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The future of mobility and its critical raw materials

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Abstract – Concerns for climate change and declining oil reserves lead to a shift of transportation systems in many industrial countries. However, alternative drive concepts contain to some extent critical raw materials. Since the availability of certain raw materials could be decisive for the success of emerging technologies, concerns are growing about the potential limitation of resources. This brought about a growing attention to the subjects of criticality and resource security of raw materials by science, policy and industry. Four of the resulting surveys are described in terms of their framing of criticality, their indicators for evaluating criticality, and their rankings of potentially critical raw materials. Critical raw materials are used in alternative drive concepts because of their specific properties. The focus of our work lies on batteries for electric vehicles with special attention to lithium-ion batteries being one of the most promising candidates for energy storage there. Lithium-ion batteries use as major cathode materials lithium, manganese and cobalt, all of which are potential critical. A material flow model of the global manganese cycle is developed. It could be identified that there is a lack of relevant data for processes and flows. The lack of data impedes a comprehensive view and therefore no final conclusions could be drawn, which advice the need for further research. Using manganese as an example, it could be illustrated how material flow analysis can contribute to compiling relevant preparatory work that can subsequently serve as a basis for a prospective support of a criticality evaluation and to inform stakeholders and policy makers about the effectiveness of various interventions to reduce the risk or the effects of supply chain disruptions.

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Two of the big challenges for sustainable development are climate change and peak-oil. The greenhouse gas emissions from vehicles as well as declining reserves of crude oil for gasoline production entail the need for alternative drive concepts. As diesel and gasoline vehicles are not sustainable there is a strong need for a shift of transportation systems in the future. Alternative mobility concepts such as natural gas vehicles (NGV)[1], fuel cell vehicles (FCV) and electric vehicles (EV) have a huge potential to reduce greenhouse gas emissions of road transport significantly [1] and they are no longer directly dependent on oil. Instead they are like many new technologies intrinsically tied to so-called critical raw materials[2] (see Tab. 1) that are often essential for the functioning of high-tech products.

Although there are different alternative transportation technologies and their successful implementation in the future is to some extent unproven there can be no doubt

[1] Natural gas vehicles use compressed natural gas (CNG) and liquefied natural gas (LNG) as fuel.

[2] A raw material is labelled as critical if it is of high importance for key and important technologies and has only few or no satisfactory substitutes in its major applications, if there is a high probability of supply disruption and if such a supply shortage might have considerable impacts on the economy of a country [2].

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Table 1. Alternative drive concepts and critical raw materials (data source [3]).

Technologies	Cr	Cu	Co	Pb	Li	Mn	Ni	PGM	REE
Natural gas vehicle		x		x			x	x	
Fuel cell vehicle (FCV)		x		x				x	
Hybrid electric vehicle (HEV)*		x					x	x	x
Plug-in hybrid electric vehicle (PHEV)*		x	x		x	x		x	
Full electric vehicle (FEV)*		x	x		x	x			
Electric motor		x							x

* Different vehicle types are shown without electric motor.
Abbreviations: PGM (Platinum Group Metals), REE (Rare Earth Elements).

that critical minerals and metals respectively will be an important component of future mobility. Especially as there is an increased interest for the electrification of transportation in many European countries, which is expressed in making e.g. such national action plans [1]:

- The Netherlands: 200 000 electric vehicles in 2020.
- Denmark: 500 000 full electric vehicles in 2020.
- Germany: one million electric vehicles in 2020.

Renault predicts an EU market with 2 million full electric vehicles in 2020. However, there are concerns about potential constraints from essential raw materials. An examination of their criticality is needed to inform policy makers in industry and governments about various measures to reduce the risk of supply chain disruptions.

1 Criticality of raw materials

In recent years several studies on resource security and critical raw materials were conducted by different institutions from science, policy and industry. A detailed analysis shows that there are differences regarding terminology and framing of criticality as well as the individual indicators and rankings of considered raw materials. That could be explained by the different backgrounds and goals of the studies.

The different terms used are for example rare metals, scarce metals, critical minerals, critical raw materials, potentially critical raw materials, vulnerable raw materials, strategic metals.

Four of these studies are described in more detail here. Although these studies used similar terms and indicators, they employed different methods to determine criticality.

The National Research Council (NRC) [4] uses two main criteria named "Supply Risk" and "Impacts of Supply Restriction" to evaluate the criticality of minerals. To analyse the supply risk, five indicators influencing present and future supply were used: US-import dependency, world reserve/production ratio, world reserve base/production ratio, relative importance of byproduct mining in world primary production, and relative importance of US secondary production in overall US consumption. For evaluating the impacts of a supply restriction three indicators were used: value of US consumption, percentage of US consumption in existing uses for which substitution is difficult or impossible, and importance of growth in emerging uses (committee's judgment). A so-called "criticality matrix" was developed to define the degree of criticality along two axes. The horizontal axis represents supply risk, the vertical axis impacts of supply restriction; both axes use a scale from 1 (low) to 4 (high). On the basis of the above-mentioned indicators, eleven minerals were placed into the matrix (cf. Tab. 2) – high numbers on both axes means increasing criticality of minerals.

IW Consult [5] developed a so-called raw material risk index by order of Vereinigung der Bayerischen Wirtschaft (vbw). This index contains eight indicators, of which five are quantitative and three qualitative. The quantitative indicators make up 60% of the index with the following shares: lifetime of reserves (12.5%), political stability of producing countries (12.5%), regional concentration of world production (15%), corporate concentration of world production (10%),

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Table 2. Overview about studies of critical raw materials.

	Critical minerals	Potential critical raw materials	Critical raw materials	Environmentally relevant ores
Elements	Copper Gallium Indium Lithium Manganese Niobium PGM REE Tantalum Titanium Vanadium	Chromium Cobalt Germanium Indium Lithium Molybdene Neodyme Niobium PGM Scandium Selenium Tungsten Yttrium	Antimony Beryllium Cobalt Fluorite Gallium Germanium Graphite Indium Magnesium Niobium PGM REE Tantalum Tungsten	Gallium Gold Indium Manganese Nickel Palladium Silver Tin Titanium Zinc
Region	USA	Bavaria (Germany)	EU-27	Germany
Source	NRC [4]	vbw [5]	EU COM [6]	Wittmer et al. [7]

and price risk (10%). The qualitative criteria sum up to 40% and comprise: importance for emerging technologies (15%), strategic industry policy (15%), and substitutability (10%). The risk index can reach 25 points at the maximum for each raw material. This index was applied to 37 metals and minerals dividing them subsequently into three different risk classes. Risk class one (high risk, 15–25 points) includes 15 raw materials (cf. Tab. 2).

To identify critical raw materials for the European Union (EU), a relative concept of criticality is applied: a raw material is labelled as critical if the risk of supply disruption and the resulting impacts on the economy are higher compared with other raw materials [6]. Based on existing methods such as NRC [4], three aggregated indicators are used: economic importance, supply risk, and environmental country risk. The economic importance corresponds to the value of products dependent on a specific raw material. This was calculated with the help of the concept of mega-sectors and their gross value added in relation to the gross domestic product (GDP) of the EU27. For determining the supply risk, four criteria were combined: concentration of worldwide production (Herfindahl-Hirschmann-Index), stability of producing countries (Worldwide Governance Indicator), recycling rate, and potential of substitution. The environmental country risk reflects the ecological risks of raw material production in these countries. This indicator was determined using an environmental country index based on the Environmental Performance Index (EPI), the regional concentration of raw material deposits, the recycling rate, as well as the substitutability. The results of the individual indicators were scaled so that the possible values lie between zero and ten representing an increasing risk. By means of these values, the raw materials could be placed into the matrix consisting of economic importance (vertical axis) and supply risk (horizontal axis). By applying this method to the EU-27, 14 critical raw materials were identified having both high supply risks (>1) and high economic importance (>5) (cf. Tab. 2).

The project "Material Efficiency and Resource Conservation" (MaRess) analysed environmentally relevant ores [7] using six indicators: world reserves, world reserve/production ratio, annual production volume, commodity price, regional concentration of production and reserves, dissipative use, and environmental relevance. The latter was determined on the basis of cumulative raw material demand (CRD), cumulative energy demand (CED) and total material requirement (TMR). The analysis covered 66 metals and metal groups and identified ten environmentally relevant ores (cf. Tab. 2).

Indicators for measuring criticality represent the current situation and do not take into account future development. Therefore,

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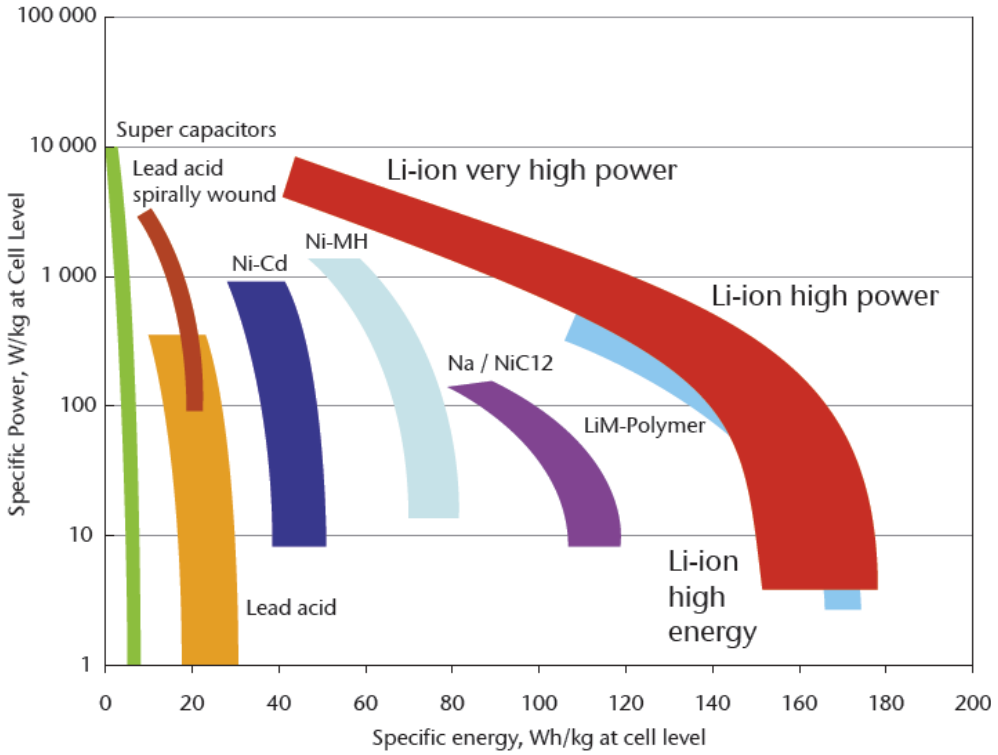


Fig. 1. Specific power and specific energy of different battery types [3].

they only provide a snapshot of the current situation rather than a detailed evaluation of the development of resource availability in the future. A change in factors such as raw material demand or political stability of producing countries could easily change the criticality of certain raw materials. Nevertheless, these studies can serve as a starting point for a more comprehensive assessment of potential supply risks.

Two of the studies identified manganese as a critical mineral or environmentally relevant ore respectively (cf. Tab. 2). This is due to its importance for most of its end-use applications, especially steel, aluminium beverage cans, and dry-cell batteries, for which no satisfactory substitutes for manganese exist so far. As steelmaking is an important driver for the US economy, the relevance of manganese is very high just as the impact of a supply restriction [4]. Given that mining of manganese ores and production of manganese alloys show a regional concentration, the supply risk for manganese is considered to be severe for all applications [4, 8]. Furthermore, as an alloying metal in steel, manganese is dissipated to some extent since there are no effective recycling processes. In addition manganese has a low reserve to production ratio (<45 years), and is highly environmentally relevant due to its high cumulative energy demand [7, 9].

2 Critical raw materials for electric vehicles

Electric vehicles, and hence batteries to power them, play an important role in concepts of future mobility. The core of electric vehicles (independent of the type – hybrid electric vehicle, plug-in hybrid electric vehicle or full electric vehicle) is formed by a rechargeable battery of differing size. Rechargeable batteries come in different types with different advantages and disadvantages for electric mobility (cf. Fig. 1). Lithium-ion batteries are the most promising candidates for implementation in future electric vehicles so far, mainly due to their exceptional characteristics such as low weight, high voltages, and high energy densities which enables a wider driving range. These characteristics are connected to

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the unique qualities of the contained metals, making them rather indispensible for the functioning. Especially the cathode materials lithium, manganese and cobalt are essential for rechargeable batteries to be implemented in electric vehicles [10].

Whereas the management of lithium resources has been the subject of detailed investigations [11–13], little attention has been given to manganese so far. However, two studies about critical raw materials identified manganese as such an element (see Sect. 2). Manganese is, among others, a vital component of lithium-ion batteries because of its good electrochemical behavior. All cathode materials for lithium based systems with an interesting energy density use manganese, cobalt and nickel as redox-active materials. Although manganese has a lower energy density than nickel and cobalt, it is a lot cheaper to manufacture; thus there are efforts to replace cobalt with manganese. Additional benefits of lithium-ion cells with manganese based electrodes are high specific power, high current resistance, increased safety, and long life [14].

3 Material flow analysis of manganese

3.1 Material flow analysis of metal cycles

Metal cycles describe the entire life cycle of metals comprising their production, use and disposal. They are dominated by anthropogenic activities throughout the metal's lifetime [15].

Material flow analysis (MFA) is a scientific method for the systematic assessment of material flows and stocks within a system defined in space and time [16]. Thus, MFA is a suitable analytical tool to characterize the quantity of material stocks and flows throughout metal cycles and to obtain insight into important driving forces of demand and basic conditions of supply in global raw material cycles at present.

3.2 Manganese

Manganese is predominantly used in the production of steel and cast iron. It is a vital alloying and refining element that improves the strength of steel. It is also deployed as a deoxidizing and desulphurizing agent during the steelmaking process. Other important uses of manganese are the battery sector (e.g. dry cell batteries) and non-steel alloys. In addition, there are nonmetallic uses of manganese such as animal feed, fertilizers, chemicals, colorants and pigments [17].

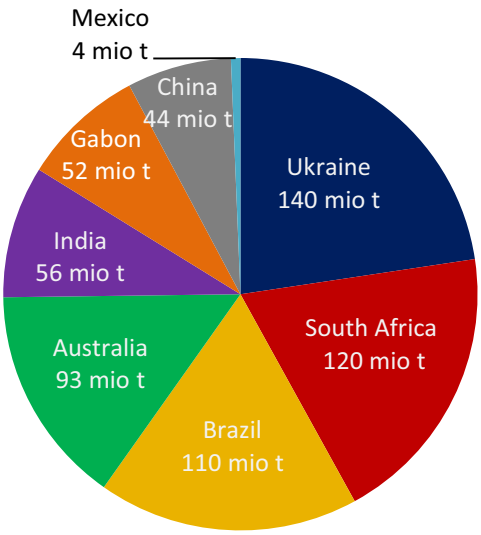


Fig. 2. Distribution of manganese reserves (data source [18]).

Manganese production is highly concentrated, with three countries being responsible for nearly 60% of global production: China, Australia, and South Africa. Manganese reserves[3] total 619 000 000 tons and show a similar regional concentration, with a share of nearly 60% being distributed in the three countries of Ukraine, South Africa and Brazil (see Fig. 2). Manganese resources[3] are concentrated even more, as South Africa accounts for about 75% of the world's identified manganese resources [18].

So far, there is no practical substitute for manganese in steel production; its characteristics make manganese indispensible for achieving steel qualities used in a wide

[3] Resources are defined as a concentration or occurrence of material of economic interest in or on the earth's crust in such form, quality, and quantity that there are reasonable prospects for economic extraction. Reserves can be determined as that part of a mineral resource which is economically mineable with existing technologies [20].

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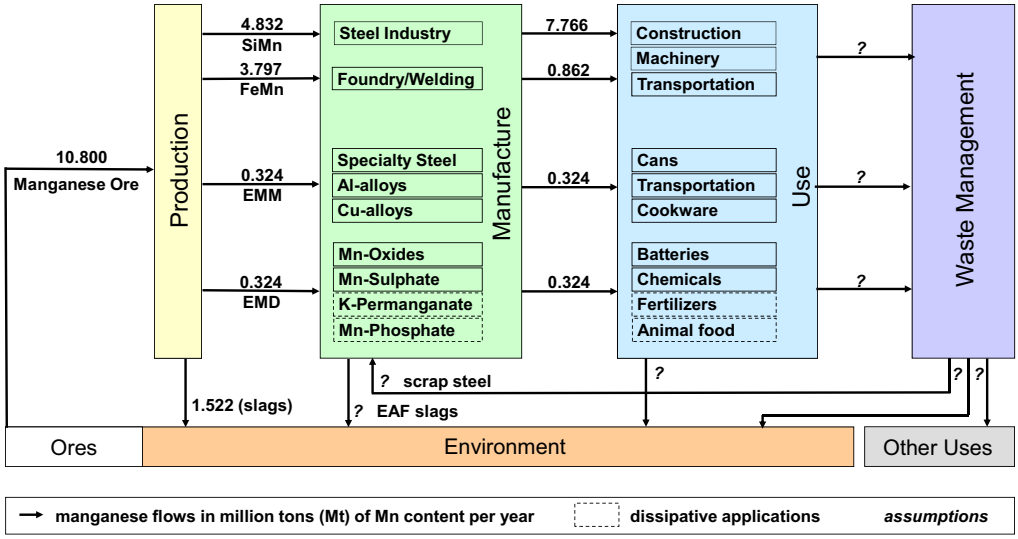


Fig. 3. Material flow model of manganese (2009) (Abbreviations: Silicomanganese (SiMn), Ferromanganese (FeMn), Electrolytic Manganese Metal (EMM), Electrolytic Manganese Dioxide (EMD), Electric Arc Furnace (EAF)) (datasource [17, 20]).

variety of applications. Since steel production is crucial for most industrial countries, the impacts of a supply shortage of manganese could be significant. The dependency on primary manganese sources is aggravated by the fact that manganese recycling is very low: scrap recovery specifically for manganese is insignificant, and manganese within steel scrap that is recycled to steelmaking is largely lost because of its removal in the decarburization step of steelmaking, and needs to be added back [19].

3.3 Modelling the global manganese cycle

We analysed the global manganese cycle including all relevant production, manufacture, use, recycling and waste management routes. Figure 3 reflects preliminary results of this material flow model (Fig. 3).

Data for global manganese consumption by end use were not available. The figures for the model were therefore calculated from production data of USGS [18] and transfer coefficients for sector split and yield losses provided Gandhi [21].

Manganese ore production accounted for 10.8 million metric tons of "Mn content" in the year 2009 [18]. The major share of manganese ore, namely 94%, is converted into manganese alloys, whereas the remaining 6% are used for making electrolytic manganese products such as electrolytic manganese metals (EMM) and electrolytic manganese dioxides (EMD). While EMM and EMD production has high yields, the production of 8.629 Mt of ferromanganese and silicomanganese has yield losses of about 15%, resulting in 1.522 Mt of slag. In manufacture 90% of manganese alloys are consumed in steel production, leaving only a small part of 10% for foundry and welding. EMM with a Mn-content of 0.324 Mt goes into specialty steel, aluminium alloys, and copper alloys, of which aluminium alloys can be recycled. EMD is used for batteries, chemicals, fertilizers, and animal food, representing also a share of 0.324 Mt of manganese.

At the moment manganese consumption through batteries is marginal. This might be subject to change due to the implementation of electric mobility in the future. For this purpose it was tried to make a first rough estimate. Given that 2 million full electric vehicles in Europe in 2020 are predicted (cf. Sect. 1) we calculated: 50% of these FEV will be equipped with NMC-batteries

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($LiNiMnCoO_2$) or LMO-batteries ($LiMn_2O_4$) owing a manganese content in cathode materials of 1/3 or higher [10,22]. Taking into account a material requirement of 23.7 kg Mn per 20 kWh battery needed for every FEV ([23], own calculations) this would result in a manganese demand of 0.024 Mt from EV batteries. That means, also on a global level, the manganese requirement for batteries in the future might be at least one order of magnitude lower than for steel production.

Although scrap steel, which often includes manganese, is recycled in large amounts, manganese metal is neither recovered in the steel, nor is it recovered as metal at present (cf. Sect. 3.2). Aluminium-manganese alloys used for beverage cans are the sole manganese application that can be recycled [24]. In addition there are research activities to recover manganese from slags [25]. Dissipative applications are fertilizers, animal food, colorants and pigments.

The model is still incomplete and the data often have significant uncertainties. Nevertheless, the first preliminary results allow for drawing some first conclusions.

3.4 Conclusion and outlook

The material flow model in its current state accounts for a fraction of the whole metal cycle and thus enables to some extent a better understanding of extraction and consumption of resources as well as of releases into the environment.

At the moment manganese is handled lavishly in its major applications since there are no effective recycling processes for most products. This means that practically no secondary metal can be used and that primary metal is always needed for manufacturing new products. Hence, there are virtually no possibilities for saving primary manganese resources at present. However, as global steel production is expected to increase further and the battery sector to gain more importance in the next years, the criticality of manganese may grow over the coming decades. It will depend on the relative price development of other technical interesting materials like cobalt, if manganese will possess a high attractiveness in battery cell production. Current manganese use for batteries is 2–3 orders of magnitude smaller than for steel applications and might not reach also in the future comparable dimensions. Changes in global manganese demand over the coming years will therefore be largely determined by the development of steel demand, while the consequences of a supply disruption would likely hurt the battery production significantly. Over the longer term, however, manganese demand for batteries has a potential to reach a higher share in global manganese consumption. The slag from steel recycling might be a potentially large source of manganese. Even if research approaches to recover manganese from slags exist this is still in the development stage at the moment. For a closer examination of a possible manganese problem a deeper understanding of the respective global raw material cycle is needed. This requires sufficient and detailed data as well as further dynamic modelling in the use sector being important to gain insight into the probable future development.

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