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Investigation of the primary production routes of nickel and cobalt products used for Li-ion batteries

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ABSTRACT

Lithium-ion batteries are crucial components of electric vehicles with respect to the technical performance of the vehicles and the environmental impacts of the vehicle life cycle. Life cycle assessment (LCA) studies of lithium-ion batteries have shown that the nature of the active cathode materials significantly influences the environmental impacts of the battery. Notably, cathode materials based on nickel and cobalt, like nickel manganese cobalt (NMC), nickel cobalt aluminum (NCA) and lithium cobalt oxide (LCO), have been identified to be associated with largest environmental burdens. The main contribution to these environmental impacts comes from upstream processes related to the extraction and beneficiation of nickel and cobalt. However, a variety of production routes originating from different ore types for both metals exists; they may vary considerably with respect to the environmental impacts due to technology and the location of production sites. Against this background, we investigated the current production systems of nickel and cobalt products as well as possible future developments based on extensive literature research and expert interviews. We identified those specific nickel and cobalt products which are used for the production of lithium-ion batteries and the production routes they originate from. We compiled process chains for the most frequent technology routes, from which we identified production sites and interconnecting product flows. In addition, we derived global flow charts for the respective nickel and cobalt products. Based on static Material Flow Analysis (MFA), we finally derived the current production shares of the routes of lithium-ion batteries. We discussed our results notably with respect to economic dynamics including possible future shifts in the shares of global production. Our results complement existing studies with in-depth information on up-stream processes of nickel and cobalt production and show global locations of production sites related to the different stages of production processes which provides basic information for an improved environmental impact assessment.

1. Introduction

Electric and hybrid electric vehicles based on lithium-ion batteries[1] are attributed a high potential to reduce the environmental impacts of traffic. In the past few years, many studies based on life cycle assessment (LCA) methodology that quantify the environmental impacts of (a) the full life cycle of electric vehicles including their batteries (Amarakoon et al., 2013; Hawkins et al., 2012; Majeau-Bettez et al., 2011; Notter et al., 2010; Samaras and Meisterling, 2008; Zackrisson et al., 2010) and (b) recycling processes for such batteries (Buchert et al., 2011; Dewulf et al., 2011; Dunn et al., 2015a) have been published. While the car's use phase contribution to the overall life cycle impacts is usually the most significant, battery manufacturing accounts for 5–15% of the impacts of most impact categories, including global warming potential and primary energy demand (Amarakoon et al., 2013; Hawkins et al., 2012; Notter et al., 2010; Samaras and Meisterling, 2008). An important part of the battery is the active cathode material, which mainly consists of cobalt, manganese, nickel, and phosphate. Primary extraction and beneficiation of these metals are responsible for 10–40% of most impacts related to battery manufacturing (Amarakoon et al., 2013; Notter et al., 2010). Studies show that one of the main benefits of future large scale recycling processes stems from the avoided burdens related to primary/virgin production of the cathode metals (Buchert et al., 2011; Dewulf et al., 2011; Dunn et al., 2015a; Yazicioglu and Tytgat, 2011). Consequently,

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[1] Subsequently, Lithium-ion batteries used for electric or hybrid electric vehicles are abbreviated as "batteries".

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information on the primary/virgin extraction is crucial for assessing whether the efforts of dismantling and recycling the batteries are outweighed by the benefits.

Promising battery chemistries that are currently applied include LCO, LMO, LFP, NMC and NCA. Three out of these contain nickel or cobalt. It was recently shown that the environmental impacts related to battery manufacturing are especially high for batteries that contain nickel and cobalt compared to other battery designs, due to the upstream recovery of primary metals (Dunn et al., 2015a; Gaines and Dunn, 2015; Majeau-Bettez et al., 2011). Similarly, the environmental burdens that can be avoided by battery recycling are larger for nickel and cobalt containing batteries. For the SO_x emissions of a battery's full life cycle, i.e. including its use phase, Dunn et al. (2015a) have shown that primary production of cathode metals may make up 30% of the life cycle emissions if nickel and cobalt are contained, while the share is only around 5% for LMO battery chemistry.

However, the appropriate inclusion of the primary production of nickel and cobalt into the environmental assessments of battery manufacturing and recycling processes is constrained by several factors. First, an extraordinary high variety of nickel and cobalt products exist.[2] Depending on their metal content and further physical and chemical properties, they are suitable for differing downstream manufacturing purposes. One crucial question that arises during modeling and in conducting LCA of batteries is how to determine the kind of nickel and cobalt products that serve as input feedstock material. Current compilations of LCI datasets for nickel and cobalt are given e.g. by UNEP (2013). Included are the respective datasets of LCA specific databases like ecoinvent (Classen et al., 2009; Hischier, 2007) or GaBi (PE International, 2011) as well as further scientific studies performed or commissioned by the Nickel Institute (Ecobalance, 2000) and the CSIRO[3] (Norgate and Rankin, 2000). None of the datasets is explicitly designed for usage in an LCA study of batteries. Furthermore, the datasets listed are based on differing functional units: while some are valid for a specific nickel and cobalt product, like nickel class I, other datasets aggregate their results to a global and unspecified mix.

Second, both the nickel and cobalt industry have seen major changes in the recent past. Nickel is won of either sulfide or laterite ores. While the sulfur content of sulfide ores implies a lower amount of energy needed to heat the ores, the high moisture content of laterites means the opposite (Mudd, 2010). Energy consumption to process laterite ores is reported to be 3–5 times higher than for sulfide ores (Mudd, 2010; Dunn et al., 2015a). In the past few years, more and more laterite ores have been processed and it is believed that this trend will continue in the foreseeable future (Kuck, 2013; Lennon, 2013).

Cobalt is mostly produced as a co-product of the copper or the nickel industry (CDI, 2013b). After dominating the global cobalt industry for most part of the twentieth century until there was a significant drop in cobalt output between 1986 and 1995, the Democratic Republic of the Congo (DRC) has regained its market shares since the early 2000s (Fisher, 2011; Pawlik et al., 2012). Similar to the trend towards nickel laterites, experts agree that the DRC will further increase their influence on the cobalt industry within the next few years (Shedd, 2013b; Bedder, 2013). This is of particular significance because the ores situated in the DRC are processed in a different manner from other cobalt containing ores which also suggests changing environmental impacts.

Third, the LCI-datasets for primary nickel and cobalt that are applied in current LCA-studies on battery manufacturing and recycling partly show significantly diverging numbers. For instance, the global warming potential of cobalt indicated by PE International (2011) and Classen et al. (2009) varies by a factor of 10, which naturally has a strong impact on the overall greenhouse gas balance of a battery recycling process as shown by Buchert et al. (2011). In addition, since many of the LCI-datasets were compiled more than ten years ago, they fail to reflect the dynamics in terms of the production routes mentioned above (Keoleian et al., 2012). Thus, important production processes are disregarded and an outdated composition of existing primary production routes is assumed. For instance, the LCA-studies of Majeau-Bettez et al. (2011) and Dewulf et al. (2011) used LCI-datasets for nickel and cobalt that are largely based on a study with the reference year 1994.

Finally, the production of nickel and cobalt is globally distributed. For the determination of environmental impacts related to the production processes, knowledge on the actual location of the production site may be important.

Against this background, an in-depth investigation of the current prevailing methods applied in the primary production of nickel and cobalt has been frequently claimed by scientists in order to improve the reliability and scientific robustness of the environmental assessments of battery manufacturing and recycling (Amarakoon et al., 2013; Dunn et al., 2015b; Gaines and Dunn, 2015). The upstream processes related to other materials such as aluminum also play a major role in the environmental impacts of battery manufacturing. However, less dynamics in terms of production routes and related environmental impacts have been reported. Also, product diversity is especially high in the case of nickel and cobalt. Finally, scientific efforts to provide reliable background data on the environmental impacts related to aluminum production in the last couple of years have been much higher compared to the efforts directed at cobalt (UNEP, 2013).

For these reasons, the research targets of our study include:

1 Investigation of the current production systems of nickel and cobalt products in order to

- identify which specific nickel and cobalt products are used for production of Lithium-ion batteries and which primary production routes these products originate from

2 Compilation of the process chains for these specific products in order to

- Identify sites and interconnecting product flows
- Identify environmental hotspots of production chains that are not considered in the LCI-datasets that are most widely applied

3 Development of global flow charts for the production of those specific nickel and cobalt products in order to

- Localize nickel and cobalt production processes and
- Compile production data

4 Display a static Material Flow Analysis (MFA) in order to

- Identify losses and validate findings of the global flow charts
- Derive production shares of the routes.

[2] The expression nickel or cobalt "product" is somewhat misleading because usually, the refined products serve as an input material for further industrial production processes (e.g. nickel products are used as an input material for the production of stainless steel). Subsequently, we will use the expression anyway because it corresponds to earlier publications on the topic (Norgate and Jahanshahi, 2011; Eckelman, 2010; Classen et al., 2009; Baylis, 2012) and it would cause confusion to call them "intermediate products" since during the production process other precipitates are termed "intermediates".

[3] Commonwealth Scientific and Industrial Research Organization.