High-tech metals are key elements for future technologies – How are their global market situations and what are the challenges?

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1. Future Technologies

New and emerging technologies have the potential to change global raw materials requirements substantially. This in turn can have significant impacts on the commodity markets such as sharp increases in prices and supply bottlenecks in the short-term as well as an increase in production in the mid-term.

An abrupt increase in demand driven by technological change rather than other economic developments can have implications on the availability of raw materials and their secure and sustainable supply. Hence, reliable estimates of potential future raw materials for emerging technologies are imperative to avoid negative economic impacts and supply shortages. This is particularly true for minor metals markets where future demand can potentially significantly outstrip current supply.

The study "Raw materials for emerging technologies 2016" (Marscheider-Weidemann, et al., 2016), looks at future raw material demand for 42 emerging technologies until 2035. Future mineral raw material demand is central to this publication and will be discussed for three of those technologies, namely wind energy and photovoltaics in the chapter renewables, and e-mobility. It is predicted that those technologies have the largest growth rates among renewable energy systems. Table 1 gives an updated overview of selected mineral raw materials, their demand in 2013 in key emerging technologies and their potential future demand in 2035 for these applications. A factor of 3.8 in the column D35/P17 means that we expect a sectoral demand of heavy rare earths (Dy/Tb) for magnets, e-cars, and wind power in 2035 accordingly 3.8 times the global production in 2017.

2. Renewables

To address the challenges of climate change, the global greenhouse gas emissions have to decrease drastically. The international community of states signed an agreement at the Climate Change Conference in Paris 2015. The Paris Agreement has the objective of holding the increase in global average temperature to well below 2 °C above pre-industrial levels. For that, the consumption of carbon dioxide intensive fossil-based energy carriers like oil or coal has to be diminished and substituted by low-carbon types of energy – mostly renewable energies. In 2017, renewables had a share of around 18 % of global primary energy consumption (BGR, 2019). Regarding global electricity generation, 25 % already came from renewable sources in 2018 (fig. 1, BP, 2019).

Global shares in electricity generation in 2018 from wind and photovoltaics were 4.8 % and 2.2 %, respectively (BP, 2019). This status quo is still significantly below the targets stipulated in the Paris Agreement, and thus requiring increased efforts to develop the sector. With renewable sources accounting for approximately 70 % of newly installed electricity worldwide in 2017 (BGR, 2019), the development of these technologies has implications on current and

Table 1: Estimated future sectoral demand for selected mineral raw materials for key emerging technologies – for a comparison the sectoral demand of these technologies in 2013, global primary production in 2017 and quotient of the sectoral demand in 2035 and the global production in 2017 are displayed as a factor (after Marscheider-Weidemann, et al., 2016).

Metal	Emerging technologies	Sectoral Demand 2013 [Tonnes]	Sectoral Demand 2035 [Tonnes]	Global primary Production 2017 [Tonnes]	Factor D35/P17[1] [rel. unit]
Heavy rare earths (Dy/Tb)	Magnets, e-cars, wind power	2.000	7.400	1,950[2]	3,8
Light rare earths (Nd/Pr)	Magnets, e-cars, wind power	29.000	64.000	24,000[2]	2,7
Lithium	Lithium-ion batteries, lightweight airframes	610	110.000	49,000[2]	2,3
Cobalt	Lithium-ion batteries, X[3] to Liquid	5.000	120.000	118,500[4]	1,0
Indium	Displays, thin layer photovoltaics	230	360	714[5]	0,5
Gallium	Thin layer photovoltaics, Integr. circuit, white LED	90	130	320[6]	0,4

[1] Demand for emerging technologies 2035 divided by primary production 2017; [2] BGR Database; [3] X = biomass, gas or coal; [4] Al Barazi, 2018; [5] Anderson, 2019; [6] Jaskula, 2019.

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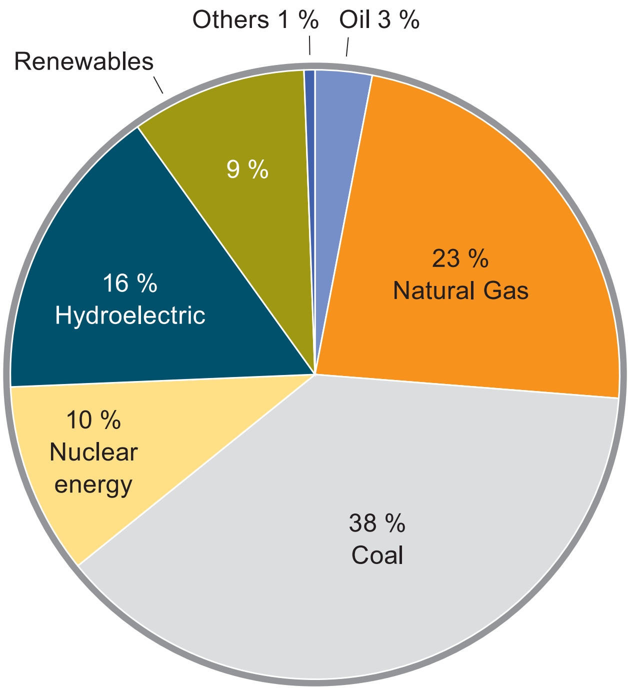

Figure 1: Global Electricity Generation by Fuel Type in 2018 (BP 2019). Hydroelectric is counted towards renewables in our definition.

future mineral raw materials demand.

2.1. Wind Energy

Wind turbines require a variety of different mineral raw materials for their construction including steel for tower and nacelle, cement for the base, compound materials for the rotor, different materials for the electronics and (especially in offshore facilities) rare earth elements, boron and iron for the permanent magnet for the generator. Low-maintenance offshore wind turbines contain neodymium, praseodymium, terbium and dysprosium in permanent magnets (Buchholz and Brandenburg, 2018). Until 2030, the wind

Metal	Demand for wind energy until 2030 [Million tonnes]	Production in 2017 [Million tonnes]
Iron	212	1264[R]
Copper	4,69	23.58[R]
Aluminium	4,69	61.24[R]
Chromium	2,23	7.38[R]
Nickel	1,64	2.04[R]
Tin	0,37	0.36[R]
Molybdenum	0,32	0.31[M]
Rare Earth Oxides	0,17	0.13[M]

[R] Refinery Production; [M] Mined Production

Table 2: Total sectoral demand of mineral raw materials for 1,625 GW wind energy capacities from 2018 to 2030 and their global production in 2017.

offshore sector is expected to grow at a much higher rate (around 20 % per annum) than the onshore sector (around 10 % per annum) (IEA, 2019) and demand of rare earth elements for use in wind turbines will remain high (Xia-Bauer et al., 2013).

In 2017, a total of 1085 TWh was derived from wind energy worldwide (BP, 2019). Global installed capacities were 539 GW in 2017, of which 52 GW was newly added that year (WWEA, 2018). Our estimates show that 1 MW requires a mineral raw material demand of 130 t of iron, 2.8 t of copper, 2.8 t of aluminium, 1.4 t of chromium, 1 t of nickel, 0.22 t of tin, 0.2 t of molybdenum, and 0.11 t of rare earth elements (rough estimates from different sources; see legend fig. 2). Figure 2 shows the development of global installed wind power capacity as well as the raw material demand for the newly installed capacity in 2017.

According to the Sustainable Development Scenario of the International Energy Agency (IEA, 2019), energy derived from wind energy should reach a total of 4,355 TWh in 2030, requiring capacities of 2,164 GW to reach that goal (assuming a constant ratio between

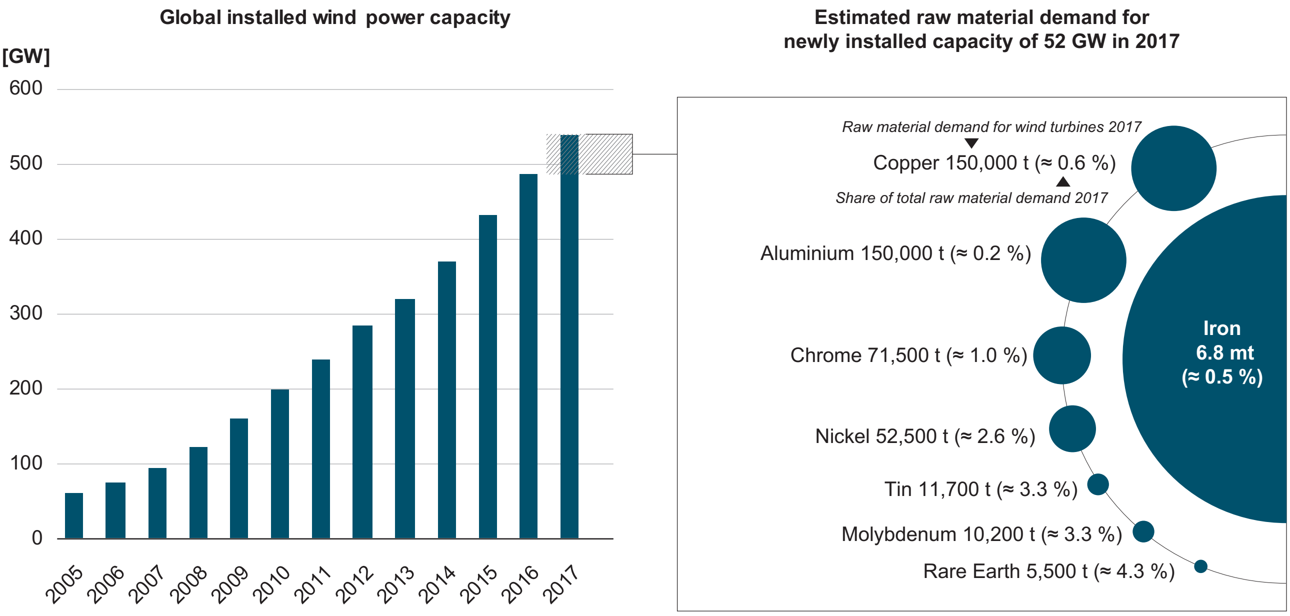

Figure 2: Global installed wind energy capacity (WWEA, 2018) and mineral raw material demand of the newly installed capacity in 2017 (Marscheider-Weidemann, et al., 2016, BGR Database; own calculations).

Metal	Demand for photovoltaics until 2030 [Million tonnes]	Production in 2017 [Million tonnes]
Iron	446	1264[R]
Copper	5,75	23.58[R]
Tin	1,21	0.36[R]
Lead	0,71	11.61[R]
Aluminium	0,27	61.24[R]
Zinc	0,01	13.22[R]

[R] Refined Production

Table 3: Total sectoral demand of mineral raw materials for 2,621 GW photovoltaic capacities from 2018 to 2030 and their global refinery production in 2017.

installed capacity and power generation). Taking the 539 GW installed capacity in 2017, an additional 1,625 GW would have to be added until 2030 (assuming current installed capacities stay in operation without power loss – hence the estimate is just an inferior limit). Table 2 lists the volumes needed until 2030, at current mineral raw material requirements, to achieve this goal.

The demand of powerful magnets for wind turbines has a particularly significant impact on the relatively small rare earth elements market. Rare Earth Elements (REE) are used in many high-tech sectors. Globally, they are used in catalysts (18 %), powerful magnets (30 %) and metallurgical applications (18 %), as well as in polishing, special glasses and ceramics (Kingsnorth, 2018). Producing wind energy is one of the key drivers for future REE demand.

REE are summarized as a group of 15 different elements which can be grouped into light and heavy REE (in most deposits, heavy REE have proportions below 10 %). Since the rare earth elements show similar chemical properties, they are jointly enriched in the ore forming processes. In consequence, they are mined and processed together.

In 2018, global mine production was approximately 175,000 t rare earth oxides (REO, official production excluding illegal mine production in China). Extraction is heavily concentrated in China (68 %). Additional rare earth elements production came from Australia (10.5 %, processing in Malaysia), Myanmar (9 %, processing in Myanmar and China), the USA (6 %, processing in China), Vietnam (2.7 %, processing in China and possibly Vietnam), Russia (1.5 %, processing in Estonia, Russia and Kazakhstan), India (1.1 %, processing in India and China), Thailand (0.6 %, processing in China), Burundi (0.4 %, processing in China), Brazil (0.3 %, processing in China) and Malaysia (processing in China).

There are only few processing facilities for rare earth oxides and elements with high-purity processing and refining facilities of rare earth ores worldwide. Today refining is taking place in China, Malaysia, Russia, Estonia and Kazakhstan. The processing of heavy rare earth elements is concentrated in China.

2.2. Photovoltaics

With approximately 90 % of shipped units and owing to their efficiency, thick-layer cells of the crystalline silicon wafer technology dominate the photovoltaics market. Thin-film technology could have the largest future potential because of their reduced raw material requirement (Buchholz and Brandenburg, 2018) as well as a continuously improving efficiency factor.

Photovoltaics had a global installed capacity of 402 GW in 2017, with 99 GW newly installed that year. Photovoltaics grew much faster than wind energy over the past few years. We estimate that 1 MW of installed photovoltaics capacity requires 170 t of iron, 2.2 t of copper, 0.46 t of tin, 0.27 t of lead, 0.10 t

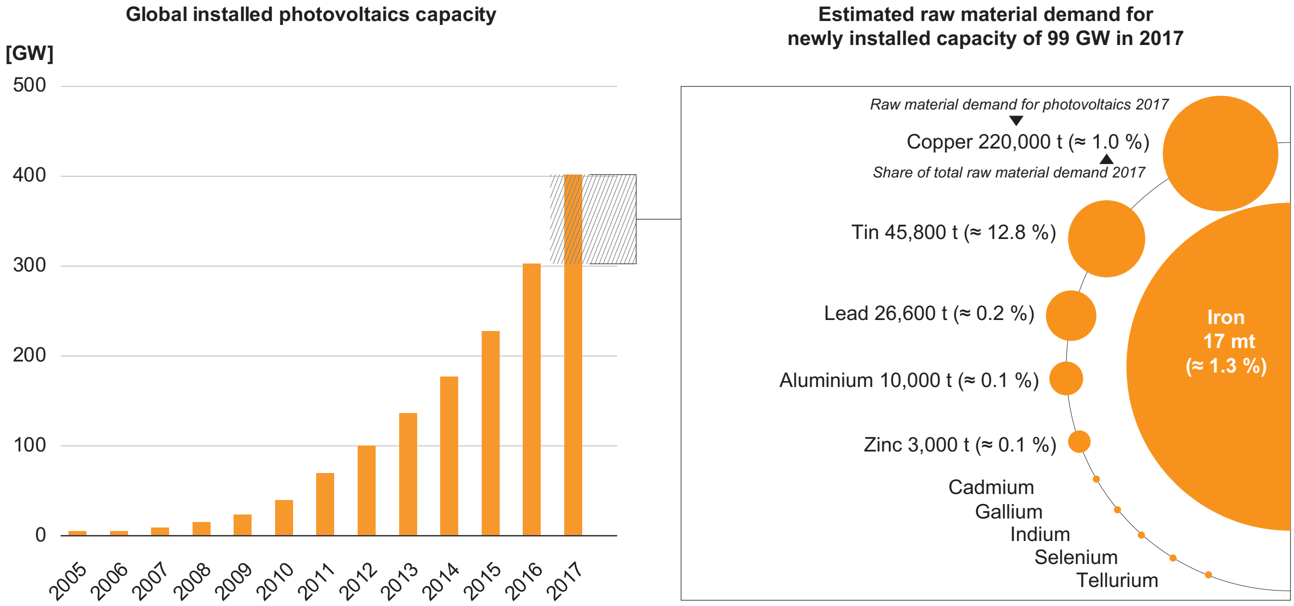

Figure 3: Global installed solar power capacity (SolarPower Europe, 2018) and mineral raw material demand of the newly installed capacity in 2017 (Müller, 2018, World Bank Group, 2017, BGR Database, own calculations).

of aluminium and 0.03 t of zinc (rough estimates from different sources; see legend fig. 3). Figure 3 shows the development of the global installed photovoltaic capacity as well as the raw material demand for the newly installed capacity in 2017.

According to the Sustainable Development Scenario of the International Energy Agency (IEA, 2019), energy derived from photovoltaics worldwide should reach 3,268 TWh in 2030, requiring additional capacities of 3,023 GW to achieve this target (assuming a constant ratio between installed capacity and power generation). In addition to global operating capacities in 2017, 2,621 GW would have to be added until 2030 (assuming current installed capacities stay in operation without power loss – hence the estimate is just an inferior limit). Table 3 lists the volumes needed until 2030, at current mineral raw material requirements, to achieve this goal.

Especially thin-film solar cells could have a huge impact on the small markets of indium, gallium, selenium, cadmium and tellurium. In thin-film solar cells, the coating materials consist, for example, of amorphous silicon (a-Si), copper indium (gallium) diselenide (CIGS) or cadmium telluride (CdTe). The technology-specific raw material demand of the semiconductor compounds of the thin-film elements of CdTe and CIGS thin-film modules is shown in table 4. The product-specific raw material content per electrical output (watt peak, Wp) depends on the layer thickness, the composition and efficiency of the solar cell, material losses during coating or rejects and the proportion of recycled material.

Gallium, germanium, indium, selenium, and tellurium are typical minor metals or high-tech metals. Minor metals share the following common characteristics (Gunn, 2014):

- low content in ores and minerals: few milligram to gram per tonne
- small markets with comparably low production rates: 10 to 100,000 tonnes/year
- mainly mined as by-products of principal metals
- complicated or undeveloped end-of-life recycling
- low substitution possibilities: very specific material characteristics

By-products can be produced from concentrates, mattes, slags or ash from primary or secondary sources due to market circumstances. Common sources for gallium are bauxite deposits and zinc ores. Coal and zinc ores can be the source for germanium, zinc ores further for indium, and copper ores for tellurium and selenium. The annual production as well as the country concentration is shown in figure 4.

3. E-mobility

In addition to autonomous driving, increasing digitalization and the principle of sharing, electric mobility stands for the mobility of the future. Electric mobility is growing at a rapid pace around the world. Approximately 2.1 million electric cars were sold globally in 2018, after 1.3 million in the previous year (fig. 5, EV Volumes, 2019). This number accounts for about 2.2 % of all vehicles newly registered in 2018 (ACEA, 2018). However, high annual growth rates for battery electric vehicles are expected in the coming years. This is associated with an increasing demand of battery raw materials, such as lithium, cobalt, nickel, graphite and manganese for lithium-ion (Li-ion) battery technology.

We modelled two demand scenarios until 2025 based on the following underlying fundamental: a base case scenario with roughly 7.4 million full electric vehicles (370 GWh – scenario 1) as well as a more optimistic scenario with 12 million full electric vehicles (600 GWh – scenario 2) in 2025. Commercial vehicles such as buses and trucks were not included. Automotive battery technology roadmaps identify Li-ion batteries as being the dominant battery type used from now to about 2050 (Concawe, 2019). Li-ion is a term applied to a group of battery chemistries that contain various materials. They all contain lithium in the cell cathode. Currently, there are six Li-ion battery technologies (Schmidt, 2017), the main difference between them being the composition of the cathode. For now, nickel manganese cobalt (NMC) chemistries are the preferred technology for the automotive industry. For our two demand scenarios we modelled the market share of different cathode chemistries. High-Ni NMC (8:1:1) cathode chemistries gain a market share of 54% in 2025.

Table 4: Worldwide production of selected raw materials and production-specific raw material demand in 2013 for CIGS or CdTe thin film photovoltaics (DS-PV) (Dorner and Liedtke, 2016; Marscheider-Weidemann, et al., 2016).

Metal	Production in 2013 [Tonnes]	Demand for thin-film photovoltaics in 2013 [Tonnes]	Specific raw material demand for CIGS* [g/kWp]	Specific raw material demand for CdTe [g/kWp]
Indium	790	35 – 103	23 – 67	-
Gallium	350	11 – 45	7 – 30	-
Selenium	3.000	92 – 230	60 – 150	-
Cadmium	22.750	178 – 315	-	60 – 105
Tellurium	500 – 550	201 – 355	-	67 – 119

* Stoichiometry: $Cu(In_{0.7}Ga_{0.3})Se_2$

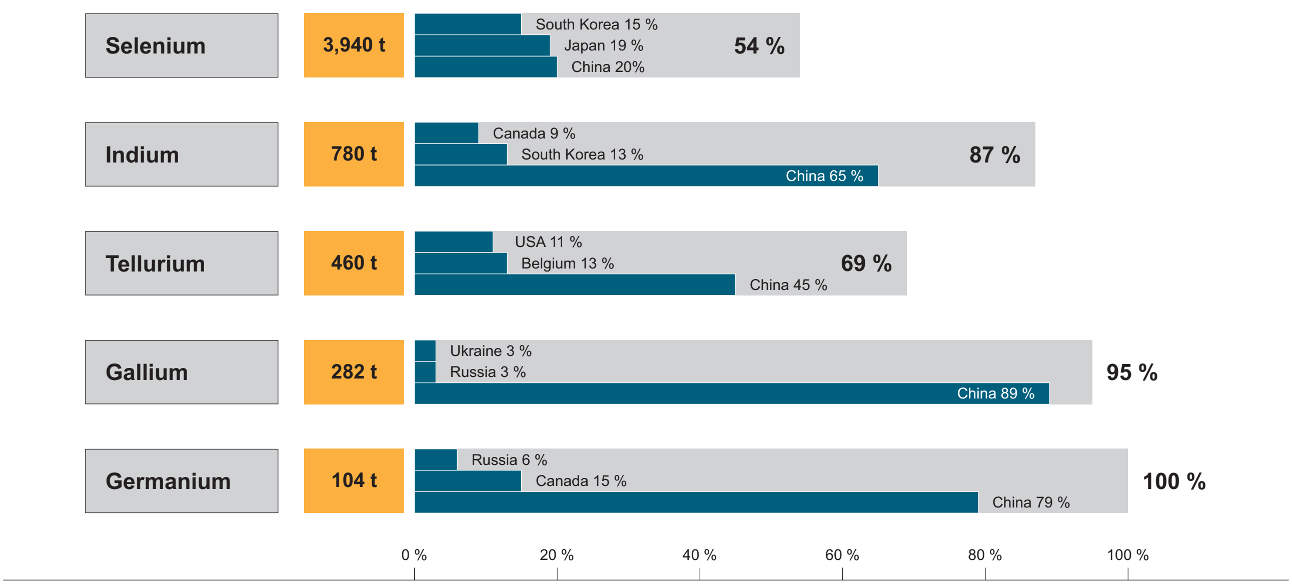

Figure 4: Global minor metals production and their country concentration in 2016 (DERA, 2019).

With the current NMC chemistry we estimate that 1 MWh of battery capacity requires on average 0.51 t of nickel, 0.22 t of cobalt, 0.2 t of manganese, 0.18 t of lithium and 0.57 t of graphite. The estimated raw material demand for the batteries of 1.3 million electric vehicles registered in 2017 is shown in figure 5.

Especially the cobalt and lithium markets have been very volatile in the last two years due to the industry's high expectations for the application of Li-ion batteries, particularly for e-mobility but also for renewable energy storage.

Lithium is mainly used for rechargeable batteries (about 37 % in 2015 and 50 % in 2018 of total demand), followed by the glass and ceramic industries. A number of further applications include polymers, metal powders, processing of air, non-rechargeable batteries, and aluminium alloys (Schmidt, 2017; Roskill, 2016).

Because of the booming e-mobility market, the demand for lithium in rechargeable batteries could increase dramatically from about 12,000 t in 2015 to about 84,000 t (scenario 1, 76 % of total demand) to 125,000 t (scenario 2, 82 % of total demand) in 2025 (Schmidt, 2017).

Global mine production was around 57,000 t lithium in 2018. About 86 % of global lithium mine production came from only three countries, namely Australia (27,000 t), Chile (15,900 t) and Argentina (6,240 t). Lithium is produced from salt brines located in large salars such as the Salar de Atacama in Chile or the Salar de Olaroz in Argentina. Furthermore, lithium is mined from pegmatite deposits, with the Greenbushes deposit in Australia currently being the largest.

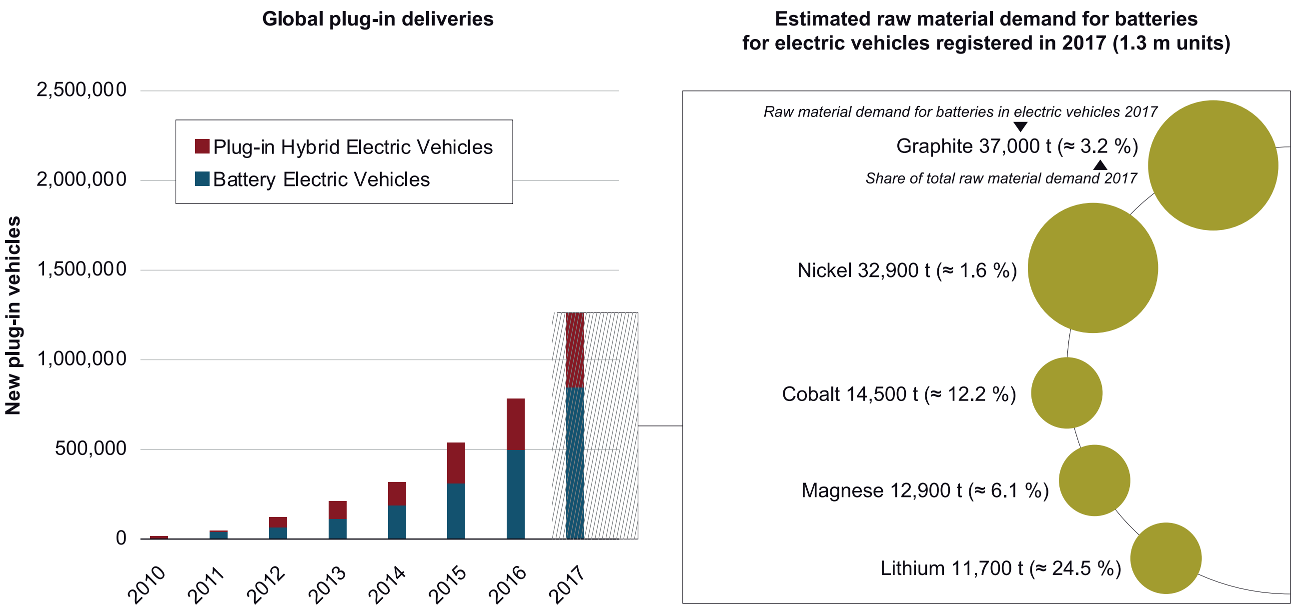

Figure 5: Global Electric vehicle registration from 2010 to 2017 (EV Volumes, 2019) and estimated raw material demand for EV-batteries in 2017 (BGR Database, own calculations).

Current supply and demand scenarios for 2025 indicate that future mine production could meet demand at annual growth rates of around 12.8 %. Higher growth rates for rechargeable batteries could, however, result in supply shortages for lithium (Schmidt, 2017).

Due to its specific properties, cobalt is used in many different applications such as the fabrication of rechargeable batteries, NiMH batteries, NiCd batteries, superalloys, carbides, dyes, and magnets amongst other applications (Al Barazi, 2018).

Cobalt is mainly mined as a by-product from copper and nickel mining. Global mine production was nearly 140,000 t in 2018. With 64 % of global supply, the Democratic Republic of the Congo (DRC) is currently the world's largest cobalt producer with production expected to increase to over 70 % in 2026. Additional supply from the DRC will mainly come from conventional industrial mining operations. However, artisanal and small-scale mining (ASM) of cobalt has long been established in the DRC and represents an essential livelihood for large parts of the population in the Haut-Katanga and Lualaba provinces. About 15 to 35 % of the DRC's total cobalt production is estimated to originate from ASM mine sites depending on the cobalt price. Amnesty International (2016) assumes that 110,000 to 150,000 people are involved in artisanal cobalt mining. Both industrial and artisanal and small-scale mining will remain relevant to meet future global demand for cobalt. Therefore, the establishment of internationally recognized and accepted standards for a responsible sourcing of cobalt from ASM is essential to improve working conditions in this sector (Al Barazi, 2018).

We assume that global cobalt demand for rechargeable batteries in the e-mobility sector will increase to 47.870 t (scenario 1, 26 % of total demand) or 77.680t (scenario 2, 36 % of total demand) by 2025, respectively. Our supply and demand scenarios for 2025 indicate that future mine production could meet demand at annual growth rates of around 8 %, assuming that all projects will commence production at full capacity.

4. Conclusions

Low-carbon technologies such as wind energy, photovoltaics and energy storage batteries for e-mobility are key for a shift to a low-carbon future. The expected dynamic change towards renewable energy systems will have a major impact on the mineral raw material markets in the next decades. The demand for base and minor metals for clean energy technologies is expected to rise substantially. Primary raw material production needs to provide most of the metals for low-carbon technologies, at least for the upcoming decade, because secondary raw material supply alone cannot accommodate the future demand. Therefore, upstream and end-of-life activities of low-carbon technologies must be taken into account to ensure firstly that the mining industry can meet the increasing demand using sustainable and responsible practices and secondly that the products can be recycled in the best possible way.

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