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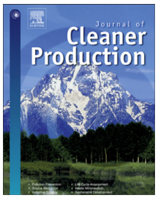

Supply risks associated with lithium-ion battery materials

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ABSTRACT

One possibility for electrification of road transport consists of battery electric vehicles in combination with carbon-free sources of electricity. It is highly likely that lithium-ion batteries will provide the basis for this development. In the present paper, we use a recently developed, semi-quantitative assessment scheme to evaluate the relative supply risks associated with the elements used in the functional materials of six different lithium-ion battery types. Eleven different indicators in four supply risk categories are applied to each element; the weighting of the indicators is determined by external experts within the framework of an Analytic Hierarchy Process. The range of supply risk values on the elemental level is distinctly narrower than in our previous work on photovoltaic materials. The highest values are obtained for lithium and cobalt; the lowest for aluminium and titanium. Copper, iron, nickel, carbon (graphite), manganese and phosphorous form the middle group. We then carry out the assessment of the six battery types, to give comparative supply risks at the technology level. For this purpose the elemental supply risk values are aggregated using four different methods. Due to the small spread at the elemental level the supply risk values in all four aggregation methods also lie in a narrow range. Removing lithium, aluminium and phosphorous from the analysis, which are present in all types of battery, improves the situation. For aggregation with the simple arithmetic mean, an uncertainty analysis shows that only lithium-iron phosphate has a measurably lower supply risk compared to the other battery types. For the "cost-share" aggregation using seven elements, lithium cobalt oxide has a substantially higher supply risk than most other types.

1. Introduction

On account of its high specific energy, relatively low cost and long cycle life, the lithium-ion battery in its various forms has found many applications in the last two decades (Eisler, 2016; Goodenough and Park, 2013; Tarascon and Armand, 2001; Yoshino, 2012). These range from consumer electronics, computer notebooks, mobile phones and power tools to electric vehicles and even stationary grid storage. As has been recently pointed out (Blomgren, 2017; Hu et al., 2017; Kim et al., 2012), installed capacity is expected to grow rapidly in future due to performance improvements and sinking costs. Electric vehicles and grid storage are likely to be particularly strong growth areas (Hu et al., 2017). The reason is to be found in the efforts currently being made internationally to limit greenhouse gas (GHG) emissions. The main goal of the climate agreement concluded in 2015 in Paris (COP21) is to hold global warming to "well below 2 °C above pre-industrial levels" and, moreover, "to pursue efforts to limit the increase to 1.5 °C" (United Nations/Framework Convention on Climate Change, 2015). This can only be achieved if sometime in the second half of this century net GHG emissions are reduced to zero globally. Since road transport alone is currently responsible for about 20% of GHG emissions in, for example, the EU (Eurostat, 2016a), one obvious route is the electrification of this sector in combination with low carbon, or carbon-free, sources of electrical energy. In the second area mentioned, namely, stationary grid storage, Li-ion battery technology may be used increasingly to combat mainly short-term intermittency problems associated with renewable energy sources (Arbabzadeh et al., 2016). The present paper is largely motivated by the current discussion on the possible, foreseeable material requirements for electrification in the transport sector and grid storage as well as on the concomitant supply risks associated with

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these metals and minerals. The supply risks require early identification and may also need international action for their mitigation (Ali et al., 2017). Using a recently developed procedure the paper compares in a semi-quantitative way the supply risks associated not only with the key metals and minerals, but also with the technologies used in Li-ion batteries.

The solution for the transport sector that has received the most attention is the battery electric vehicle (BEV). Other battery solutions, such as the hybrid or plug-in hybrid electric vehicle, are unlikely to satisfy the strict emission requirements likely to become obligatory in the course of the next few decades (e.g. Hu et al., 2016; Marina Martinez et al., 2017). (So-called extended range electric vehicles might satisfy the requirements, if the supplementary liquid fuel derives from renewable sources.) If a complete switch to BEVs were to occur in the next two or three decades, then it is likely, at least for cars and vans, that they would also be powered by lithium-ion batteries. In the longer term, it is possible that other battery types, such as lithium-sulphur or lithium-oxygen, will by then have more favourable characteristics, such as higher specific energy and/or lower costs. The other alternative for the power train in an electric vehicle is the hydrogen-powered PEM fuel cell, where PEM stands for “proton exchange membrane” (Gröger et al., 2015). In this case there are also material problems: not only the fuel cell itself, but also the electrolyser for producing the hydrogen fuel from water, is likely to require electrodes composed of platinum group metals. There are considerable supply risks associated with these materials; their costs are also considered rather high, at least in comparison with lithium and the transition metals used in Li-ion batteries. On the other hand, fuel cell electric vehicles (FCEVs) in the category “mid-size family car” already have, unlike BEVs, a driving range of ~500 km using hydrogen stored in high pressure tanks. Which of the two power train systems will ultimately prevail, may depend on public acceptance. The reader is referred to the review article by Gröger et al. (2015) for a fuller discussion. A glance at a recent document of the European Commission shows that detailed plans are being laid, and incentives planned, in order to promote the introduction in Europe of low and zero emission vehicles on the timescale indicated above (European Commission, 2016).

The recent increase in the contribution of renewable energy to electrical supply, at least in Europe (2014: 27.5% of gross electricity consumption (Eurostat, 2016b)), derives mainly from the installation of photovoltaic modules and wind turbines. These intermittent sources give rise, however, to an increased demand for electricity storage capability that will inevitably increase in coming years. This will occur at various levels. Firstly, there is the need for balancing, or “smoothing” stochastic fluctuations on the scale of seconds and minutes which come about not only because of intermittency in supply but also because of consumer behaviour. Secondly, fluctuations occur inevitably on the timescale of a day, or of a few days, for example, the differences between night and day, but also as a result of extended periods of weather not conducive to electricity generation. Combatting fluctuations of this sort is sometimes referred to as “load levelling” or “peak shaving”. Thirdly, there are fluctuations on a seasonal level, i.e. on the scale of months, in particular differences between summer and winter. Because of the huge amounts of energy that would be required for coping with seasonal variations, it is generally agreed that pumped hydroelectric storage (PHS) is probably the only viable solution. At present, battery-based solutions in connection with the first two categories represent less than 1% of the total installed storage capacity in Europe (Geth et al., 2015). At the time of writing, it is not possible to estimate the likelihood of battery-based storage playing a major role in the grid of the future.

Nevertheless, from our present vantage point, it is clear that the decarbonisation of transport can only occur through the large-scale introduction of BEVs or FCEVs. Whereas it is unlikely that both technology approaches will be applied in parallel because of the high infrastructure costs, the chances that the BEV will make the running are good. The advantages of Li-ion battery technologies over other rechargeable batteries are consistent in technical, environmental and cost assessments (Hammond and Hazeldine, 2015). Since a rough estimate would put the number of cars and vans in the global road vehicle fleet at approximately 10^9 (we exclude trucks, as well as other transport forms, in particular shipping and air traffic, for which other solutions will probably have to be found), the question of the raw materials required for lithium-ion batteries and the concomitant supply risks needs to be addressed. The rapid market growth and a lack of closed-loop recycling of Li-ion batteries make it unlikely that secondary material sources will be available in the near future (Zeng et al., 2014). Because of the different chemistries in different types of battery, we also consider here, apart from lithium itself (Li availability is also discussed in other scientific papers, e.g. (Vikström et al., 2013), as well as in magazine articles, e.g. (The Economist, 2017)), the supply risks associated with the several other elements used as functional materials.

The supply risks for raw materials, in particular for rare metals,[1] are influenced by such factors as the possible dwindling of resources, increases in demand for the element in other industrial applications or the occurrence of monopolies and cartels. Physical shortage and longer delivery times as well as price rises and geopolitical tension could have substantial negative implications for battery or car producers and complicate the large-scale introduction of BEVs. The increased attention paid to such questions of raw material supply dates back to a study of the National Research Council (NRC) of the US National Academies in 2008 with the title “Minerals, critical minerals, and the US economy” (U.S. National Research Council, 2008). Many investigations have since followed, several of them concerned specifically with energy-related materials (Goe and Gaustad, 2014; Moss et al., 2013, 2011; Roelich et al., 2014; U.S. Department of Energy, 2011; Zepf et al., 2014). The US Department of Energy (2011) assessed the supply risks associated with various materials required for different technologies in the clean energy sector such as photovoltaics, wind turbines and electric vehicles. Similarly, Moss et al. (2013) identified resource requirements for various green energy technologies necessary for the implementation of the EU decarbonisation strategy and evaluated supply risk. Subsequent studies, such as that of Goe and Gaustad (2014) focussed on the US, looked at the raw materials necessary for specific green energy technologies, but without comparing specifically the different technical solutions (e.g. in thin-film photovoltaics).

As described in two earlier papers (Helbig et al., 2016; Tuma et al., 2014), our philosophy is somewhat different from that in most previous resource studies. We think it is only meaningful to assess supply risks semi-quantitatively (i.e. the likelihood of supply being unable to meet demand), if it is done on a comparative basis. In the present paper, we therefore first determine the supply risks associated with the elements required for the functional materials. Eleven indicators covering the main areas of supply risk are used, as in our previous work on thin-film photovoltaics (Helbig et al., 2016); these are categorized and weighted for the specific case of

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[1] An element is normally considered “rare“ if its concentration in the Earth's crust is below about 0.1%. In a recent, more popular, but percipient work on minerals and commodity markets Abraham (2015) also seems to prefer “rare metals“ to “critical metals”, a term for which there is no agreed definition (Bradshaw et al., 2013).