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Comprehensive Raw Material Assessment for Battery and Fuel Cell Electric Vehicles

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Summary

This publication determines critical raw materials for battery electric vehicles (BEV) as well as for fuel cell electric vehicles (FCEV) and analyses them according to a variety of aspects. These include the monopolistic character of the supply market, the development of production and reserves, the development of market prices, as well as greenhouse gas emissions and social issues related to the material supply. Considering the quantities required for BEV and FCEV and the volume of the global vehicle market, the risk of physical material depletion seems rather unlikely. Nevertheless, the necessary increase in current annual production volumes emphasises the need to overcome the challenges that are related to raw materials supply.

Keywords: BEV (battery electric vehicle), fuel cell electric vehicle (FCEV), materials, sustainability

1 Introduction

Battery electric and fuel cell electric vehicles (BEV and FCEV) are both considered as highly promising technologies for reducing the environmental impact of the mobility sector. This can be achieved through an increasing use of renewable energies for the use of these vehicle technologies. However, both BEV and FCEV require certain raw materials, for which concerns are often raised. These concerns address a variety of aspects, e.g. the potential depletion of such materials and short-term supply restrictions, growing dependence on certain countries that are relevant for the supply, risks of increasing material prices, and environmental as well as social issues related to the supply of these materials.

To assess the raw material demand of BEV and FCEV in more detail and its implications on the above-mentioned aspects, this comprehensive study was conducted.

2 Methods

In a first step, we reviewed the technologies in BEV and FCEV with a focus on their key components. We screened different technologies that are useable for them based on their suitability in vehicle applications. For the batteries of BEV, the most promising options for the near and mid-term future are lithium ion batteries with nickel-manganese-cobalt (NMC), nickel-cobalt-aluminium (NCA), and lithium-iron-phosphate cathodes (LFP) using a graphite-based anode. The most promising fuel cell technology for FCEV are proton-exchange-membrane fuel cells (PEMFC) and high-pressure storage tanks for carrying compressed gaseous hydrogen onboard of the vehicle. This technology review was conducted based on interviews with experts from industry and academia.

In a next step, we summarised the relevant options for raw materials in these most promising technologies. For example, the bipolar plates in PEMFC can be made from titanium, graphite, or stainless steel. For identifying the most relevant materials required for BEV and FCEV, we used the concept of resource criticality. This assessment approach characterises a raw material according to two independent dimensions: the risk of a supply shortage on one hand, and the severity of such a shortage on the other hand (often referred to as "vulnerability" or "material importance") [1, 2].

Several such assessments have been conducted for the material demand of a certain national economy or for a particular industry sector. In this application, however, the focus is on using the raw materials for BEV and FCEV.

We used a standardised procedure for quantifying the supply risk of the raw materials related to the indicators provided in the German standard for resource efficiency [3]. These are based on geological and market statistics for primary material production, which are provided by public authorities, such as BGR/DERA [4] and USGS [5]. For the quantification of the severity, we asked experts from industry and academia about the technical and economic consequences of a supply shortage on the technologies in BEV and FCEV. These may be small, if technically and economically feasible alternative materials exist, but it is high for materials that are essential for the intended application. Those materials with a high supply risk and a high severity of a supply shortage for the technologies are identified as materials critical for the application of BEV and FCEV.

Subsequently, a large variety of aspects related to the supply and use of these individual materials is assessed within the study:

- The supplying countries
- The use of the materials besides the assessed use in BEV and FCEV
- The development of material supply since 1995
- The development of the economically viable reserves[1] since 1995
- The development of the raw material prices between 1995 and 2015
- The price developments within the recent past
- Forecasts of supply and demand in the near future
- Environmental aspects related to the raw material supply, indicated in primary energy demand and greenhouse gas emissions
- Ethical and social aspects related to the raw material supply
- The potential of recycling the raw materials

After the assessment of these aspects for the individual critical raw materials, we set our focus on the vehicle level by first determining the amounts of raw materials required in BEV and FCEV. Subsequently, this leads to analysing the cost contribution of the different raw materials as well as their contribution towards the GHG emissions. Additionally, we calculated the effect of using the raw materials in BEV and FCEV on the necessary expansion of current supply volumes and on the current raw materials reserves.

Based on all the analyses, we derived recommended actions for different stakeholder groups, e.g. policy-makers, material suppliers, the vehicle industry and society.

3 Results and Discussion

3.1 Identifying critical raw materials for BEV and FCEV

As described already, the first step of the study was the identification of materials critical for the use in BEV and FCEV. Figure 1 shows the characterisation of all materials assessed with respect to the supply risk and the severity of the individual material's supply shortage.

[1] A definition of the term "reserves" as it is used in this publication is provided in section 3.2.1.

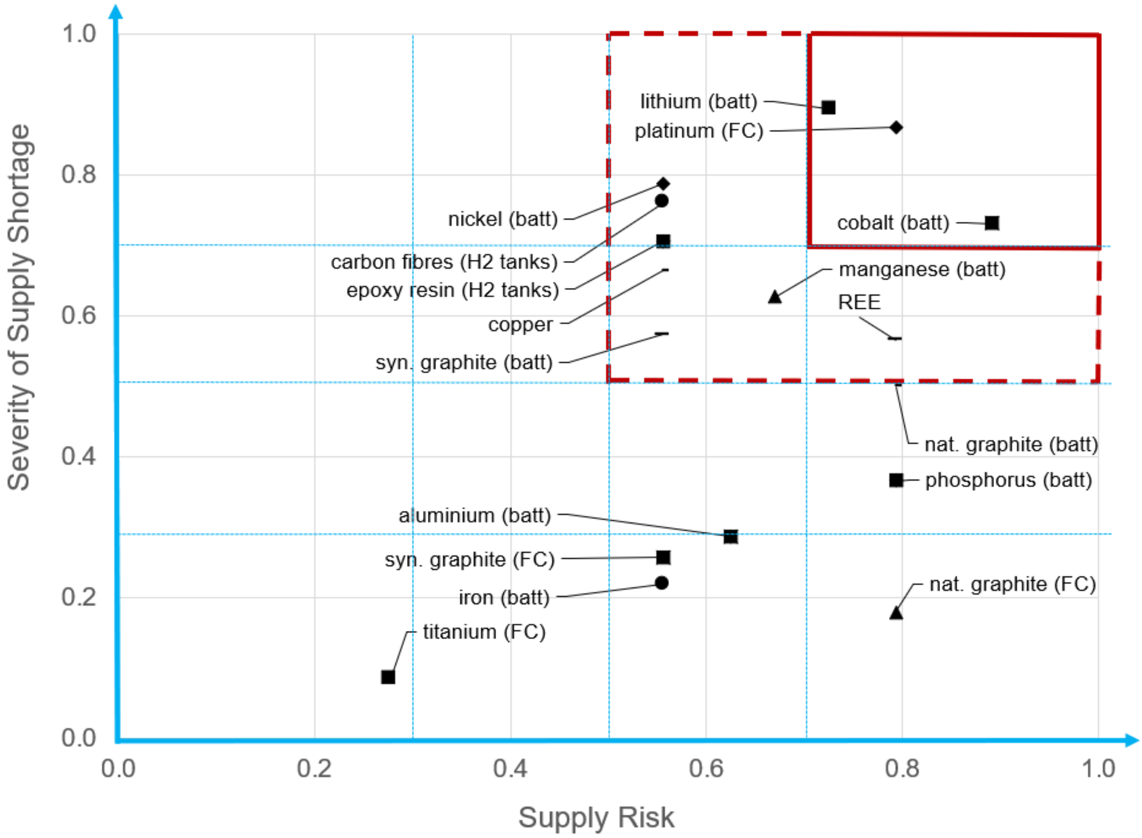


Figure 1: Results from the criticality assessment of raw materials for batteries in BEV (Batt) or fuel cells in FCEV (FC)

Three raw materials unequivocally rank as critical for BEV and FCEV, namely lithium, cobalt, and platinum. A number of other raw materials also show elevated values of supply risk and severity of a supply shortage, but to a lower extend. Of these, nickel, rare earth elements (REE) for permanent magnets in motors and copper for the overall use in BEV and FCEV were also selected for the subsequent in-depth analysis since they might play a significant role in the future.

3.2 Assessing relevant aspects for the raw materials critical for BEV and FCEV

Although we assessed all the aspects mentioned in section 2 for the six selected raw materials, a detailed description of all results is beyond the scope of this paper. Instead, we highlight the most important findings in the following paragraphs.

3.2.1 Development of raw material supply and reserves

Not surprisingly, the supply of all analysed materials, i.e. lithium, cobalt, nickel, platinum, rare earth elements, and copper, has increased since 1995. Whereas the supply increase of platinum and rare earth metals was rather small, the amount of lithium, nickel, and copper supplied in 2015 was about twice as high as 1995. The supply of cobalt has grown significantly in the observed period and results in about a six-fold increase compared to 1995 (Figure 2).

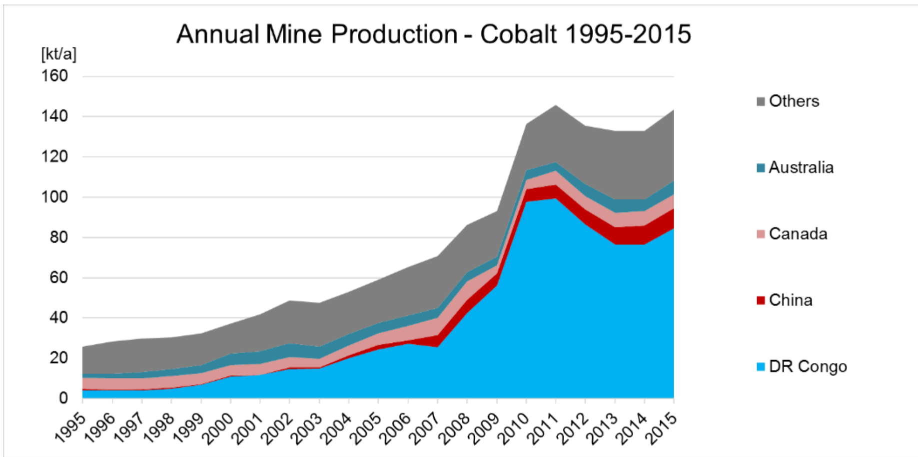


Figure 2: Annual mine production of cobalt 1995 – 2015 (Data source: [4])

Another important aspect related to the material supply is the distribution of supply among different countries and the occurrence of monopolistic supply structures: the supply of cobalt, platinum, and rare earth metals is indeed quite monopolistic. The most important countries of origin for these materials are the DR Congo (59 % of global mine production in 2015, see Figure 2), South Africa (73 % in 2013), and China (84 % in 2015) [5, 6]. While the supply of lithium is based on a few countries (43 % Australia, 33 % Chile, 11 % Argentina), the supply of nickel and copper is distributed across a larger number of supplying countries.

Interestingly, not only the primary production but also the *reserves* of all six materials have increased during the period of 1995 - 2015. In this context, it is important to clearly define the term "reserves". The USGS defines reserves as commodity concentrations "(…) which could be economically extracted or produced at the time of determination." [5]. For this reason, the reserves "(…) may be reduced as ore is mined and (or) the feasibility of extraction diminishes, or more commonly, they may continue to increase as additional deposits (known or recently discovered) are developed, or currently exploited deposits are more thoroughly explored and (or) new technology or economic variables improve their economic feasibility." [5]. The latter can be observed for the reserves of many materials where higher demand increases commodity prices which makes the production of previously sub-economic deposits a viable option in the future. In contrast to the reserves, the so-called *resources* of a material are a less dynamic characteristic, indicating the amount of a material which "is currently or potentially feasible." [5].

While the reserves of platinum and rare earth metals have only slightly increased between 1995 and 2015, those of cobalt, nickel, and copper have approximately doubled. Significantly higher was the increase of lithium reserves, which saw a seven-fold increase in 2015 compared to 1995 (Figure 3).

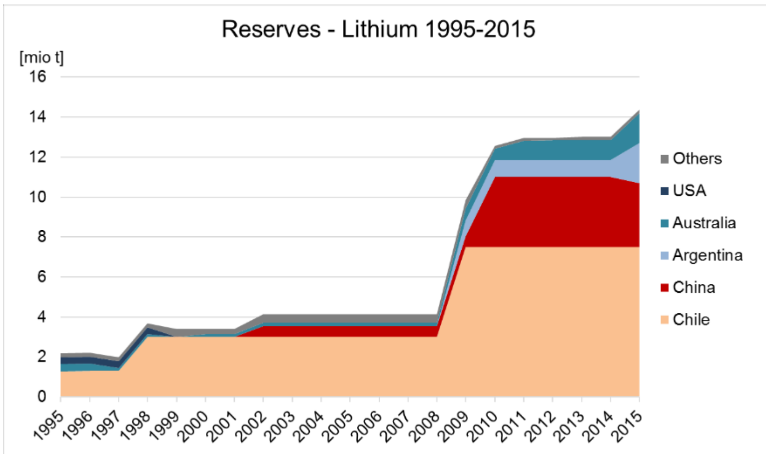


Figure 3: Development of global lithium reserves 1995 – 2015 (Data source: [4])

3.2.2 Raw material price volatility

Another important parameter that can be subject to significant changes are material prices. We assessed the long-term development in the time-period from 1995 – 2015 and the price developments in the recent past and determined large price volatility for all six raw materials assessed.

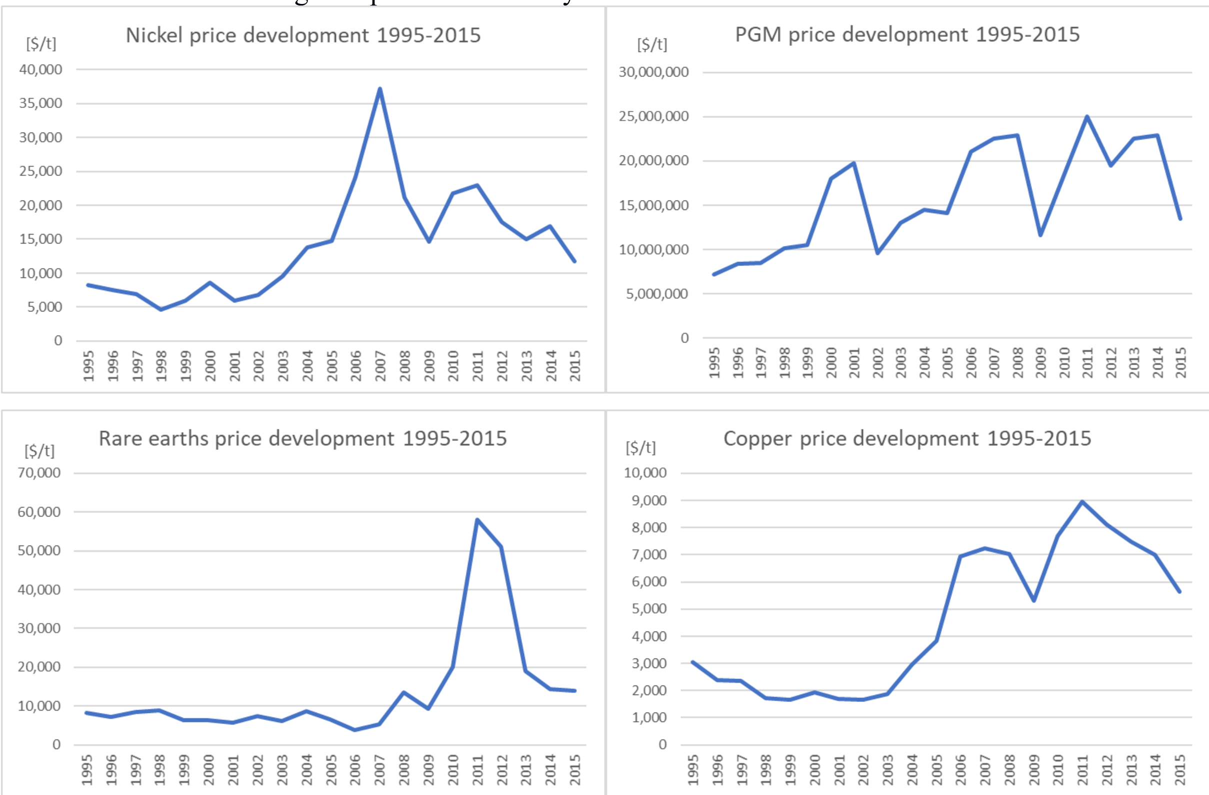
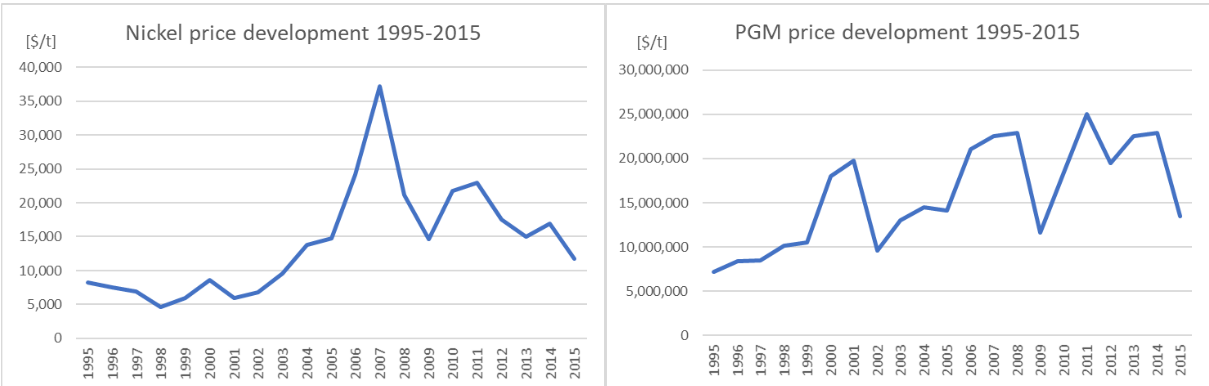
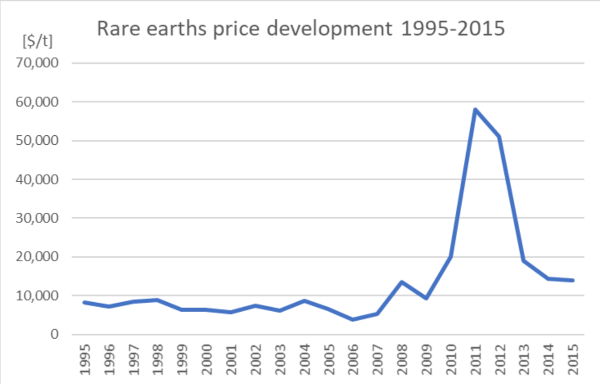


Figure 4 indicates, sharp price peaks appeared for example for nickel and rare earth elements. The latter one is quite famous and occurred because of regulations in China which reduced the exports of rare earths. The price development of platinum group metals shows a continuous up and down movement, while the copper price peaked at about 9,000 US$/t in 2011, which is more than four times the copper price of 8 years earlier.





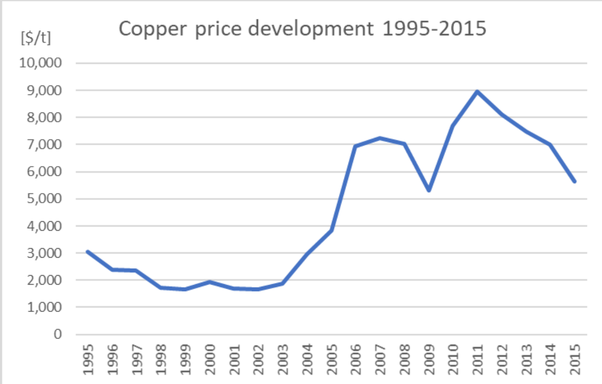
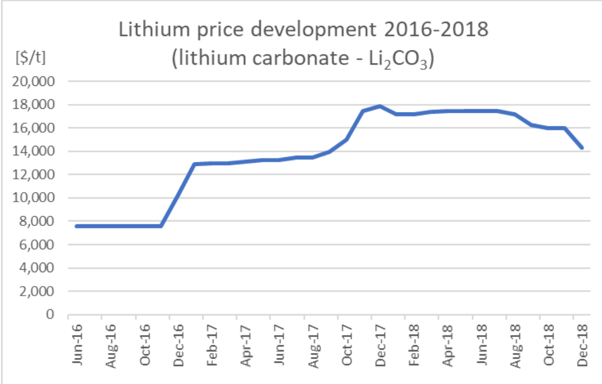


Figure 4: Development of nickel price (top left), PGM price (top right), rare earth metals (bottom left), and copper (bottom right) during the period 1995 – 2015 in nominal USD (data source [7])

Large price fluctuations are not only visible on a long-term perspective, but also within more recent price developments.



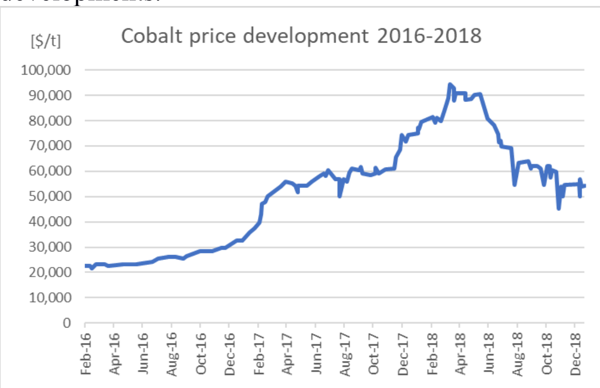


Figure 5 shows the steep price increase of lithium carbonate, which more than doubled within about one year (left) and the cobalt price, which more than tripled within about 18 months and then fell again significantly in about half a year.

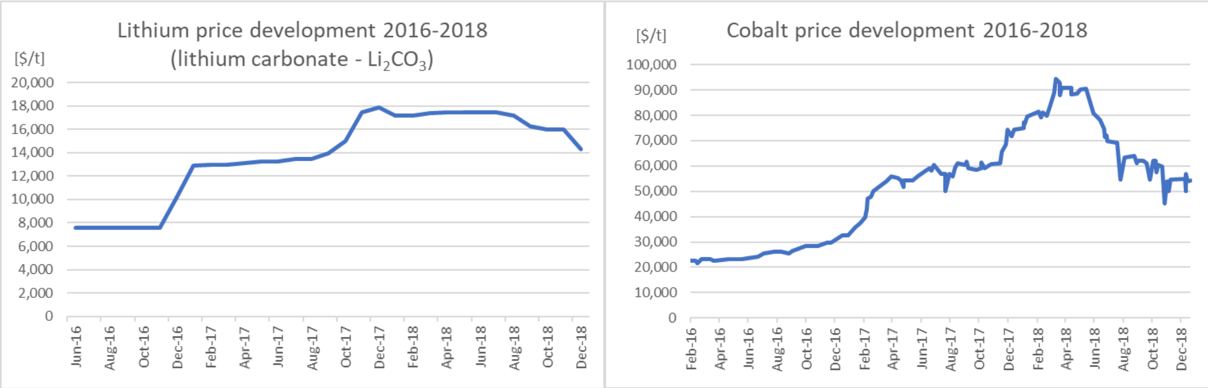


Figure 5: Development of lithium price (left, data source: [8]), and cobalt price (right, data source: [9]) in nominal USD

The mentioned examples illustrate the magnitude of possible price fluctuations and the short time periods in which they can occur. They also emphasise the necessity to ensure a reliable supply of raw materials in a short- and long-term perspective and avoid undesirable influences on the material supply markets.

3.2.3 Environmental assessment of greenhouse gas emissions

A highly important topic related to raw material supply is the environmental impact of sourcing raw materials. Material production usually requires significant amounts of energy and water, it represents a major impact on ecosystems, and it causes a variety of emissions, e.g. exhaust gases, sulphur dioxide, dust etc., with different possible negative effects, such as global warming, acidification and toxicity. For these reasons, it is of fundamental importance to keep track of the potential environmental impacts of material supply in the individual natural systems and to decrease the related environmental impacts as much as possible.

Since greenhouse gas (GHG) emissions are currently one of the most important environmental issues, we assessed the GHG emissions related to the supply of the six raw materials selected for the analysis. Figure 6 shows the ranges for the GHG emissions for the supply of 1 kg of raw material indicating the variations of different material supply routes, different processing technologies or different countries of material supply.

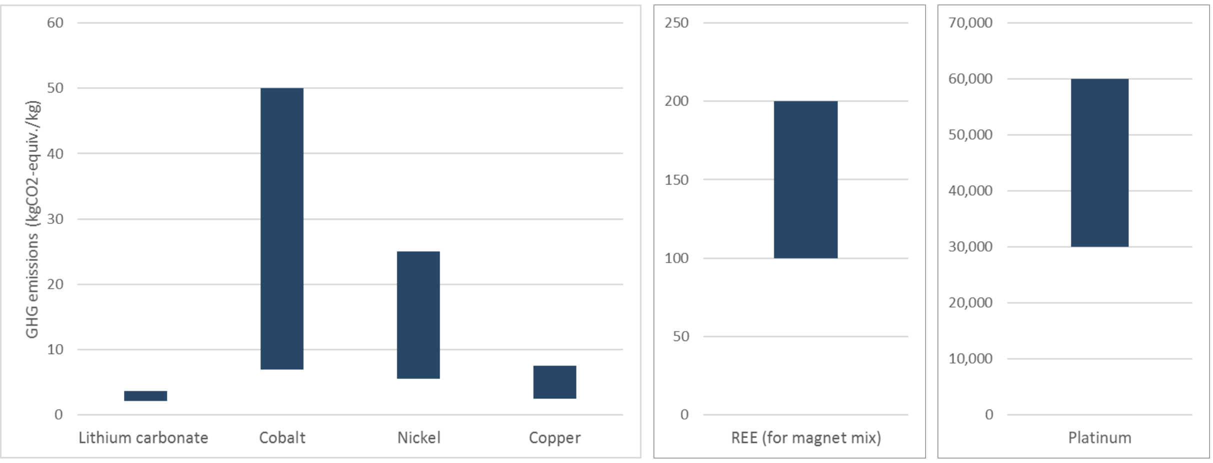


Figure 6: Range of GHG emissions related to the raw material supply (data source: [10])

As indicated in Figure 6, the GHG emissions caused by the supply of 1 kg of lithium carbonate and copper are rather small, while the supply of cobalt and nickel lead to higher GHG emissions. The emissions from the supply of the rare earth elements used for permanent magnets is more than one order of magnitude above that of copper, whereas those of platinum supply are even several orders of magnitude higher. Interestingly, this correlates with the ratio of the commodity concentrations in the individual ores, which is in a low percent range for copper, but only a few grams per ton for platinum [11, 12].

We also estimated the potential of decreasing the GHG emissions by using electricity from renewable energies for producing these raw materials. While the improvement potential is negligible for lithium carbonate, 30 – 60 % of the GHG emissions related to the supply of cobalt, nickel, and copper can be reduced if electricity from renewable sources are used to produce these materials. For the rare earth elements this reduction potential is even higher in the range of about 70 % and for platinum this theoretical reduction potential is up to 90 %.

One important aspect in this context is the fact that different metals are often so-called companion metals, i.e., they occur in the same ore and so the production efforts are shared between multiple metals. This requires the distribution of these efforts and the related environmental impacts among the materials, which is called allocation and can be conducted according the individual mass of the different materials or other properties such as market value. Different allocation methods will hence lead to different individual results.

3.2.4 Social aspects

Another highly relevant field of raw material supply are social and ethical aspects related to the raw material supply. Since the mining activities of many materials take place in low-income countries, a huge variety of important issues exists that need to be considered related to raw material supply. These include the working conditions in the mining activities, environmental harm with consequences on the life of the local population, the violation of civil rights, especially child labour, and the overall socio-economic and political framework of the supplying countries in which the mining activities take place.

The social conditions related to the cobalt supply and the conditions in its most important country of origin, the DR Congo, have been discussed in many publications (e.g. [12, 13]). Therein, the work conditions, especially in the artisanal mining sector, child labour and the overall political situation are addressed. Beyond these pressing factors, we found indications for worrying social conditions related to the supply of all six selected raw materials in corresponding publications.

A general challenge in this domain is the transparency in the supply chain, which is a prerequisite for efficient and effective improvements of related social aspects. For this reason, many actors along the material supply chains cooperate within initiatives. These aim for common approaches to increase the transparency in the supply chains uncovering grievances and fostering desirable social conditions along them.

3.3 Assessing the raw material use of BEV and FCEV

In a next step, the six selected raw materials are assessed considering their quantity which is used in BEV and FCEV. The individual material masses required for the components of both vehicle technologies are determined, which is shown in

Table 1, assuming a lithium ion battery with NMC-622 and 80 kWh capacity as well as a PEM fuel cell and an electric motor of 100 kW nominal power. Since the amount of platinum in the fuel cell is a highly influencing parameter, two different scenarios are assessed in the following, assuming a high or low necessary platinum loading in the fuel cell. The difference in the required amount of copper in BEV and FCEV mainly results from the copper inventory in the battery.

Table 1: Inventory of the analysed raw materials in BEV and FCEV (metal content)

	Lithium	Cobalt	Nickel	Platinum	REE (Nd, Dy)	Copper
BEV	10 kg	14 kg	42 kg	--	0.5 kg Nd	95 kg
FCEV	--	--	--	15 – 35 g	0,1 kg Dy	41 kg

Table 2: 2018 yearend prices (for metal content) for the selected metals (data sources: [8, 9])

	Lithium	Cobalt	Nickel	Platinum	REE (Nd, Dy)	Copper
Price (USD/kg)	75	54	11	25700	58, 244	6

Based on the individual masses required for the two vehicle technologies, the cost contributions of the individual materials were determined for their market prices at the end of the year 2018 (Table 2) and are shown in Figure 7. While the mentioned prices lead to a high cost contribution of lithium, cobalt, nickel and copper, the cost related to the demand of REE for permanent magnets is rather small. The cost related to platinum strongly depends on the amount of platinum required for the fuel cell. As mentioned before, the market prices for these materials are very volatile and hence significant changes can occur over time. For example, the cobalt price has decreased to a level around 32,000 USD per metric ton until the beginning of March 2019 and hence decreases the related cost contribution by more than a third. Nevertheless, the indicative character of the illustrated cost contributions remains the same.

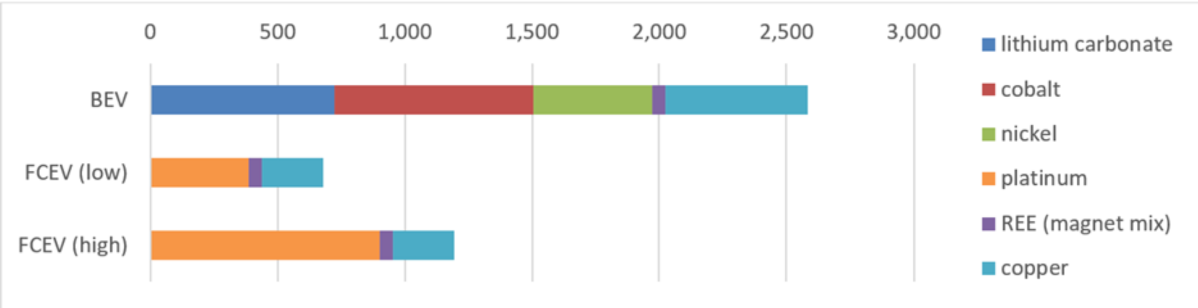


Figure 7: Cost contributions of the different raw materials assessed in the study in USD

Similarly, the GHG emissions from the selected raw materials are illustrated in Figure 8. In this regard, lithium and REE show a minor impact, whereas the GHG emissions related to cobalt, nickel, platinum, and for the BEV also copper is more significant. Especially the platinum dominates the GHG emissions of the materials assessed for FCEV.

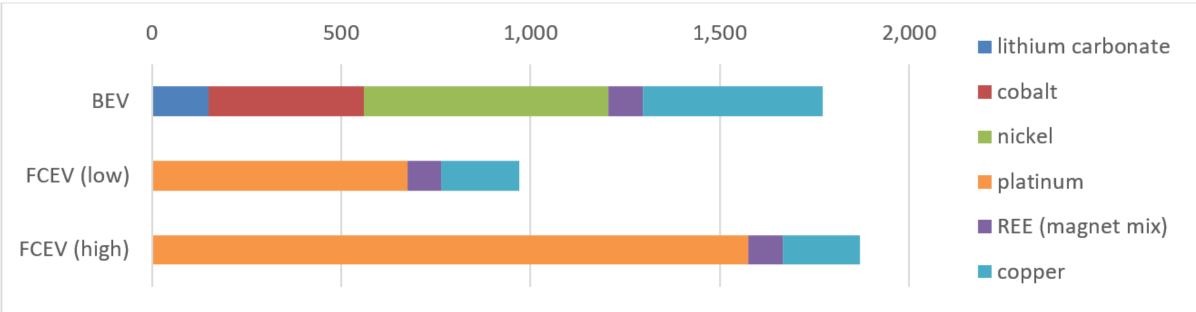


Figure 8: GHG emissions from the different raw materials assessed in the study in kg CO2-equiv.

For these analyses, it is important to remember that only some materials in BEV and FCEV are selected and assessed in the study, so no direct comparisons between these vehicle technologies or between batteries and fuel cells can be derived. For doing so, comprehensive life cycle analyses are necessary such as life cycle costing for economic or life cycle assessment for environmental indicators.

Another important aspect related to the use of raw materials are effects towards the depletion of resources. To assess these, we assume that 25 % of the current passenger vehicle fleet, which counted 950 million vehicles worldwide in 2015 [15], would be BEV or FCEV. Table 3 shows the total cumulative mass of the six materials assessed for BEV and FCEV in comparison with the existing reserves of those materials. The highest demand compared to the reserves arises from cobalt, for which about half of current reserves would be necessary to allow 25 % of today's passenger vehicle fleet being BEV. More than 20 % of today's calculated platinum reserves are required for having the same amount of FCEV if the higher limit of platinum loading is assumed. For the lower platinum loading, this value reduces to about 10 %. The demand of lithium and nickel accounts for about 15 % of today's reserves, while considerably smaller shares of the neodymium, dysprosium, and copper reserves are necessary. Since the resources of all assessed materials are even higher than their reserves (Table 3) and since recycling can contribute positively, physical depletion through the use in BEV and FCEV appears highly unlikely for these materials.

Table 3: Comparison of cumulative raw material demand (assuming 25 % of today's passenger vehicle fleet was BEV or FCEV) with today's global reserves and resources [4, 5].

	Li	Co	Ni	Pt (low)	Pt (high)	Nd	Dy	Cu
Total raw material demand - BEV	2.3 Mt	3.4 Mt	10.1 Mt	---	---	119 kt	24 kt	22.6 Mt
Total raw material demand - FCEV	---	---	---	3.6 kt	8.3 kt	119 kt	24 kt	9.7 Mt
Reserves 2015	14.7 Mt	7.2 Mt	79.2 Mt	37.5 kt[2]	37.5 kt[2]	20.7 Mt[3]	1.5 Mt[3]	720 Mt
Ratio – BEV	16 %	48 %	13 %	---	---	0.6 %	1.6 %	3.1 %
Ratio – FCEV	---	---	---	9.5 %	22 %	0.6 %	1.6 %	1.4 %
Resources (ident. & terr.)	> 53 Mt	> 25 Mt	> 130 Mt	> 57 kt[2]	> 57 kt[2]	n/a	n/a	2,100 Mt

A different aspect, however, is the necessary expansion of the current production volume, which is required for a certain annual production. For quantifying this in more detail, we assume that 25 % of today's yearly production, which sums up to more than 73 million cars [16], was BEV or FCEV. Table 4 illustrates that the global mine production has to increase significantly in order to meet the raw material demand imposed by BEV and FCEV production in the assumed order of magnitude. The annual demand for a share of 25 % of BEV in the current yearly car production requires more than five times of current lithium and almost double of current cobalt production. For FCEV, more than triple or about 1.5 times of today's primary platinum production is necessary depending on whether a high or low platinum loading is required for the fuel cells. Also nickel, neodymium, and especially dysprosium production needs to be increased significantly, whereas the demand increase in copper through BEV and FCEV is relatively small. It is important to note that this comparison does not account for secondary material supply that comes from the recycling of used components.

[2] Reserve data is usually only available for all platinum group metals (PGM), for which the Pt share was assumed to be 57 % based on [4]. The same share was used for quantifying the platinum resources.
[3] Reserve data is usually only available for rare earth elements as a group, for which the Nd and Dy shares were assumed to be 19.1 % and 1.4 % respectively, based on [12].

Table 4: Comparison of annual raw material demand (assuming 25 % of today's passenger vehicle production was BEV or FCEV) with today's mine production.

	Li	Co	Ni	Pt (low)	Pt (high)	Nd	Dy	Cu
Annual raw material demand – BEV	175 kt	263 kt	774 kt	---	---	9 kt	2 kt	1.7 Mt
Annual raw material demand – FCEV	---	---	---	275 t	640 t	9 kt	2 kt	750 kt
Mine production 2015	32 kt	144 kt	2.1 Mt	188 kt[4]	188 kt[4]	20 kt[4]	1.5 kt[4]	18.2 kt
Ratio – BEV	545 %	185 %	37,5 %	---	---	45 %	120 %	10 %
Ratio – FCEV	---	---	---	145 %	340 %	45 %	120 %	5 %

4 Conclusions

The supply of raw materials required for innovative future technologies such as BEV and FCEV is a pressing topic that increasingly receives attention. It is essential to develop strategies to overcome the challenges that are related to the raw material supply, e.g. identifying materials that are critical, securing their supply on a short- and long-term perspective, decrease the risk of price volatility and high price levels as well as ensuring positive environmental and social conditions along the material supply chains.

Different stakeholder groups can contribute to these targets, especially the material users such as the automotive industry, the material suppliers, and policy makers. Long-term collaborations between material suppliers and the manufacturing industry creates planning security regarding necessary volumes and prices on both sides, and hence lowers the investment risks. Decreasing the demand of critical materials and flexibility with respect to the useable materials and components help to reduce supply dependencies. Similarly, increasing the recycling of materials from used components by closing the materials loops reduces the pressure on primary material supply in the future. Finally, it is essential to reduce potential environmental impacts and to improve the social conditions along the supply chains as well as to increase the level of public awareness of all mentioned issues. Policy-makers can set regulations based on a holistic scope to support developments towards overall positive progress.

If all relevant aspects are considered in the strategies and solutions for material supply, BEV and FCEV can truly improve the transport sector in a sustainable way.

Acknowledgments

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[4] The same shares of platinum production within the PGM production as well as of Nd and Dy in REO production were assumed as for the reserves

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