,7 times higher and the GWP for the entire production chain up to 12,5 t CO2 eq. / t LHM. Thus, the benefits resulting from the integrated production chain at Keliber can be considered significant. However, as already mentioned, the standards ISO 14040 and 14044 strictly define the issues of comparability. In cases where the systems are not sufficiently equivalent or the equivalence has not been reliably assessed, the comparison can only be made as an indicative estimate of the order of magnitude.

In terms of the CO2-emissions, the use of soda ash in leaching has about four times the emissions compared to the more commonly used sulfuric acid. However, the soda leaching process is expected to be more energy efficient and especially differ significantly in waste generation. Sulfuric acid leaching produces gypsum waste as a by-product whereas soda leaching generates inert analcime sand that has a high potential for recovery in the local port area.

In terms of literature, direct figures for carbon footprint with sufficient background data seem to be limited for lithium hydroxide and/or lithium carbonate equivalent (LCE). In addition, it should be remembered that direct comparison between different LCA results is only possible for studies for which the assumptions and context are equivalent. Ecoinvent database resource for the production of lithium hydroxide has an environmental profile 5,78 kg CO2 eq. / kg. The resource is based on the production of lithium hydroxide by hydration of lithium carbonate by calcium hydroxide and appears to include only activities from the reception of lithium carbonate and calcium hydroxide at the factory gate, to the production of lithium hydroxide.

Roskill white paper on lithium's carbon footprint offers mineral industry a weighted average of 9,3 t CO2 / t LCE (i.e. per tonne of refined lithium product stoichiometrically normalized to a lithium carbonate equivalent). According to the report, the average is skewed lower by some efficient large-scale producers but on the other hand the figure also represents the coal-based Chinese manufacturers and long transport distances from Australia. (Wells 2020, 13.)

The article on energy, greenhouse gas, and water life cycle analysis of lithium carbonate and lithium hydroxide monohydrate by Kelly et al., 2021, provides a relatively comprehend insight for the LCI process and declares a carbon footprint value of 15,7 t CO2 eq. / tonne LiOH•H2O. The figure is based on the production of concentrated spodumene from ore in Western Australia and its conversion into the final product in China. Industry data utilized for China represents facilities that provide process heat from coal. (Kelly et al. 2021, 8.)

Due to more or less fundamental differences in LCA studies the comparison of energy intensity can offer a less risky (albeit more incomplete) way of assessing the performance. According to the Roskill white paper the energy intensities for mineral producers (from highest to lowest) vary approximately between 62 000-32 000 kWh / tonne of LCE (Wells 2020, 9). The total energy intensity calculated for Keliber in this study is 21 840 kWh / tonne of LHM or 24 820 kWh / tonne of LCE assuming a conversion factor 0,88 from LHM to LCE (Savannah Resources, 2021).

Focusing solely on the carbon footprint in the interpretation of the results easily overlooks other impact categories. For example, the effects on land use can be considered significant when disposing of the extraction waste on site.

To obtain a more detailed insight, the impacts from transportation should be specified (in other words the transports at the mine site assessed and chemical transports confirmed when more detailed data comes available). Certain inputs, of which some are hazardous wastes or contain substances of very high concern (SVHC), have been excluded on the basis of negligible amount. However, for a more detailed assessment of the environmental impacts they should be considered too. Also the possible benefits from the recovery of analcime sand in soil construction and the potential supply of excess heat to the local district heating network are worth assessing more closely when actual figures from production are available.

9 CHALLENGES OF LCA IN THE MINING INDUSTRY

Despite the growing popularity of life cycle assessment, its use in the mining industry has been limited. This has had far reaching consequences, as mining provides most of the raw materials for various industrial processes and their final products. Thus, the lack of data from mining industry also directly reflects the reliability of other life cycle assessments. The data deficiency has been due to the difficulty of quantifying the various inputs and outputs and, at least in part, also to the industry's caution with regard to data disclosure. However, the inappropriateness of the LCA to the mining industry can be considered an equal reason as most examples, data, and software tools do not take into account the specificities of the mining sector. (Awuah-Offei et al. 2011, 85.) The following sections aim to address the challenges of LCA methodology in the mining industry from a variety of perspectives.

9.1 Lack of source literature

Although a series of LCA studies in lithium batteries exists, there's a clear scarcity of those regarding the impacts of the actual acquirement of the raw material, and especially the mineral extraction of it (Kaunda 2020, 244). The main focus in the mining LCA studies seems to be on the evaluation of the mine operations due to which the extraction of the ore and especially the handling of the extractive waste is neglected. (Lesage, P. et al. 2008, 5.) Compared to the data available for the extraction from brine reserves, the production of lithium from rock is much more complex and needs to be carefully designed and constructed to meet the site-specific conditions and requirements of a particular deposit. (Kaunda 2020, 240.)

Another problem concerning LIB-related LCA studies is that they are very heterogeneous and therefore difficult to compare. The differences are reflected especially in relation to the scope, the system boundaries, the units and the assumptions applied. In addition, the existing studies tend to be inbred, i.e. they often rely on the inventory data of previous publications. It has been found that the actual pedigree of the original LCI data in mining industry is worryingly narrow and thus its reliability is comparably weak. (Peters et al. 2017, 493.)

Due to the large variation and differences in LCA studies it is also difficult to evaluate the environmental performance of different LIB chemistries. For example, the inclusion (or exclusion) of recycling aspects, and the extent and approach of it, has a considerable influence on the results as recycling involves both emission-reducing and emission-increasing characteristics. (Peters et al. 2017, 493.) LCI modelling for material recycling is currently subject to intense debate especially in metal industries. The recycling methodologies applied in LCAs are roughly divided into two categories; recycled content approach and end-of-life recycling. The recycled content approach considers the share of recycled content in the raw materials that are used for manufacturing a product. Instead of impacts from extraction and refining of primary metal, the burdens attributed to the recycled content are those of collection, beneficiation and refining of the scrap. The end-of-life recycling approach in turn considers the end-of-life of the product, where the share of material is allocated to the next life cycle according to the recycling efficiency rate. In order to avoid double-counting the benefits, care must be taken to ensure that scrap inputs into production are balanced out. The remaining net amount of scrap and the burden of recycling it into secondary material are then used to quantify credits that describe the avoided burden from primary materials. (Hendry 2014, 32.)

The end-of-life approach has been widely endorsed by the metal industries because the recycled content approach neglects the recyclability which is a key material property for metals. Thus, metal industries have strongly preferred the avoided burden approach that also considers recycling rates and offers ability to account for material downcycling issues and recycling efficiencies. (Hendry 2014, 33-34.) In terms of lithium, it has not been just the lack of data, but rather a lack of economically and sustainably viable technologies for recycling of LIB materials. However, progress is being made and, for example, in 2019 Fortum Oyj announced having developed an efficient technology to recycle the lithium in rechargeable lithium-ion batteries. (Fortum 2020.)

9.2 Methodological issues

The lack of adequately defined and uniformly quantifiable impact categories and functional units seems to be a significant contributor to the challenges of LCA and other environmental impact evaluation tools in the mining industry. This increases the environmental concern especially in relation to an impact-intensive industry. (Kaunda 2020, 242.)

A careful selection of the included life cycle stages is especially important for metal products that can clearly benefit from the recovery options at end-of-life. Cradle-to-gate studies do not take this advantage into account and are therefore generally not preferred especially in comparative assertions with non-metal products. However, cradle-to-gate assessment have their place in providing data for more comprehensive cradle-to-grave studies performed by other practitioners. The use of cradle-to-gate is also justified in cases where the intended use of the final product is undefined. (Hendry 2014, 11.)

9.2.1 Units and practices

One of the most challenging differences in mining LCA studies stems from the fundamental difference in their functional (or declared) unit (Awuah-Offei et al. 2011, 85). Mass is usually an inappropriate unit of comparison as it does not capture the performance characteristics of the (metal or mineral) product. Mass can, however, be used as a declared unit if the precise function of the product is not stated but it is essential to remember that declared units are not directly comparable (Hendry 2014, 16). Functional unit is often stated in terms of a unit of production or, for greater comparability, in terms of the rate of production (e.g., tons per hour). The studied products determine whether the units need to be stated as for refined product or of quantity of ore production. Variation in units makes it difficult to generate emission factors from the studies. Also, the publicly available data is often in the form of corporate sustainability reports from which it is difficult to trace back data for smaller unit processes. (Awuah-Offei et al. 2011, 85.) Even in cases where the same unit is used, the use of different characterization factors can make any level of comparison impossible (Peters et al. 2017, 499). Thus, in order to make any comparative assertions it should always be ensured that the systems under study are functionally equivalent and include characterization of impacts from all relevant life cycle stages (Hendry 2014, 16).

However, the mining itself is many times considered in the studies as a black box, meaning without the possibility to assess the contribution of different process practices. The use of generic data in mining LCA is also often inadequate and cannot accurately account for the geographic and temporal environmental burdens that contribute to the more complex downstream systems like various industries. (Awuah-Offei et al. 2011, 83.)

Cut off – rules are set to guide the omission of inputs based on the lack of significance in the overall results. Standard ISO 14044 does not provide specific instructions for actual tresholds and the use of percentage-based limits is mainly facilitating the work in cases where the insignificance is more or less obvious. In less obvious cases the application of such percentage limits is altogether many times impracticable as one would first need to include everything in order to be able to establish the 100% reference on which to compare. In case of abundant and complex LCI data this can be laborious. (Santero,& Hendry 2016, 1546.)

One of the challenges related to mining LCAs is the generation of co-products. Joint production is common in the mining industry and often highly interconnected systems produce various metals commodities from different ores and production stages. This often makes it difficult to assess each metal and its impacts independently. In case allocation is needed, the approach applied to it makes a significant difference. Using economic allocation instead of mass-based is most often the only suitable option for mining products and is also advised as a baseline method for LCAs (Jiang et al. 2020, 3). However, understanding the interactions in joint production is crucial and in case the co-products or side streams are intermediate products that are not traded on markets, it is likely to be difficult to determine a truthful price for them. Unifying the existing data for metals would help to increase the transparency on co-production issues and ease up the sensitivity analysis, for example, on the different approaches of allocation. (Nuss & Eckelman 2014, 4, 9.)

9.2.2 Impact categories and characterization factors

It has been widely recognized that some of the standard impact categories in LCA methodology are not enough to describe the environmental impacts from mining (Awuah-Offei et al. 2011, 84). Some impact categories might be required by product-specific standards or guidelines like, for example, in EPDs the categories are defined by the product category rule. In some cases the decision is, however, left to the practitioner as ISO standards do not take a stand on which ones must be used. For the sake of consistency, the white paper by PE International on the harmonization of LCA methodologies for metals (Hendry 2014, 38) recommended the following set of impact categories for fully comprehensive LCAs involving metals:

- Global warming potential
- Acidification potential
- Eutrophication potential
- Smog potential (e.g., photochemical oxidant creation potential)
- Ozone depletion potential

In addition, primary energy demand (total, fossil, and renewable) and net water consumption were identified as important parts of the environmental profile and their reporting was recommended to be considered.

LCIA can be conducted using various methodologies that define the characterization factors. The most commonly used are TRACI, CML and ReCiPe. Methodologies differ through their choice of characterization models and even though some categories like GWP are universal, others can result in different values depending on the chosen method. (Hendry 2014, 38.) Background science provides information for characterization factors on characteristics like geography, population densities, chemistry and emission rates. Due to advances in research, also the characterization factors are continuously evolving. The availability and quality of research data varies between categories and although some (like GWP) are well-established and widely accepted, some are more controversial and thus often less applicable. (Hendry 2014, 38.)

9.2.3 Controversiality in impact categories

Impact categories that have been identified to prove problematic in LCAs involving metals, included categories like resource depletion, water use, toxicity and land use. Despite their relevancy as environmental concerns, the reliability of the characterization of them from the inventory data has not been valued high enough in metal industry to benefit decision-making. (Hendry 2014, 39.)

As regards resource depletion and abiotic depletion potential, the varying definitions of “resources” and “reserves” and diverse estimates of their quantity have been found to cause unacceptable variability in results. (Hendry 2014, 44.) A resource relates to a known concentration and character of minerals at a certain location whereas a reserve is an estimate of the amount and mineral content of a deposit that can be mined profitably (Kaunda 2020, 238). Acknowledging resource depletion as a global problem also makes it extremely difficult to determine an internationally accepted baseline of a total global resources (or reserves) for any mineral commodity and there is considerable variation in figures between the assessing experts and the timelines applied. (Hendry 2014, 45.)

In terms of water use the difference between water use and water consumption is worth considering especially in the mining industry that can have a high water use but relatively low water consumption. This refers to the situation where the water is released within the same watershed after use. Regarding environmental impacts, the consumed fraction is the most relevant. However, in terms of water use there has been uncertainty about the extent to which the characterization factors have been successful in incorporating site-specific characteristics and achieving consistency across databases. (Hendry 2014, 45.)

In relation to toxicity, issues, like the need for improvement in assessing and characterizing the ecotoxicity impact potential for metals in solid waste deposits, have been identified. The issue is particularly relevant in mining industry and needs more attention in order to harmonize the results that are obtainable from the available models and, instead of assuming that the total amount of metals in waste deposit will mobilize, to specify the case-specific amount that actually is mobilizable. (Lesage et al. 2008, 11.) These type of significant uncertainty related to the low precision of characterization factors have led to the toxicity issue being recommended for use in the mining industry mainly for an indicative and cautious assessment only. (Hendry 2014, 47.)

The effects of land use have perhaps been the subject of the most intense debate due to their high relevance to communities, companies and other stakeholders (Awuah-Offei et al. 2011, 84). The difficulties of assessing land-use impacts are not unique to the mining industry but given the quantities of waste generated and the treatment of extraction waste at site, the related aspects become particularly relevant for the industry sector.

Although it has been recognized that the impacts from land use are significant for most of the industrial activities, the difficulty in the evaluation still prevents them from becoming adequately taken into account. Many of the international and national agreements and guidelines concentrate on assessing land use and land use change only from the greenhouse gas perspective (Mattila et al. 2011, 8). Developing reliable, measurable indicators for effects on biodiversity, life support functions and biomass production is lacking consistent framework and widely accepted method of implementation. The challenge is compounded by the fact that the actual effects on site vary considerably due to the site-specific features, such as soil quality and rainfall etc. (Lesage et al. 2008, 11.) In addition to challenging environmental issues, land use frequently involves also social and economic impacts which should also be considered (Mattila et al. 2011, 10).

The land use related terminology in LCA studies is diverse; for example, the terms land use and land use change can refer to different aspects and meanings that easily lead to misunderstanding and confusion. In addition, some indicator results are incomprehensible to parties that are not familiar with the environmental discipline. (Mattila et al. 2011, 58.)

Accoding to the Finnish environmental administration the effects of land use have been widely underestimated in life cycle studies in general. The conclusion is based on a vast international literature review which focused on assessing how the reference state for land use was determined in LCA studies. Reference state refers to the state against which the impacts are estimated. The conclusion was that typically the existing land use was chosen as the reference or the issue was not addressed at all. This ignores the fact that terrestrial ecosystems are constantly changing and land use mostly prevents the land from returning to its natural state. Hence, to describe the environmental effects of land use in a consistent way, the reference state should be selected to reflect the return of land to its natural state. (Finnish environmental administration, 2015.)

9.2.4 Uncertainties

The application of uncertainty and sensitivity analysis is important step for any LCA study to be used in a decision-making. Basically, there are three sources of uncertainty in LCA models; variation in the primary data (meaning the data from the manufacturer), uncertainty in the secondary data (data from other LCAs) and uncertainty based on impact assessment models. Variation in primary data might usually be the easiest to reduce as it often involves concrete actions to improve sampling and data collection. (Awuah-Offei et al. 2011, 87.) However, while the reliability of the LCA depends on the data used in it, the importance of obtaining primary data is often focused only on the onsite production processes meaning, that the data for upstream processes is often obtained from databases or literature. This facilitates the data collection process but increases uncertainty. (Jiang et al. 2020, 1.)

Assessing the uncertainty related to secondary data would require the LCA practitioners to objectively quantify the related uncertainty deriving from the differences between the system providing the data and the system under study. These differences include things like geography, age of data, technology, size of operation, allocation method etc. (Awuah-Offei et al. 2011, 87.) Also, understanding the components is crucial to be able to apply secondary data for them. Future developments should aim at outlining a framework that could help to standardize a screening method for upstream processes that are particularly significant and prone to misinterpretation. (Jiang et al. 2020, 5.)

In addition, there are inherent uncertainties related to the impact assessment models used for deriving the equivalence factors for different emissions. As the standard impact categories are not fully satisfactory for assessing the impacts of mining in the first place, this further adds to the uncertainty especially in the mining industry. (Awuah-Offei et al. 2011, 87.)

Considering the use of mining related resources as secondary data in LCI, it is worth noting that the quality of mining data in databases varies significantly. In the most extensive ones it includes energy use, blasting, infrastructure, chemicals, inputs from and outputs to the environment (like water and minerals or direct emissions) and at least to some extent, also waste treatment. In less comprehensive databases many of them are either excluded or the inclusion is deficient. However, even the most comprehensive databases are usually lacking important aspects like effects from the exploration, ore losses and case-specific factors that affect the nature of environmental impacts. Also, the increase in environmental impacts strongly correlates with the decline in ore grade which would need special attention in the assessments (Yao et al., 2021).

In terms of waste management, the datasets often fail to consider especially the long-term emissions from sulfidic tailings and the resources required to manage these wastes over time. Adding temporal aspects in mining LCAs, especially in terms of waste management, is favorable but involves challenging issues like how to reliably model future situations (for example, leaching rates or durability of structures) or how to evaluate whether the burdens of today will have the same impact and meaning in the future. (Lesage et al. 2008, 10.)

Despite the number of issues, a clear minority of studies employ a sufficient uncertainty analysis and even fewer use systematic and quantitative methods. The practitioners’ ability to do the tests and assess the full risk profile of the impacts is mostly hampered by the fact that most of the LCA studies are done with limited data. The challenges related to uncertainty analysis and reliability of the results need more attention as LCA is becoming an important decision-making tool also for the mining industry. (Awuah-Offei et al. 2011, 86.)

9.3 Societal concerns

LCA typically does not address economic or social aspects which tend to play an important role especially in an environmentally burdensome industry with a wide range of both local and off-site impacts. Economic impacts, however, tend to gain interest through other means while social ones are easily ignored. The importance of including especially the impacts from local mining activities is emphasized in order to adequately address the sustainability of lithium ion batteries along their life cycle.

The biggest challenges are often related to mining activities in areas with already sensitive environmental conditions like, for example, Chile and Bolivia where brine mining has significantly contributed to a severe water scarcity. The challenges related to brines are comparatively higher than for mineral extraction. (Agusdinata et al. 2018, 9.) However, long supply chains that cross national or even continental boundaries and multiple political jurisdictions are likely to cause environmental and social challenges for all companies, regardless of their deposit types. With highly decentralized operations the management of supply chain becomes challenging and exposes companies and their stakeholders to unpleasant surprises related to corporate responsibility (Koipijärvi 2020, 158).

In terms of literature, publications tend to concentrate mainly on the impacts of production and end-of-life of lithium-ion batteries (LIBs). The main area of interest in the studies is largely focused on energy use and CO2- emissions. However, the effects of the production and end-of-life are likely to affect societies in relatively industrialized countries whereas the impacts from raw material extraction hit lower-income countries. These effects are often more severe and the less developed countries, and especially their indigenous groups, usually have difficulties in getting attention to their concerns. (Agusdinata et al. 2018, 10.)

Addressing social concerns calls for flexible methodological approaches and analytical tools that can be tailored to local conditions and could integrate challenging societal issues into more easily measurable parameters (Agusdinata et al. 2018, 11).

10 FUTURE PERSPECTIVES

In addition to the limited number of LCA studies in the mining industry, the range of methodological approaches used in them has been wide. Harmonization attempts have been made to reach a consistent approach needed to comply with the increasing sustainability efforts in the public and private sectors. One example of these attempts was a whitepaper providing guidance for conducting LCAs for metals and metal products, prepared by PE International for various mining associations in 2014. However, due to a wide range of material-specific issues related to metal and mineral products it has also been recognized that a complete harmonization within the industry is not feasible. (Hendry 2014, 8.)

The most common challenges identified during harmonization efforts have included issues related to the treatment of co-products, scoping, end-of-life recycling and life cycle impact assessment (LCIA). Recommendations for alignment on these issues have included, for example, the appliance of the following substantial practices:

- system boundaries should be set to include end-of-life disposal, recycling and use phase (whenever possible)
- co-product allocation methods should consider the type and properties of co-products
- recycling allocation should use the end-of-life recycling approach instead of the recycled content approach (as the pursuit of recycled content might disturb markets and cause environmental and economic inefficiencies)
- LCIA should use well-established and scientifically defensible impact categories (which could be defined the most important issue as it seems to be the fundamental challenge for mining industry in the current system)

(Hendry 2014, 48.)

Despite the methodological problems, the biggest challenge for the mining industry in the future will be how to meet the demand for the raw materials required by green technologies without relying on fossil fuels, and how to avoid a situation where poor countries have to pay the environmental and social costs of emission reductions in rich countries. The challenge is strongly linked to the global need to move from over-consumption and the pursuit of continuous growth to a level of consumption that safeguards human well-being and technological development within planetary limits. (EEB 2021, 5, 29.)

11 DISCUSSION

The research objectives set for this study were to identify the hotspots in Keliber's environmental footprint and to assess the challenges related to the implementation of LCA methodology in the mining industry. The LCA study prepared in the practical part of this thesis identified energy use as the biggest source of CO2-emissions together with the use of calcium oxide as a process reagent at the chemical plant. Energy use was assessed to cover 61% of the total CO2-emissions whereas transportation in its entirety, proved to be a minor contributor to the carbon footprint with just 3% share of the emissions. The total carbon footprint calculated in this preoperational study for 1 tonne of LHM from Keliber's process is 9,4 t CO2 eq. Majority of the emissions (77%) derive from the operations at the chemical plant which was expected as the conversion stage uses most of the energy and chemicals. In addition to the greenhouse gas emissions, the production process was identified to generate significant amounts of extractive waste and contribute to the depletion of fossil resources through the use of non-renewable energy sources. Based on the results, decarbonizing fuels and energy would offer the most efficient tool for emission mitigation.

As the project goal and scope were set to recognize the environmental hotspots during the entire production chain, the interpretation of the results focused on the GWP. As an indicator, GWP brings together CO2-emissions from production, transportation and refining of lithium resources into the final product. However, although GWP is widely recognized as one of the key issues permeating lithium's sustainability credentials, its exclusive use in impact assessment can be misleading. Focusing on greenhouse gas emissions easily neglects other important impact types like waste generation, acidification and resource depletion (Peters et al. 2017, 503). The use of GWP has also been criticized for being based on a CO2 –equivalent which groups together greenhouse gases with significantly differing radiative efficiencies and lifetimes. Some of the short-lived species may have a lifetime of a few years whereas some of the long-lived species can lasts for thousands of years. Thus, also the changes in climate come in both the short- and long-term impacts. Planning emission reductions on the basis of a CO2-equivalent does not allow for a mitigation measures to be targeted by the type of an emission. For the outcome it, however, makes a lot of difference whether the emission reductions are targeted on long-lived or short-lived species. As a suggestion for improvement, GWP has been proposed to be presented in two different categories (short-term and long-term effects). (UNEP 2016, 63.)

In terms of challenges of LCA methodology in the mining industry, several needs for customization and harmonization have been identified in order to realize the full potential of life cycle methodology for the sector. Further development is required, for example, to increase the suitability of impact categories to meet the specificities of mining industry. Currently also the fundamental differences in methodological issues like units and practices, characterization models and allocation approaches are likely to introduce unacceptable variation into the results.

Despite the challenges faced by the mining industry in adopting life cycle assessment, its importance as a methodology will grow in the future as consumers become more environmentally aware and stakeholders become more demanding. Future environmental performance is no longer about regulatory compliance but more about vital competitiveness in ability to conduct business while ensuring all aspects of sustainability. A well-functioning life cycle assessment can provide industries with a tool to quantitatively measure their performance and pursue the goal of continuous improvement set by certified environmental management systems. (Awuah-Offei et al. 2011, 88.) Also, given the wide range of environmental impacts associated with mining activities, both on-site and off-site, LCA has been proposed to play a role in supporting environmental impact assessments (EIAs) that traditionally address only locally occurring impacts. Including an LCA into an EIA has been suggested to bring about significant improvements by widening the perspective and introducing additional impacts that have traditionally been absent in EIA studies. (Yao et al. 2021, 465.) In terms of societal sustainability, social aspects will play an increasingly important role in the future as one of the biggest challenges for mining industry will relate to the industry's ability to offer raw materials for green technologies without relying on fossil fuels and shifting the burdens of extraction to the low-income countries.

Full implementation of life-cycle methodology in the mining industry is particularly important because the assessment of the environmental impacts of other products depends directly or indirectly on the information provided by the mining industry. Although the environmental impacts of lithium batteries have been relatively well assessed and LCA-studies on them are abundant in number, there is a clear lack of data on the impacts of the direct extraction and processing of lithium metal (Kaunda 2020, 244). This confirms the view that the role of LCA in mining industry is both to assist the industry itself to develop its environmental performance, and to provide LCA community with a reliable and up-to-date data to reduce the interdependence of the existing LCI data (Lesage et al. 2008, 1).

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APPENDICES

Appendix 1. Life cycle inventory data.

TABLE 3: List of processes included in A2.

Resource	Quantity	Distance (km)	Trip	Transport	Souce	Date	Comments	Data quality
Bulk emulsion explosive	66.0 kg	194	1	Market for transport, freight, lorry >32 metric ton, euro5	Ecoinvent 3.6	2019	Explosive used at mine. Transport Central Finland -Kaustinen, 100% occupancy rate	Good
Transported quantity	11000.0 kg	140	1	Market for transport, freight, lorry >32 metric ton, euro5	Ecoinvent 3.6	2019	Spodumene concentrate Kaustinen-Kokkola, occupancy rate 50%	Good
Market for fatty acid	69.0 kg	440	1	Market for transport, freight, lorry >32 metric ton, euro5	Ecoinvent 3.6	2019	Flotation chemical used at concentration plant. Transport South East Finland -Kaustinen, 100% occupancy rate	Good
Market for hydrochloric acid, without water, in 30% solution state	64.0 kg	500	1	Market for transport, freight, lorry >32 metric ton, euro5	Ecoinvent 3.6	2019	Process chemical for pH adjusting etc., used at chemical plant. Transport Eastern Finland-Kokkola, 100% occupancy rate	Good
Market for polyacrylamide	20.0 kg	500	1	Market for transport, freight, lorry >32 metric ton, euro5	Ecoinvent 3.6	2019	Flocculant used at chemical plant. Transport South East Finland -Kokkola, 100% occupancy rate	Good
Market for quicklime, milled, packed	1600.0 kg	4500	1	Market for transport, freight, sea, container ship	Ecoinvent 3.6	2019	Reagent used at chemical plant. Transport Western Europe-Kokkola, 100% occupancy rate	Good
		150	2	Market for transport, freight, lorry >32 metric ton, euro5	Ecoinvent 3.6	2019		
Market for soda ash, light, crystalline, heptahydrate	1440.0 kg	1000	1	Market for transport, freight, sea, container ship	Ecoinvent 3.6	2019	Reagent used at chemical plant. Transport Central Europe - Kokkola, 100% occupancy rate	Good
		150	2	Market for transport, freight, lorry >32 metric ton, euro5	Ecoinvent 3.6	2019		

continues

Resource	Quantity	Distance (km)	Trip	Transport	Souce	Date	Comments	Data quality
Market for sodium hydroxide, without water, in 50% solution state	21.0 kg	2500	1	Market for transport, freight, sea, container ship	Ecoinvent 3.6	2019	pH adjusting chemical used at concentration plant (320t). Transport Western Europe-Kaustinen, 100% occupancy rate	Good
		58	2	Market for transport, freight, lorry >32 metric ton, euro5	Ecoinvent 3.6	2019		
Market for sodium hydroxide, without water, in 50% solution state	20.0 kg	2500	1	Market for transport, freight, sea, container ship	Ecoinvent 3.6	2019	Process chemical for pH adjusting etc., used at chemical plant (300 t). Transport Western Europe-Kokkola, 100% occupancy rate	Good
		40	2	Market for transport, freight, lorry >32 metric ton, euro5	Ecoinvent 3.6	2019		
Market for steel, low-alloyed, hot rolled	55.0 kg	25000	1	Market for transport, freight, sea, container ship	Ecoinvent 3.6	2019	Grinding balls and rods etc. used at concentration plant. Supplier not known, assumed to come from Asia, 100% occupancy rate	Good
		500	2	Market for transport, freight, lorry >32 metric ton, euro5	Ecoinvent 3.6	2019		
Market for trisodium phosphate	100.0 kg	25000	1	Market for transport, freight, sea, container ship	Ecoinvent 3.6	2019	Precipitant used at chemical plant. Transport assumed from Asia, 100% occupancy rate	Good
		500	2	Market for transport, freight, lorry >32 metric ton, euro5	Ecoinvent 3.6	2019		

TABLE 4: List of processes included in A3.

Resource	Quantity	Distance (km)	Trip	Transport	Souce	Date	Comments	Data quality
Bulk emulsion explosive	66.0 kg	194	1	Market for transport, freight, lorry >32 metric ton, euro5	Ecoin-vent 3.6	2019	Explosive used at mine. Transport Central Finland-Kaustinen, 100% occupancy rate	Good
Market for fatty acid	69.0 kg	440	1	Market for transport, freight, lorry >32 metric ton, euro5	Ecoin-vent 3.6	2019	Flotation chemical used at concentration plant. Transport South East Finland -Kaustinen, 100% occupancy rate	Good
Market for hydrochloric acid, with-out water, in 30% solution state	64.0 kg	500	1	Market for transport, freight, lorry >32 metric ton, euro5	Ecoin-vent 3.6	2019	Process chemical for pH adjusting etc., used at chemical plant. Transport Eastern Finland-Kokkola, 100% occupancy rate	Good

Resource	Quantity	Distance (km)	Trip	Transport	Souce	Date	Comments	Data quality
Market for metalliferous hydroxide sludge	22.0 kg	50	1	Market for transport, freight, lorry 16-32 metric ton, euro5	Ecoin-vent 3.6	2019	Slurry from nanogeotube	Good
Market for polyacrylamide	20.0 kg	500	1	Market for transport, freight, lorry >32 metric ton, euro5	Ecoin-vent 3.6	2019	Flocculant used at chemical plant. Transport from South East Finland -Kokkola, 100% occupancy rate	Good
Market for quicklime, milled, packed	1600.0 kg	4500	1	Market for transport, freight, sea, container ship	Ecoin-vent 3.6	2019	Reagent used at chemical plant. Transport Western Europe-Kokkola, 100% occupancy rate	Good
		150	2	Market for transport, freight, lorry >32 metric ton, euro5	Ecoin-vent 3.6	2019		
Market for soda ash, light, crystal-line, heptahydrate	1440.0 kg	1000	1	Market for transport, freight, sea, container ship	Ecoin-vent 3.6	2019	Reagent used at chemical plant. Transport Central Europe-Kokkola, 100% occupancy rate	Good
		150	2	Market for transport, freight, lorry >32 metric ton, euro5	Ecoin-vent 3.6	2019		
Market for sodium hydroxide, with-out water, in 50% solution state	21.0 kg	2500	1	Market for transport, freight, sea, container ship	Ecoin-vent 3.6	2019	pH adjusting chemical used at concentration plant (320t). Transport Western Europe-Kaustinen, 100% occupancy rate	Good
		58	2	Market for transport, freight, lorry >32 metric ton, euro5	Ecoin-vent 3.6	2019		
Market for sodium hydroxide, with-out water, in 50% solution state	20.0 kg	2500	1	Market for transport, freight, sea, container ship	Ecoin-vent 3.6	2019	Process chemical for pH adjusting etc., used at chemical plant (300 t). Transport Western Europe-Kokkola, 100% occupancy rate assu-med	Good
		40	2	Market for transport, freight, lorry >32 metric ton, euro5	Ecoin-vent 3.6	2019		
Market for steel, low-alloyed, hot rolled	55.0 kg	25000	1	Market for transport, freight, sea, container ship	Ecoin-vent 3.6	2019	Grinding balls and rods etc. used at concentration plant. Supplier not known, assumed to come from Asia	Good
		500	2	Market for transport, freight, lorry >32 metric ton, euro5	Ecoin-vent 3.6	2019		
Market for trisodium phosphate	100.0 kg	25000	1	Market for transport, freight, sea, container ship	Ecoin-vent 3.6	2019	Precipitant used at chemical plant. Transport assumed from Asia, 100% occupancy rate	Good
		500	2	Market for transport, freight, lorry >32 metric ton, euro5	Ecoin-vent 3.6	2019		

TABLE 5: List of resources included in A3.

Stage	Resource	Quantity	Unit	Comment	Region	Date	Data Source	Data quality score
A3	Bulk emulsion explosive	66.0	kg	Explosive used at mine. Transport Central Finland-Kaustinen, 100% occupancy rate	finland	2020	EPD Offshore Kemiitti	Good
A3	Diesel, burned in building machine	2.6	MWh	Diesel use in mining 3150 tpa (9,8 kWh/l, density 0,8kg/l). Includes machine work + transports at the mine site + transportation to the contentration plant	world	2019	Ecoinvent 3.6	Good
A3	Heat production, natural gas, at industrial furnace low-nox >100kw	25000.0	MJ	Natural gas 50MJ/kg, runtime 7500h = 375 000 GJ/15000 t. Used in barrel furnace to produce heat	europe, albania, andorra, austria, belarus, belgium, bosniaHerzegovina, bulgaria, channelIslands, croatia, cyprus, czechRepublic, denmark, estonia, finland, france, germany, gibraltar, greece, hungary, iceland, ireland, italy, jersey, kosovo, latvia, lichtenstein, lithuania, luxembourg, macedonia, malta, moldova, monaco, montenegro, netherlands, norway, poland, portugal, romania, russia, sanMarino, serbia, slovakRepublic, slovenia, spain, sweden, turkey, ukraine, unitedKingdom, vatican	2019	Ecoinvent 3.6	Good
A3	Heat production, wood chips from industry, at furnace 5000kw	6804.0	MJ	Approx. 3MW heating plant, 28 280 MWh/a	world	2019	Ecoinvent 3.6	Good
A3	Market for electricity, medium voltage	1.0	MWh	Electricity use at the mine (2MW*7500h/15000 t)	finland	2019	Ecoinvent 3.6	Good
A3	Market for electricity, medium voltage	2.0	MWh	Electricity use in concentration plant 29879,485 MWh/a	finland	2019	Ecoinvent 3.6	Good
A3	Market for electricity, medium voltage	4.1	MWh	Electricity use in chemical plant (8,1MW*7500h/15 000t) + pumping of analcime sand (0,0444 kW*7500h/15000)	finland	2019	Ecoinvent 3.6	Good
A3	Market for fatty acid	69.0	kg	Flotation chemical used at concentration plant. Transport South-East Finland-Kaustinen, 100% occupancy rate	world	2019	Ecoinvent 3.6	Good
A3	Market for hydrochloric acid, without water, in 30% solution state	64.0	kg	Process chemical for pH adjusting etc., used at chemical plant. Transport East Finland-Kokkola, 100% occupancy rate	europe	2019	Ecoinvent 3.6	Good

Stage	Resource	Quantity	Unit	Comment	Region	Date	Data Source	Data quality score
A3	Market for metalliferous hydroxide sludge	22.0	kg	Slurry from nanogeotube	world	2019	Ecoinvent 3.6	Good
A3	Market for polyacrylamide	20.0	kg	Flocculant used at chemical plant. Transport from South-East Finland - Kokkola, 100% occupancy rate	world	2019	Ecoinvent 3.6	Good
A3	Market for quicklime, milled, packed	1600.0	kg	Reagent used at chemical plant. Transport Western Europe-Kokkola, 100% occupancy rate	europe	2019	Ecoinvent 3.6	Good
A3	Market for soda ash, light, crystalline, heptahydrate	1440.0	kg	Reagent used at chemical plant. Transport Central Europe-Kokkola, 100% occupancy rate	world	2019	Ecoinvent 3.6	Good
A3	Market for sodium hydroxide, without water, in 50% solution state	21.0	kg	pH adjusting chemical used at concentration plant (320t). Transport Western Europe-Kaustinen, 100% occupancy rate	world	2019	Ecoinvent 3.6	Good
A3	Market for sodium hydroxide, without water, in 50% solution state	20.0	kg	Process chemical for pH adjusting etc., used at chemical plant (300 t). Transport Western Europe-Kokkola, 100% occupancy rate assumed	world	2019	Ecoinvent 3.6	Good
A3	Market for steel, low-alloyed, hot rolled	55.0	kg	Grinding balls and rods etc. used at concentration plant. Supplier not known, assumed to come from Asia	world	2019	Ecoinvent 3.6	Good
A3	Market for sulfuric acid	73.0	kg	pH adjusting chemical used at chemical plant. Transport along pipeline from KIP-area, 100% occupancy rate	europe	2019	Ecoinvent 3.6	Good
A3	Market for tap water	10000.0	kg	Factory water from tap, used at chemical plant	europe, albania, andorra, austria, belarus, belgium, bosniaHerzegovina, bulgaria, channelIslands, croatia, cyprus, czechRepublic, denmark, estonia, finland, france, germany, gibraltar, greece, hungary, iceland, ireland, italy, jersey, kosovo, latvia, lichtenstein, lithuania, luxembourg, macedonia, malta, moldova, monaco, montenegro, netherlands, norway, poland, portugal, romania, russia, sanMarino, serbia, slovakRepublic, slovenia, spain, sweden, turkey, ukraine, unitedKingdom, vatican	2019	Ecoinvent 3.6	Good

Stage	Resource	Quantity	Unit	Comment	Region	Date	Data Source	Data quality score
A3	Market for trisodium phosphate	100.0	kg	Precipitant used at chemical plant. Transport assumed from Asia, 100% occupancy rate	world	2019	Ecoinvent 3.6	Good
A3	Market for water, deionised	1600.0	kg	Demineralized water used at chemical plant.	europe, albania, andorra, austria, belarus, belgium, bosniaHerzegovina, bulgaria, channelIslands, croatia, cyprus, czechRepublic, denmark, estonia, finland, france, germany, gibraltar, greece, hungary, iceland, ireland, italy, jersey, kosovo, latvia, lichtenstein, lithuania, luxembourg, macedonia, malta, moldova, monaco, montenegro, netherlands, norway, poland, portugal, romania, russia, sanMarino, serbia, slovakRepublic, slovenia, spain, sweden, turkey, ukraine, unitedKingdom, vatican	2019	Ecoinvent 3.6	Good
A3	Steam production, as energy carrier, in chemical industry	12060.0	MJ	Steam use 14.37 t/h --> 6.7 MW/7500 h (/15000 t). Used in pressure leaching, crystallization and drying.	europe	2019	Ecoinvent 3.6	Good
A3	Treatment of non-sulfidic overburden, off-site	286.0	ton	waste rock at the mine + bottom slurry from water treatment	world	2019	Ecoinvent 3.6	Good
A3	Treatment of non-sulfidic overburden, off-site	7.0	ton	Sorter reject	world	2019	Ecoinvent 3.6	Good
A3	Treatment of non-sulfidic tailing, off-site	26.0	ton	Prefloat and magnetic fractions + tailings and slurry	world	2019	Ecoinvent 3.6	Good
A3	Treatment of wastewater, average, capacity 1e9l/year	8.0	m3	Process water drained to the treatment plant	europe, albania, andorra, austria, belarus, belgium, bosniaHerzegovina, bulgaria, channelIslands, croatia, cyprus, czechRepublic, denmark, estonia, finland, france, germany, gibraltar, greece, hungary, iceland, ireland, italy, jersey, kosovo, latvia, lichtenstein, lithuania, luxembourg, macedonia, malta, moldova, monaco, montenegro, netherlands, norway, poland, portugal, romania, russia, sanMarino, serbia, slovakRepublic, slovenia, spain, sweden, turkey, ukraine, unitedKingdom, vatican	2019	Ecoinvent 3.6	Good

Appendix 2. Printout of the results (GWP)

Stage	Resource	User input / 1 t LHM	Unit	Global warming kg CO_2eq. / 1 t LHM
A2	Transported quantity (spodumene concentrate)	11	ton	138,73
A2	Market for sodium hydroxide, without water, in 50% solution state (Reference product: sodium hydroxide, without water, in 50% solution state)	20	kg	0,54
A2	Market for polyacrylamide (Reference product: polyacrylamide)	20	kg	0,9
A2	Market for sodium hydroxide, without water, in 50% solution state (Reference product: sodium hydroxide, without water, in 50% solution state)	21	kg	0,6
A2	Market for steel, low-alloyed, hot rolled (Reference product: steel, low-alloyed, hot rolled)	55	kg	15,34
A2	Market for hydrochloric acid, without water, in 30% solution state (Reference product: hydrochloric acid, without water, in 30% solution state)	64	kg	2,88
A2	Bulk emulsion explosive, Offshore Kemiitti (Oy Forcit Ab, plant Vihtavuori)	66	kg	1,15
A2	Market for fatty acid (Reference product: fatty acid)	69	kg	2,73
A2	Market for trisodium phosphate (Reference product: trisodium phosphate)	100	kg	27,9
A2	Market for soda ash, light, crystalline, heptahydrate (Reference product: soda ash, light, crystalline, heptahydrate)	1440	kg	32,93
A2	Market for quicklime, milled, packed (Reference product: quicklime, milled, packed)	1600	kg	88,99
A2_preV				**312,71**
A3	Market for electricity, medium voltage (Reference product: electricity, medium voltage)	1	MWh	239,71

continues

A3	Market for electricity, medium voltage (Reference product: electricity, medium voltage)	2	MWh	479,42
A3	Diesel, burned in building machine (Reference product: diesel, burned in building machine)	2,6	MWh	850,74
A3	Market for electricity, medium voltage (Reference product: electricity, medium voltage)	4,1	MWh	982,81
A3	Treatment of non-sulfidic overburden, off-site (Reference product: non-sulfidic overburden, off-site)	7	ton	0
A3	Treatment of wastewater, average, capacity 1e9l/year (Reference product: wastewater, average)	8	m3	3,83
A3	Market for sodium hydroxide, without water, in 50% solution state (Reference product: sodium hydroxide, without water, in 50% solution state)	20	kg	25,72
A3	Market for polyacrylamide (Reference product: polyacrylamide)	20	kg	56,86
A3	Market for sodium hydroxide, without water, in 50% solution state (Reference product: sodium hydroxide, without water, in 50% solution state)	21	kg	27,01
A3	Market for metalliferous hydroxide sludge (Reference product: metalliferous hydroxide sludge)	22	kg	0,92
A3	Treatment of non-sulfidic tailing, off-site (Reference product: non-sulfidic tailing, off-site)	26	ton	0
A3	Market for steel, low-alloyed, hot rolled (Reference product: steel, low-alloyed, hot rolled)	55	kg	101,69
A3	Market for hydrochloric acid, without water, in 30% solution state (Reference product: hydrochloric acid, without water, in 30% solution state)	64	kg	37,57
A3	Bulk emulsion explosive, Offshore Kemiitti (Oy Forcit Ab, plant Vihtavuori)	66	kg	73,26
A3	Market for fatty acid (Reference product: fatty acid)	69	kg	304,14
A3	Market for sulfuric acid (Reference product: sulfuric acid)	73	kg	7,68
A3	Market for trisodium phosphate (Reference product: trisodium phosphate)	100	kg	226,88
A3	Treatment of non-sulfidic overburden, off-site (Reference product: non-sulfidic overburden, off-site)	286	ton	0

A3	Market for soda ash, light, crystalline, heptahydrate (Reference product: soda ash, light, crystalline, heptahydrate)	1440	kg	651,88
A3	Market for quicklime, milled, packed (Reference product: quicklime, milled, packed)	1600	kg	1833,29
A3	Market for water, deionised (Reference product: water, deionised)	1600	kg	0,67
A3	Heat production, wood chips from industry, at furnace 5000kw (Reference product: heat, district or industrial, other than natural gas)	6804	MJ	124,94
A3	Market for tap water (Reference product: tap water)	10000	kg	3,35
A3	Steam production, as energy carrier, in chemical industry (Reference product: heat, from steam, in chemical industry)	12060	MJ	1234,98
A3	Heat production, natural gas, at industrial furnace low-nox >100kw (Reference product: heat, district or industrial, natural gas)	25000	MJ	1848,61
A3_preV				**9115,95**