# Life Cycle Modelling of Extraction and Processing of Battery Minerals – A Parametric Approach

**Nelson Bunyui Manjong [1,2,*], Lorenzo Usai [1,2], Odne Stokke Burheim[2], and Anders Hammer Strømman [1,2,*]**

1 Industrial Ecology Programme, Norwegian University of Science and Technology, 7491 Trondheim, Norway; lorenzo.usai@ntnu.no

2 Department of Energy and Process Engineering, Faculty of Engineering, Norwegian University of Science and Technology, 7491 Trondheim, Norway; odne.s.burheim@ntnu.no

* Correspondence: nelson.manjong@ntnu.no (N.B.M.); anders.hammer.strømman@ntnu.no (A.H.S.)

Table S1. Assumptions and range of values for parameters used in model.

| *Value Chain* | *Process Stage* | *Levers (Parameters)* | *Parameter Description* | *Range* | *References* | *Number of distinct LCA Simulations* |
|---|---|---|---|---|---|---|
| *Copper* | Mining and concentration | • Mine Type | The type of mine determines the mining operations carried out. As underground mining presents distinct properties from open-cast (also called open pit) mining, the life cycle inventory, especially the energy use, is also different for these mine types. We include this as a parameter in copper mining to test its effect on the GWP. | [Underground, Open-Cast] | [1] | 300 |
| | | • Mine depth | For underground mines, the depth of the mine determines the efforts and consequently energy required to sustain mining operations. We adopt mine depth as a parameter as this allows us to calculate the efforts (energy use) as a function of the mine depth. Consequently, the GWP will vary as a function of the depth. We use 450m as the maximum for our simulations. | [0 - 450m] | [1] | |
| | | • Ore grade | Ore grade is a typical characteristic of copper mining operations, and this determines the efforts needed to extract the mineral from the ground. More rock material is required to be mine at low copper ore grades than high at ore grades. This variation in the ore grade affects the mining energy and molar concentration of reactants to process the ore. Ore grades determine the energy and material consumption at mining sites. We, therefore, adopt this as a parameter to | [1 - 5%] copper | [1][2] | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | investigate its effect on the GWP. | | | |
| | | • Recovery Efficiency | The recovery efficiency applied for the concentration phase measures how concentrated ore is recovered without waste (material waste). At lower concentrate recovery efficiency, more material and energy is needed to produce a unit of the desired material that is being wasted due to the loss in recovery efficiency. This idea prompts us to adopt the recovery efficiency of the copper concentration phase into a parameter. | [80 - 96%] | [3] | |
| | | • Carbon Intensity of Electricity Mix | The energy intensity of the mix measures the GHG emissions of the electricity mix used in the copper concentration phase. | [0.2 - 1.1] $kgCO_2e/kWh$ | [4],[5] | |
| | Smelting and Refining | • Recovery Efficiency | Converting copper concentrate into copper matte through smelting also considers the matte's recovery efficiency, which measures how effectively the matte is recovered after production. We include this recovery for the smelting process (conversion into matte) and refining into pure metal as parameters. | [80 - 96%] | [6] | 150 |
| | | • Smelting Technology | In copper smelting, various smelting technologies have different energy requirements and material consumption. According to the technologies, we adopt smelting technology as a parameter in our model due to energy and process efficiency variations. | Flash, Isasmelt, Mitsubishi, KH-Outokumpu Flash, KH-Hot Calcine Reverb | [7] | |
| | | • Carbon Intensity of electricity mix | Same as in copper mining and concentration | [0.2 - 1.1] $kgCO_2e/kWh$ | [4],[5] | |
| *Aluminum* | Bauxite and Alumina | • Bauxite ore grad | The alumina content in bauxite ore, also called bauxite ore grade or resource quality, determines how much effort (energy and material) is consumed to produce a unit of alumina from the bauxite. At low bauxite resource quality, more bauxite is needed to be mined to produce a unit of alumina, consequently increasing energy and material consumption. | [31 - 52% ] Alumina content | [8] | 289 |
| | | • Overburden to bauxite ratio | Overburden refers to the topsoil layer which must be removed to extract the bauxite resource. The | 0.02-6 | [8] | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | thickness of the overburden layer determines the amount of material to be dug up before accessing the bauxite resource. This overburden layer can range from 0-20m in some mines. The ratio of the thickness of the overburden layer to the thickness of bauxite layer is used as a parameter to determine the amount of material to be extracted before accessing the bauxite resource which directly determines the energy requirements of the process. | | | |
| | | • Recovery Efficiency | Recovery efficiency in the bauxite and alumina stages refers to the effectiveness of recovering the bauxite mined for the mining stage and recovering the alumina produced in the Bayer process. This recovery efficiency determines the material and energy use. Like recovery efficiency in the copper concentration process | [70 – 95%] | [9] | |
| | | • Carbon intensity of electricity mix | The energy intensity of the mix measures the GHG emissions of the electricity mix used in the bauxite mining and Bayer process. Some mining operations used direct electricity from grid while others used fossil fuels to produce electricity on site for mining operations. Similarly, for the Bayer process, grid electricity can be used, or direct electricity produced on the process plant. | [0.2 - 1.4] $kgCO_2e/kWh$ | [10],[5] | |
| | Electrolysis and ingot casting | • Technology type | For the electrolysis stage, the prebake and the Søderberg technologies have been commonly used. Within the prebake technology, the point feeder prebake (PFPB), the centre work prebake (CWPB), and the side work prebake (SWPB) are also available. Similarly, within the Søderberg technology, the horizontal stud Søderberg (HSS) and the vertical stud Søderberg (VSS) exists. We adopt the average values for the prebake and the Søderberg technologies as representative technologies of the sub-variants. | [Prebake, Søderberg] | [11] | 289 |
| | | • Recovery efficiency | Recovery efficiency parameter in the Hall-Heroult process refers how to the effectiveness in fully | [80 -98%] | [6] | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | obtaining the primary liquid produced. | | | |
| | | • Carbon intensity of the electricity mix | The intensity of the carbon intensity is a very important parameter for this as there is high energy consumption in this stage, so the source of electricity is simulated as a parameter | [0.2 - 1.4] $kgCO_2e/kWh$ | [5] | |
| | | • Energy efficiency improvements | Due to the high electricity consumption in the aluminum smelting process, the effects of increasing energy efficiency are considered as a parameter to capture the efforts of smelting industries increasing energy efficiency. | [2 - 10%] | [12] | |
| *Nickel* | Mining and concentration | • Mine Type | Mine type for this process is like the copper mining process | [Underground, Open-Cast] | [13,14] | 280 |
| | | • Ore grade | Ore grades follow a similar explanation like for the copper mining process. However, nickel ores have lower grades than copper ores. In most mining operations, the ores extracted contain various proportions of copper, nickel, and cobalt metals. | [1,5 – 3,5%] nickel content | [15] | |
| | | • Recovery Efficiency | Recovery efficiency follows the same thinking as explained in the copper mining and concentration process | [80 - 90%] | [6] | |
| | | • Carbon intensity of electricity mix | The consideration of this parameter follows similar explanation as other carbon intensities of electricity mix described above | [0.2 - 1.1] $kgCO_2e/kWh$ | [16], [5] | |
| | Smelting and Refining | • Recovery Efficiency | This parameter follows similar explanation as the recovery efficiency for copper smelting and aluminum electrolysis previously explained | [85 - 96%] | [6] | 160 |
| | | • Carbon Intensity of electricity mix | This parameter is the same as the one for copper smelting previously described. | [0.2 - 1.1] $kgCO_2e/kWh$ | [16],[5] | |
| | | • Energy Efficiency improvements | Energy efficiency in the smelting process here follows a similar explanation as energy efficiency in the aluminum smelting process previously explained. | [2 – 14%] | [17] | |
| *Manganese* | Mining and Concentration | • Ore grade | The explanation of manganese ore grade is as those of copper, nickel and bauxite ore grades previously explained. However, manganese has very high ore grades compared to copper and nickel. | [10 - 50%] | [18,19] | 119 |
| | | • Recovery Efficiency | This follows similar explanation as for copper and nickel mining and | [80 - 96%] | [20] | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | concentration previously explained. | | | |
| | | • Carbon efficiency of electricity mix | Follows similar explanations as the for the value chains explained above. | [0.2 - 1.4] kgCO2e/kWh | [21][5] | |
| | Smelting and Refining | • Recovery Efficiency | Follows similar explanation for the smelting and refining processes for the value chains previously explained. | [80 - 96%] | [18,20] | 145 |
| | | • Carbon Intensity of electricity mix | Similar description as for the other value chains previously described. | [0.2 - 1.4] kgCO2e/kWh | [21][5] | |
| *Graphite* | Natural graphite | • Ore grade | Natural graphite can exist in amorphous or flake forms. Amorphous graphite has higher ore grades by carbon content measured in 50 to 90% C content. However, amorphous carbon is not suitable for battery applications and is primarily used in refractories. The ore grades used in this study represent those of flake graphite which are practical for battery anode production. The flake graphite ore grade also determines the amount of energy and other inventories used in the mining and the beneficiation, as previously explained for the value chains above. | [7 -20%] | [22] | 119 |
| | | • Recovery Efficiency for mining and beneficiation | Recovery efficiency for the graphite value chain follow similar explanation as for those of other value chains already described above. | [80 - 96%] | [23] | |
| | | • Carbon intensity of electricity mix | Carbon intensity of electricity mix is used as parameter as explained in the previous value chains | [0.2 - 1.4] kgCO2e/kWh | [0.2 - 1.4] | |
| | Synthetic graphite | • Technology choice | The Acheson and the Castner furnaces have different energy requirements and configurations which leads to various impacts and are therefore modeled as parameter. | [Acheson, Castner] | [24] | 59 |
| | | • Recovery efficiency for synthetic graphite production | The recovery efficiency of synthetic graphite determines the inputs of pitch and coke and energy used for the baking and graphitization process which changes the overall impacts as already explained in the value chains previously described. | [80 - 96%] | [23][25] | |
| | | • Carbon intensity of electricity mix | Carbon intensity of electricity mix is used as parameter as explained in the previous value chains | [0.2 - 1.4] kgCO2e/kWh | [0.2 - 1.4] | |
| *Lithium Carbonate* | Spodumene Route | • Ore grade | Spodumene ore grades affect the amount of energy used in mining as well as the quantity of reactants used in the concentration process as | [0.58 – 2%] | [26] | 39 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | previously explained for the value chains above | | | |
| | | • Recovery Efficiency for spodumene mining and lithium carbonate production | This parameter characterizes the material recovery efficiency for both the mining and the concentration process. | [70 - 95%] | [27] | |
| | | • Carbon intensity of energy mix | Carbon intensity of electricity mix is used as parameter as explained in the previous value chains. | [0.2 - 1.0] $kgCO_2e/kWh$ | [21][5] | |
| | Brine Route | • Brine Quality | This parameter determines the conditions for brine evaporation. High quality means the brine is extracted using solar evaporation only, while for low quality, solar evaporation and additional heating provided by natural gas is used | [Low Quality, High Quality] | [28] | 20 |
| | | • Recovery Efficiency for brine extraction and lithium carbonate production | Like other recovery efficiencies for other value chains previously described. | [70 - 95%] | [27] | |

For consecutive unit processes in the value chain, the recovery efficiency $\eta$ is used in the foreground defined as:

$$Quantity\ of\ material_{process\ i} = \frac{element\ content\ in\ process_i}{element\ content\ in\ process_{i-1}} * \eta$$

Recovery efficiency signifies the degree to which the material produced is effectively recovered without losses (a measure of production or conversion losses). This means that at an $\eta$ of 100%, all the element contained in process i-1 is converted without any losses in process i. This applies to all the processes in the value chains described below.

In addition, for all value chains investigated, the carbon intensity of the mix for different geographic regions are evaluated from ecoinvent v3.2 [5] using the LCA activity browser tool [29].

## 1. Copper

### *1.1 Copper Mining and Concentration*

For the energy used in copper mining and beneficiation, we use ore-grade energy equations from references [1,30–32] as shown in Table S2.

The copper ore grade represents the copper element content in a quantity of material extracted expressed as a %.

Table S2: Energy used in copper mining and concentration

| | Energy Used | Explanation | Author |
|---|---|---|---|
| *Total Mining and Concentration Energy* | $15.697 * G^{-0,573}$ | G is ore grade | Northey et al.(2013) |
| | $15.63 * G^{-0,529}$ | | Kuipers et al. (2018) |
| | $23.81 * G^{-0,529}$ | | Valero and Valero (2014) |
| | $\alpha + \gamma . D + \frac{\beta}{G}$ | D is mine depth in metres | Koppelaar and Koppelaar (2016) |
| | | G is ore grade | |
| | | $\alpha, \gamma, \beta$ are fitting parameters | |
| *Diesel* | $1.564 - 0.00073 * D + \frac{0.0064}{G}$ | D is depth in meters and G is ore grade in % | |
| *Electricity* | $1.569 + 0.00066 * D + \frac{0.0067}{G}$ | | |

Other inventories for the mining and concentration phase relate to the ore grade following regressed relationships from ecoinvent v3.2. These relationships are of the form $A.G^{-\alpha}$; where A and $\alpha$ are fitting coefficients and G is the ore grade.

### *1.2 Copper Smelting*

Data for energy used in copper smelting is taken from Coursol et al. [7] as illustrated in Table S3.

Table S3: Energy requirements for Copper Smelting

| Smelting Route | Electric Energy(kWh/kg ) | Fossil Fuel(MJ/kg ) |
|---|---|---|
| Flash | 0,979 | 1,518 |
| Isasmelt | 0,729 | 4,175 |
| KHCalcineR | 0,196 | 15,9 |
| KHMitsubishi | 0,623 | 9,3 |
| KHNoranda | 0,817 | 5,22 |
| KHOutokumpuF | 0,675 | 6,76 |
| Mitsubishi | 0,898 | 2,498 |
| Noranda_ElTeniete | 1,065 | 2,657 |

### *1.3 Copper Electricity Mix Intensity*

Electricity mix for the 9 regions are used for the background process parameters for copper simulation as shown in Table S4.

Table S4: Electricity mix for Copper Value Chain

<table>
<tr><th></th><th>RSA</th><th>RAF</th><th>RND</th><th>RNA</th><th>Canada</th><th>European Average</th><th>China</th><th>Australia</th><th>Russia</th></tr>
<tr><td>Hydropower electricity</td><td>35,2 %</td><td>30,7 %</td><td>34,6 %</td><td colspan="6" rowspan="8">Ecoinvent V3.2 background processes</td></tr>
<tr><td>Natural gas electricity</td><td>25,6 %</td><td>0,0 %</td><td>2,0 %</td></tr>
<tr><td>Coal electricity</td><td>20,3 %</td><td>62,3 %</td><td>5,0 %</td></tr>
<tr><td>Nuclear electricity</td><td>1,3 %</td><td>3,7 %</td><td>40,5 %</td></tr>
<tr><td>oil electricity</td><td>4,3 %</td><td>1,7 %</td><td>0,3 %</td></tr>
<tr><td>Wind power</td><td>4,7 %</td><td>1,3 %</td><td>10,3 %</td></tr>
<tr><td>Biofuels/waste</td><td>6,1 %</td><td>0,1 %</td><td>7,2 %</td></tr>
<tr><td>Solar PV</td><td>2,5 %</td><td>0,2 %</td><td>0,3 %</td></tr>
</table>

**RSA:** South America (Argentina, Bolivia, Chile, Brazil, Colombia, Mexico, Peru)
**RAF:** Africa (Zambia, Congo, South Africa)
**RND:** Nordics (Sweden, Finland)
**RNA:** North America (excluding Canada)

To ensure that we allocate an electricity mix that matches the production percentages within a region, the percentages of electricity mix for the regions RSA, RAF, RND, and RNA in Table S4 represent the weighted average of the total quantity of copper produced and the electricity mix for each country within the region. This mix is calculated as follows:

$$Regional\ electricity\ of\ mix\ for\ energy\ technology_i = \frac{\sum_1^n \left(\frac{copper\ production_j}{\sum_1^n copper\ production}\right) * country\ generation\ of\ energy\ technology_i}{Total\ regional\ generation}$$

Where n is the number of production countries and $i$ is the generation technology.

## 2. Aluminum value Chain

*2.1 Bauxite Mining*

The total quantity of bauxite mined per unit alumina produced is taken from Ter Weer [33] and as expressed as :

$$bauxite\ mined = \frac{1}{\eta_{baux} * B} * \frac{1}{\alpha * \eta_{alum}} * (1 + e)$$

$\eta_{baux}$: Mining recovery (dry basis).

$B$: Beneficiation(also referred to as "ore concentration") recovery, % (dry basis). For a project not applying beneficiation, B is considered to be 100%.

$\alpha$: Percentage available alumina, otherwise called bauxite quality or bauxite ore grade, % (dry basis).

$\eta_{alum}$: Alumina recovery efficiency %.

$e$: Overburden/bauxite ratio, representing the total ground to be dug before reaching a bauxite resource.

*2.2 Alumina Processing*

For alumina processing by the Bayer process, we assume that the bauxite resource quality will also affect the quantity of materials and energy used to produced alumina. As such, lower bauxite quality will require more caustic soda, material inventory, and energy. However, due to the complexity in modelling this relationship, we adopt a mathematical approach that permits us to scale the materials and energy as a function of the bauxite quality. We begin with a global bauxite resource average of 41%, which translates into approximately 2.5 kg of bauxite per kg of alumina produced and corresponds to the base inventory adopted. We define a factor $k$ (allows for the proportionate scaling of the base inventory), which is the ratio of the quantity of bauxite used in the Bayer process at a given ore grade ($\alpha$) to the bauxite used at 41% alumina content.

$$k = \frac{bauxite\ quantity\ at\ \alpha\ grade}{bauxite\ quantity\ at\ 41\%\ ore\ grade}$$

$$k = \frac{\frac{1}{\eta_{baux} * B} * \frac{1}{\alpha * \eta_{alum}} * (1 + e)}{2.5}$$

For simplicity, we assume there is no beneficiation (B=100%). Therefore, k can be expressed as follows

$$k = \frac{\frac{1}{\eta_{baux}} * \frac{1}{\alpha * \eta_{alum}} * (1 + e)}{2.5}$$

*2.3 Aluminum Smelting*

For aluminum smelting, we use the energy for prebake and Søderberg technologies taken for International Aluminum Institute [11,34], as shown in Figure S1. In addition, we include the energy improvement efficiencies, which captures reduction in energy used for the electrolysis phase.

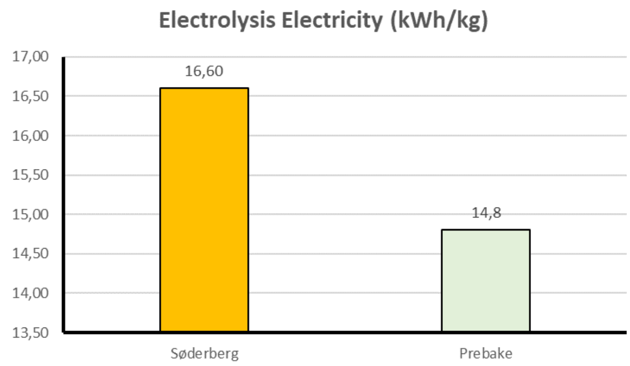


Figure S1: Electricity use for aluminum electrolysis

If $\gamma$ is the energy improvement efficiency (%), the new energy value becomes:

$$E_{paramaterized} = (1 - \gamma)E_{base\ inventory}$$

*2.4 Aluminum Electricity Mix*

The set of values of electricity mix for aluminum production is from ecoinvent v3.2, however, we add a designed mix specifically for the Nordic region as shown in Table S5.

Table S5: Electricity mix for aluminum Value Chain

| | RND | EU 27 &EFTA | IAI 1 | IAI 2 | IAI 3 | IAI 4 & 5 | RUS/RER | CNA | OCE | GCC | CAN |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Hydropower electricity | 90,2 % | Ecoinvent v3.2 background processes | | | | | | | | | |
| Natural gas electricity | 1,6 % | | | | | | | | | | |
| Coal electricity | 0,2 % | | | | | | | | | | |
| Nuclear electricity | 3,9 % | | | | | | | | | | |
| oil electricity | 0,0 % | | | | | | | | | | |
| Wind power | 3,4 % | | | | | | | | | | |
| Biofuels/waste | 0,6 % | | | | | | | | | | |
| Solar PV | 0,0 % | | | | | | | | | | |

RND: Nordic Region

Description of the regional electricity mix classification (for the ecoinvent v3.2 background processes) in Table S5 can be found on the https://geography.ecoinvent.org/

## 3. Manganese Value Chain

*3.1 Manganese Mining and Concentration*

The energy for mining and concentrating manganese ore is taken from reference [19] given by the formula:

$$E = 143.7G^{-1}$$

Where G is the ore grade

The energy E is split into diesel and electricity by using ratios from ecoinvent v3.2, which yields 25%

for electricity and 75% for diesel.

To further parameterize the mining and ore concentration phase, we assume that all the materials used for this process stage will relate to the ore grade following an inverse relationship of the form

$$material\ inventory = A.G^{-1}$$

Where G is the ore grade and A is a fitting coefficient.

Based on ecoinvent data of G=35.7%, we proceed to calculate the value of A for each material in the inventory list. This permits us to deduce a generic following relating ore grade and material inventory for the mining and concentration stage of the manganese value chain.

*3.2 Production of electrolytic manganese metal (EMM)*

Apart from a recovery efficiency applied to this phase, there is no change in the inventories. Inventories are taken from ecoinvent v3.2.

*3.3 Electricity mix for Manganese*

The range of the mix for manganese value chain is taken to represent that of major producing countries as shown in Table S6.

Table S6: Electricity mix for Manganese Value Chain

| Australia | Brazil | Canada | China | India | France | Japan | Norway |
|---|---|---|---|---|---|---|---|
| Ecoinvent V3.2 electricity mix (medium voltage) | | | | | | | |

## 4. Nickel Value Chain

*4.1 Nickel Mining and Concentration*

The energy used to mine and concentrate nickel ore is expressed as a function of the ore grade and mine type according relationship calibrated with data from references [6,35] as shown in Table S7. Similarly, the quantity of explosives use to mine a ton of ore is taken from reference [35] which calculates this at 1.1kg of explosive per kg of ore mined. We transform this into a relationship to include ore grade as shown in Table S7:

Table S7: Energy and explosive requirements for Nickel Mining

| | Underground Mine | Open Cast |
|---|---|---|
| Diesel (MJ/kg Ni) | $6.6 * G^{-1}$ | $14.1 * G^{-1}$ |
| Electricity (kWh/kg Ni) | $9.6 * G^{-1}$ | $7.2 * G^{-1}$ |
| Explosives (kg) | $0.11 * G^{-1}$ | |

*4.2 Nickel Matte and Nickel Refining*

All the inventories for nickel matte are taken from reference [13] except the energy used in smelting which is the average of the INCO and Fortaleza smelters taken from reference [35]. Inventories for nickel refining are taken from [13] except the energy use which is taken from [6].

We also include the effect of efficiency improvements ( $\gamma$ in % ) in energy used as :

$$E_{parameterize} = (1-\gamma)E_{base\ inventory}$$

*4.3 Electricity mix for Nickel*

The range of the electricity mix for nickel value chain is taken to represent that of major producing countries as shown in Table S8.

Table S8: Electricity mix for Nickel Value Chain

| Australia | Brazil | Canada | China | Europe | Finland | Russia | South Africa | China | Europe | Japan |
|---|---|---|---|---|---|---|---|---|---|---|
| Ecoinvent V3.2 electricity mix (medium voltage) | | | | | | | | | | |

**5. Graphite**

*5.1 Natural Graphite*

For natural graphite, the energy used for mining and beneficiation is taken from [36]. We adopt the generic energy-ore equation of the form $E = A.x^{-0.5}$ , which is taken from [32]. Using an ore grade of 6.24% C content taken from same reference, we calibrate the fitting parameters A for diesel, electricity, and natural gas. The energy requirements are displayed in Table S9.

Table S9: Energy requirements for natural graphite

| | |
|---|---|
| Diesel (MJ/kg) | $26.1 * G^{-0.5}$ |
| Natural gas (MJ/kg) | $6.118 * G^{-0.5}$ |
| Electricity (kWh/kg) | $2.67 * G^{-0.5}$ |

*5.2 Synthetic Graphite*

Synthetic graphite is modeled with inventory from reference [25], we distinctly model the graphitization energy used for Castner and Acheson furnaces based on lower and upper limit data from [24].

Table S10: Energy requirements for Castner and Acheson furnaces

| | Lower Limit (kWh/kg) | Upper Limit (kWh/kg) |
|---|---|---|
| Castner Furnace | 2 | 3 |
| Acheson Furnace | 3 | 4 |

The upper limits of the energy used in graphitization may increase than the stated values in Table S10 as suggested by reference [37], but due to lack of high resolution data, we use these numbers from [24,25] as a good approximation for our parametric modelling.

For synthetic graphite, we include the conversion efficiency $\eta$ from reference [25], which measures the efficiency in converting petroleum coke and coal tar pitch to synthesized graphite as.

$$\eta = \frac{quantity\ of\ graphite\ synthesized}{coal\ tar\ input + \ petrol\ coke\ input}$$

*5.3 Electricity mix for Graphite*

The carbon intensity of the mix for graphite electricity regions are shown in Table S11.

Table S11: Electricity mix for graphite value chain

| Canada | China | India | Russia | Norway | Ukraine | Brazil |
|---|---|---|---|---|---|---|
| Ecoinvent V3.2 electricity mix (medium voltage) | | | | | | |

**6. Lithium Carbonate**

*6.1 Lithium carbonate from spodumene*

The relationship between ore grade (G) and energy used (E) for mining and concentration of spodumene is taken from [32], given by

$$E = 3.58. G^{-0.5}$$

From the percentage of diesel and electricity used in mining and concentration from [28], we split the energy (E) used for mining and concentration of spodumene which yields 35% electricity and 65% diesel.

We further base our material inventory assumptions for mining and concentration of spodumene on those from reference [28] , which uses an inverse proportion to scale material inventory to the ore grades. From reference [28], when the ore grade (Lithium content) increased from 0.58% to 1.86% ( a factor of 3.21), the inventory reduced by approximately the same factor. We use the inventory for an ore grade of 0.58% as the base inventory and scale other material inventories to this base inventory.

The scaling factor k for each inventory element for mining and concentration is thus calculated by:

$$k = \frac{0.58\%}{Ore\ grade\ (G\ in\ \%)}$$

The base inventory of carbonation of spodumene to lithium carbonate from reference [28] is only modified by including a recovery efficiency in the carbonation process.

*6.2 Lithium carbonate from Brines*

The base inventory for "high grade" brine is taken from [28]. For "low grade" brine, we use the inventory from [38] which includes the extra energy from natural gas to heat up the brines. Recovery efficiency is also included in the brine extraction and carbonation process. The electricity mix for the different countries investigated are shown in Table S12.

Table S12: Electricity mix for Lithium Carbonate

| Spodumene | | | | | Brine | | |
|---|---|---|---|---|---|---|---|
| Australia | China | Brazil | Portugal | Finland | Chile | Bolivia | Argentina |
| Ecoinvent V3.2 electricity mix (medium voltage) | | | | | | | |

## References


1. Koppelaar, R.H.E.M.; Koppelaar, H. The Ore Grade and Depth Influence on Copper Energy Inputs. *Biophys. Econ. Resour. Qual.* **2016**, *1*, 1–16.
2. Basov, V. The World's Top 10 Highest-Grade Copper Mines Available online: https://www.mining.com/the-worlds-top-10-highest-grade-copper-mines/ (accessed on 10 October 2020).
3. Azizi, A.; Masdarian, M.; Hassanzadeh, A.; Bahri, Z.; Niedoba, T.; Surowiak, A. Parametric Optimization in Rougher Flotation Performance of a Sulfidized Mixed Copper Ore. *Minerals* **2020**, *10*, 1–19.
4. Brininstool, M.; Flanagan, D.M. Copper. In *USGS - 2015 Minerals Yearbook*; 2017; p. 30.
5. Wernet, G.; Bauer, C.; Steubing, B.; Reinhard, J.; Moreno-Ruiz, E.; Weidema, B. The Ecoinvent Database Version 3 (Part I): Overview and Methodology. *Int. J. Life Cycle Assess.* **2016**, *21*, 1218–1230.
6. Wei, W.; Samuelsson, P.B.; Tilliander, A.; Gyllenram, R.; Jönsson, P.G. Energy Consumption and Greenhouse Gas Emissions of Nickel Products. *Energies* **2020**, *13*, 5664.
7. Coursol, P.; Mackey, P.J. Energy Consumption in Copper Sulphide Smelting. In Proceedings of the Proceedings of Copper 2010, June 6-10; Hamburg, Germany, 2010; pp. 649–668.
8. Wagner, C.; IAI; BAC Sustainable bauxite mining - A global perspective. In *Essential Readings in Light Metals*; Donaldson, D., Benny Raahauge, Eds.; Springer, Cham, 2017; Vol. 1, pp. 54–59 ISBN 9783319481760.
9. Kaußen, F.M.; Friedrich, B. Methods for Alkaline Recovery of Aluminum from Bauxite Residue. *J. Sustain. Metall.* **2016**, *2*, 353–364.
10. Bray, E.L. Bauxite and Alumina. In *USGS - 2017 Minerals Yearbook*; 2020; p. 14.
11. International Aluminum Institute *Life Cycle Inventory Data and Environmental Metrics for the Primary Aluminum Industry*; 2017;
12. Haraldsson, J.; Johansson, M.T. Review of Measures for Improved Energy Efficiency in Production-Related Processes in the Aluminum Industry – From Electrolysis to Recycling. *Renew. Sustain. Energy Rev.* **2018**, *93*, 525–548.
13. Boonzaier, S.; Gediga, J. *Life Cycle Assessment of Nickel Products*; 2020;
14. Gediga, J.; Sandilands, J.; Roomanay, N.; Boonzaier, S. *Life Cycle Assessment of Nickel Products.*; Leinfelden – Echterdingen, 2015;
15. Norgate, T.; Jahanshahi, S. Energy and Greenhouse Gas Implications of Deteriorating Quality Ore Reserves. In Proceedings of the 5th Australian Conference on Life Cycle Assessment, Melbourne, 22-24 November 2006; Melbourne, 2006; pp. 1–10.
16. McRae, M.E. Nickel. In *2016 Minerals Yearbook*; 2016; pp. 42.1-42.15.
17. Kulczycka, J.; Lelek, Ł.; Lewandowska, A.; Wirth, H.; Bergesen, J.D. Environmental Impacts of Energy-Efficient Pyrometallurgical Copper Smelting Technologies: The Consequences of Technological Changes from 2010 to 2050. *J. Ind. Ecol.* **2016**, *20*, 304–316.
18. Singh, V.; Chakraborty, T.; Tripathy, S.K. A Review of Low Grade Manganese Ore Upgradation Processes. *Miner. Process. Extr. Metall. Rev.* **2020**, *41*, 417–438.
19. Valero, A.; Valero, A.; Domínguez, A. Trends of Exergy Costs and Ore Grade in Global Mining. *Soc. Mining, Metall. Explor.* **2011**, 301–315.
20. Westfall, L.A.; Cramer, M.H.; Davourie, J.; Mcgough, D.; Ali, M. Life-Cycle Impacts and Costs of Manganese Losses and Recovery during Ferromanganese Production. In Proceedings of the The Fourteenth International Ferroalloys Congress; 2015; pp. 626–635.
21. USGS Mineral Commodity Summaries Available online: https://pubs.er.usgs.gov/publication/mcs2021 (accessed on 1 January 2021).

22. Robinson, G.R.; Jr. Jane M. Hammarstrom; Olson, D.W. Graphite. In *Critical Mineral Resources of the United States — Economic and Environmental Geology and Prospects for Future Supply*; Klaus J. Schulz, John H. DeYoung, Jr., Robert R. Seal II, and D.C.B., Ed.; U.S. Geological Survey, 2017.
23. Jara, A.D.; Betemariam, A.; Woldetinsae, G.; Yong, J. International Journal of Mining Science and Technology Purification , Application and Current Market Trend of Natural Graphite : A Review. *Int. J. Min. Sci. Technol.* **2019**, *29*, 671–689.
24. Jäger, H.; Frohs, W.; Banek, M.; Christ, M.; Daimer, J.; Fendt, F.; Friedrich, C.; Gojny, F.; Hiltmann, F.; Meyer zu Reckendorf, R.; et al. Industrial Carbons. In *Ullmann's Encyclopedia of Industrial Chemistry*; Wiley-VCH Verlag GmbH & Co: Weinheim, 2010; Vol. 6, pp. 732–770.
25. Dunn, J.B.; James, C.; Gaines, L.; Gallagher, K.; Dai, Q.; Kelly, J.C. *Material and Energy Flows in the Production of Cathode and Anode Materials for Lithium Ion Batteries*; 2015;
26. SGS *Hard Rock Lithium Processing*; 2010;
27. Yaksic, A.; Tilton, J.E. Using the Cumulative Availability Curve to Assess the Threat of Mineral Depletion: The Case of Lithium. *Resour. Policy* **2009**, *34*, 185–194.
28. Stamp, A.; Lang, D.J.; Wäger, P.A. Environmental Impacts of a Transition toward E-Mobility: The Present and Future Role of Lithium Carbonate Production. *J. Clean. Prod.* **2012**, *23*, 104–112.
29. Steubing, B.; de Koning, D.; Haas, A.; Mutel, C.L. The Activity Browser — An Open Source LCA Software Building on Top of the Brightway Framework. *Softw. Impacts* **2020**, *3*, 100012.
30. Kuipers, K.J.J.; van Oers, L.F.C.M.; Verboon, M.; van der Voet, E. Assessing Environmental Implications Associated with Global Copper Demand and Supply Scenarios from 2010 to 2050. *Glob. Environ. Chang.* **2018**, *49*, 106–115.
31. Northey, S.; Haque, N.; Mudd, G. Using Sustainability Reporting to Assess the Environmental Footprint of Copper Mining. *J. Clean. Prod.* **2013**, *40*, 118–128.
32. Valero, A.; Valero, A. The exergy replacement cost of Mineral Wealth. In *Thanatia: The Destiny Of The Earth's Mineral Resources- A Thermodynamic Cradle-to-cradle Assessment*; World Scientific Publishing Co.Pte.Ltd, 2014; pp. 351–367 ISBN 9814273937.
33. Ter Weer, P.H. Sustainability and Bauxite Deposits. In *Light Metals 2014*; John Grandfield, Ed.; Springer, Cham, 2014; pp. 149–154 ISBN 978-3-319-48143-2.
34. Nunez, P.; Jones, S. Cradle to Gate: Life Cycle Impact of Primary Aluminum Production. *Int. J. Life Cycle Assess.* **2016**, *21*, 1594–1604.
35. Eckelman, M.J. Facility-Level Energy and Greenhouse Gas Life-Cycle Assessment of the Global Nickel Industry. *Resour. Conserv. Recycl.* **2010**, *54*, 256–266.
36. Zhang, Q.Q.; Gong, X.Z.; Meng, X.C. Environment Impact Analysis of Natural Graphite Anode Material Production. *Mater. Sci. Forum* **2018**, *913*, 1011–1017.
37. Minviro *Battery Grade Graphite. It's Not All about Carbon.*; London, 2020;
38. Ambrose, H.; Kendall, A. Understanding the Future of Lithium: Part 2, Temporally and Spatially Resolved Life-Cycle Assessment Modeling. *J. Ind. Ecol.* **2020**, *24*, 90–100.