Future Resource Availability for the Production of Lithium-Ion Vehicle Batteries

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***Abstract*—In this analysis we discuss the future availability of materials which will be required for the production of lithium-ion batteries in hybrid and electric vehicles. We look closely at the raw materials used in two common lithium-ion battery types, i.e. those with lithium nickel manganese cobalt oxide and lithium iron phosphate cathodes. Three different scenarios are used to model the future increase of hybrid and electric vehicles in the global vehicle fleet as well as to derive the mass flows required for battery production and for other uses of the materials assessed. Further, we consider the available material flows obtained from recycling and estimate the remaining necessary primary material production. The required growth of raw material production is analyzed and the cumulated material production is compared with the reserves and resources known today. As expected, for the materials considered there is not a serious risk of scarcity in the future, although a high penetration of hybrid and electric vehicles is assumed in the analysis. The known reserves and resources of lithium would provide enough of the element to cover demand until 2050 and well beyond. Only for cobalt and natural graphite do we detect a certain risk for reserve/resource depletion and ensuing scarcity. However, as cobalt is not required for lithium iron phosphate batteries and as natural graphite can be substituted by (more expensive) synthetic graphite, there are two possibilities of overcoming this potential threat.**

Keywords—lithium; cobalt; graphite; lithium ion; battery technology; resource depletion; resource availability.

I. Introduction

The introduction of electric vehicles is considered to be a measure of the transformation towards environmental friendliness and sustainability in the mobility sector. Several concepts exist, ranging from hybrid vehicles (HEV) running on a conventional engine and chargeable plug-in hybrid vehicles (PHEV) to pure battery electric vehicles (BEV). A range-extended battery electric vehicle (RE-BEV) can use a small engine and a generator for charging the battery while driving. A fuel cell electric vehicle (FCEV) is equipped with a fuel cell generating electricity from hydrogen or other fuels and a small battery helps as a buffer to feed the electric motor of the vehicle. [1]

These vehicle technologies require batteries of different size, which are expected to provide a high energy density, a high power density, high safety and low cost. Having used lead acid batteries in electric vehicles more than a century ago [2] and, more recently, nickel cadmium and nickel metal hydrate batteries in hybrid vehicles, lithium-ion batteries are the technology of choice today [3].

Depending on the detailed electrochemistry several different types of lithium-ion battery are in use: nevertheless, a lithium nickel manganese cobalt oxide cathode or a lithium iron phosphate cathode together with an intercalated graphite anode seem to be viable ways for the future. These battery technologies are often referred to using the abbreviations Li(NMC) and LiFeP, respectively.

The use of these battery technologies in hybrid and electric vehicles means that various elements, mainly metals, might be required in large quantities in future. On the other hand, the availability of economically mineable deposits may decrease due to mineral depletion, so that the production of such quantities may not be a straightforward matter. Generally, it is not yet clear whether in specific cases mineral depletion has already led to "scarcity" (in its purely economic sense), although we know that the average ore grade for several elements has fallen in recent years. "Complete" depletion is highly unlikely to occur, but decreasing ore grades mean higher extraction costs and potentially more serious environmental problems.

It must also be mentioned that short-term supply restrictions can also occur for political reasons rather than due to physical depletion. Indeed, any restriction of the currently installed production capacity can lead to a supply shortage and trigger price increases.

Important factors are the resources and reserves, terms which require some explanation. The United States Geological Survey (USGS) defines resources as "a concentration of naturally occurring solid, liquid, or gaseous material in or on the earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible." [4] On the other hand, the reserves are defined as: “That part (…) which could be economically extracted or produced at the time of determination. The term reserves need not signify that extraction facilities are in place and operative. Reserves include only recoverable materials;” [4] Such figures obviously refer only to the known resources and reserves. Over the years *unknown* resources, some of which may have been hitherto classified as putative resources, become *known* resources, as the USGS explains for the case of copper [4]. We still feel, however, that the comparison of known resources and reserves with annual production rates is a useful exercise, since it tells us how long a particular element may be available at its present price level and with currently available production technologies. Moreover, it emphasizes the fact that the unbridled consumption of natural resources is not a sustainable solution.

For assessing the future availability of materials required for battery production, we choose the following approach: as a result of a literature survey, we identify all materials relevant for the production of battery cells for electric vehicles. Subsequently, we propose three possible scenarios for the future share of hybrid and electric vehicles in the global car fleet. Short summaries of the relevant materials are given, including their annual production rates, reserves and resources. Then we focus on the recycling possibilities of these materials from automotive batteries and make an estimate of the recycling possibilities from other uses. All this information is used in a very simple material flow analysis (MFA) from which the required primary material production is derived for each year between today and 2050. Finally, the results are presented and an interpretation is given.

II. Literature Survey

A. Relevant materials

In recent years, battery electric and hybrid vehicles (BEVs and HEVs) have become a widespread hope for the reduction of environmentally harmful substances which are emitted in the mobility sector. This applies particularly to greenhouse gas emissions which lead to global warming [5], but presume of course that the batteries used are charged with electricity produced from renewable sources. Nevertheless, the production of electric and hybrid vehicles requires various materials which previously have been used only in rather small quantities. Since their production and use will most likely undergo a significant change in future, these materials and their future availability have been discussed in various studies [6-9]. In the following a short outline of these investigations will be given.

Together with appropriate industry partners, the German Öko-Institut assessed 12 materials which play an important role in the technologies of electric vehicles [6]. These are: copper, gallium, germanium, palladium, silver, indium, platinum, gold, praseodymium, neodymium, terbium, and dysprosium. The two elements lithium and cobalt were not treated, since they were analyzed in a different project. Among the materials considered, only copper is used in relevant quantities in modern lithium-ion batteries.

The situation with regard to copper was investigated in a study by the Fraunhofer ISI [7]. According to their calculations, the economically viable copper reserves today might be depleted by 2030. Nevertheless, as geological copper resources are quite abundant, the availability of copper will most probably not be restricted on this time-scale.

An assessment of the elements lithium and cobalt for lithium-ion battery technology and their recycling was given in the so-called LiBRi [10] and LithoRec [11] reports. In a detailed analysis, the consumption of lithium until 2050 stays well below the level of the reserves that are considered economically feasible today [12]. For cobalt, the study predicts that, according to a moderate scenario, present reserves might be used up before 2050, whereas for a larger penetration of electric vehicles the cumulative demand would require all the resources known today [12].

The Fraunhofer ISI has also produced a report on the future availability of lithium [8]. In this study the amount of reserves is reported to be about half of that assumed in the LithoRec report [12]. Hence, according to these calculations the reserves might be exceeded by future demand; nevertheless, the latter will stay well below the available resources.

A different approach to illustrate potential supply restrictions is the calculation of the so-called cumulative supply or cumulative availability curve (see [13]), which shows the increase in cost over time, expressed in terms of the accumulated quantity of the element supplied. Hence, such a plot shows, amongst other things, the rising technological and economic effort that has to be expended as ore deposits of increasingly lower grade have to be exploited (see above). Fig. 1 shows such a curve for lithium from Yaksic and Tilton [14]. These authors assess the predicted lithium demand and the available deposits and find that there is a low probability for a shortage of lithium in coming decades

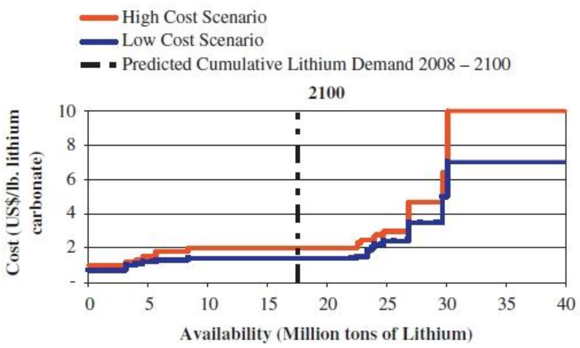


Fig. 1. Cumulative supply curve for lithium [14]

Although there are already numerous publications addressing the question of future resource availability, they rarely come to definitive conclusions. The approach of Tilton [13] is interesting because it allows for the fact that reserves and resources are subject to variations in time. Whereas the amount of resources is only increased by discoveries of new deposits, a rising raw material price alone increases the amount of reserves, as more deposits become economically feasible.

Fig. 2 shows the development of both the price and the reserves of phosphate rock. It seems evident that the high price level 2007 - 2008 led to the increase of economically mineable reserves. As the market prices of some commodities can be very volatile, the amount of reserves has been subject to substantial variations. Hence, regular updates can reveal new insights.

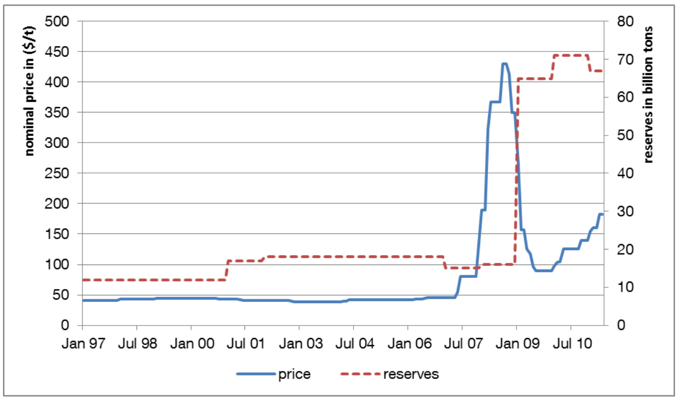


Fig. 2. Price and reserves of phosphate rock (according to USGS and World Bank [15])

B. The scenarios:The role of electric and hybrid vehicles in the future global vehicle fleet

As the automotive industry is an important key sector in many developed and developing economies, sound statistics exist on the production and the registration of vehicles. However, a prediction regarding future vehicle production and sales is hard to make and only a few data can be found. A summary obtained in a literature survey is given in Annex A.1 and A.2 which estimates future vehicle sales until 2030. From this we derive our baseline assumption for the average annual increase of the car production which we set at 3.0% p.a. We use this growth rate for the entire time period of the assessment i.e. from 2013 to 2050.

In a second step the shares of the relevant powertrain technologies among the cars produced need to be estimated. There are numerous reports which estimate the development of electric and hybrid vehicles in the future car fleet on the global or national levels. Often, different scenarios are established which consider the growth possibilities for various technologies or are based on particular policies supporting one technology or another. We have taken the predicted share of relevant vehicle technologies according to five different studies in which favorable conditions for electric vehicles were assumed [8, 16-19]. As the battery capacity of both HEVs and FCEVs is usually quite small (e.g. Opel HydroGen4 [20], VW Touran-HyMotion [21], see also [22]), we merged the shares of these two technologies. The summary of the literature survey and the assumptions used for this study can be found in Annex B. The resulting scenario we describe as the "baseline scenario".

As mentioned earlier, however, we would like to use in addition other scenarios for the growth of future car production. One possibility is to assume that the world population grows to 9.6 billion people in 2050 [23] and that economic wealth – including the demand for cars – is globally on a high level similar to that today. We call this scenario the "economic prosperity scenario".

Fig. 3 shows the development of vehicles per population over per-capita income for some countries according to [24]. The authors of this paper attempt to predict the vehicle ownership assuming individual saturation levels for each country which are estimated to have values between about 500 and 850 vehicles per 1,000 people.

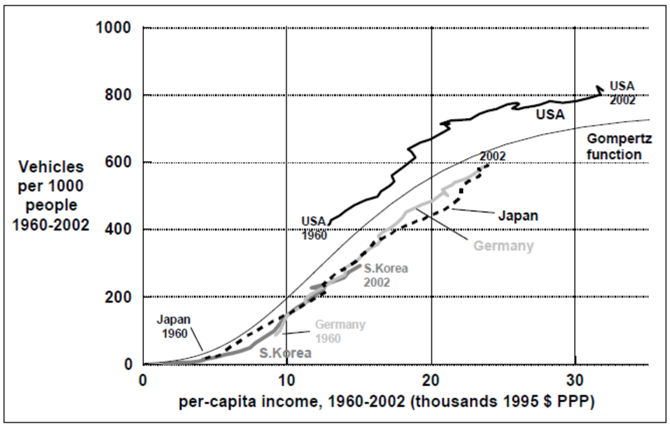


Fig. 3. Number of vehicles over income for several countries [24]

Also, the World Bank publishes statistics regarding the current number of vehicles and passenger cars per capita in each country [25]. A summary can be found in Table I which shows that many countries and hence the world average today is far below the values for developed countries.

TABLE I. STATISTICS REGARDING THE NUMBER OF VEHICLES AND PASSENGER CARS PER 1,000 PEOPLE IN 2010 [25]

country	vehicles	cars
United States	797	423
Japan	591	453
France	580	481
Germany	572	517
Russia	271	233
Brazil	209	178
Singapore	149	117
China	58	44
India	18	12
High income countries	620	446
Euro area	593	n.a.
World average	176	124

For our analysis we assume in accordance with [19] that there will be a global average of 500 passenger cars per 1,000 people in 2050. We also assume that the average vehicle life will be similar to that of cars in developed markets today which is reported to be 8.3 years in the EU [26] and 11.4 years in the US [27]. Hence, we estimate an average vehicle age of 10 years for the future global passenger car fleet which results in a yearly car production of 480 million cars per year to maintain the total stock of vehicles in 2050. Assuming an exponential growth of production, this leads to an annual growth rate of 5.5% p.a.

In our third scenario we would like to describe a situation in which the extended use of information and communication technology (ICT) leads to a higher utilization rate of vehicles, thus decreasing the total production demand of passenger cars. Car-sharing is a well-known instrument already applied today, but more approaches exist which aim for a more efficient utilization of vehicles. Although it is hard to predict the achievable reduction of vehicles in the future, a typical order of magnitude seems to be 30% [19, 28]. These figures lead to a global production of only 336 million cars per year which represents an average production growth of 4.5% p.a. until 2050. We refer to this below as the "ICT scenario".

C. *Characteristics of relevant materials*

1) *General information on battery technologies*

Electric vehicles provide several advantages such as energy efficiency and reduced energy dependence compared to conventional vehicles. Nevertheless, their disadvantages include some serious limitations which are mainly related to the vehicle battery. These comprise a limited driving range, a long charging time, the high cost of the battery pack and its size and weight.

In contrast to earlier commercialized battery technologies, lithium-ion batteries have facilitated huge advances in mobile device technology in the last 10 – 20 years. These include small, light devices such as tablets and laptops, cameras and mobile phones. In hybrid vehicles this battery technology has also replaced that of metal hydrate batteries [3].

Two common types of lithium batteries will be assessed within this study. The first one is often referred to as Li(NMC)-battery, as it uses a mixed cathode which contains the elements lithium, nickel, manganese and cobalt. By using the latter three elements in the cathode the properties of the battery can be influenced regarding the battery performance, safety, and cycle stability [29]. The high price of cobalt in particular was a major reason why suitable alternatives have been sought. One of the most promising is the lithium iron phosphate battery (LiFeP) which contains the abundant elements iron and phosphorous. Nevertheless, the battery chemistry shows certain disadvantages compared to the Li(NMC) batteries. The first one is the lower cell voltage of 3.3 V compared to 3.7 V [29]. Due to this difference more LiFeP than Li(NMC) cells are required and need to be connected to form a battery pack of a certain typical voltage level, e.g. 400 V. Furthermore, its energy density is usually lower, which results in a heavier battery pack and in turn a higher electricity consumption of the vehicle [11]. This leads to a larger battery required for providing the same electric range. Both battery technologies usually use intercalated graphite for the anode.

2) *Information on relevant elements*

In the following paragraphs, the materials which are relevant for the two battery technologies considered here are presented briefly and their characteristics regarding, production, reserves and resources given.

a) Lithium

Lithium which obviously is the most important element in these battery technologies has a relatively high abundance in the earth's crust of 60 ppm. This makes lithium the 27th most abundant element in the lithosphere [30]. Its global reserves and resources are estimated to be 13 and 39.5 million tons, respectively [4]. The annual production is estimated at 29,350 t/a (average of USGS [4] and BGS [31]) resulting in about 440 years for the static lifetime of the reserves. Main applications for lithium are glass and ceramics (37%), batteries (20%), lubricants (11%), aluminum smelter (7%), and air treatment (5%) among others [8]. The price for battery-grade lithium carbonate in China is reported to be 6,750 US$/t in 2011 [33].

b) Nickel

The global reserves of nickel are estimated to amount to 75 million tons and its land-based resources more than 130 million tons [4]. With a production of about 1.9 million tons per year [4, 31] its reserves have a static lifetime of around 40 years. The metal is usually used for various alloys: the production of chromium nickel steel consumes about two thirds of the total nickel produced [30]. Its price is rather high with an average of 22,890 US$/t in 2011 [33].

c) Manganese

The manganese concentration in the earth's crust is quite high at about 0.1% [30]. The reserves are estimated to be 630 million tons while the USGS reports that the resources are quite extensive [4]. The annual production amounts to 16 million tons, which gives a static lifetime of ca. 40 years for the reserves [4]. The element is of great importance for many alloys, especially for the production of iron and steel [30]. With a price of about 4,010 US$/t for manganese metal the material is much cheaper than nickel [33].

d) Cobalt

Cobalt is an element with a long history, and with a concentration of 20 ppm in the lithosphere, has a similar abundance to lithium. However, only few regions exist where the cobalt concentration is high enough for economic production [30]. Its annual production is estimated to about 130,000 tons [4, 31] of which the Democratic Republic of

Congo produces a major share. The global reserves are estimated at 7.5 million tons resulting in a static lifetime of about 60 years. The identified resources are about 15 million tons [4, 33]. Besides its use in batteries (27%), cobalt is used for super alloys and magnets (26%), for the production of hard metals (14%) and pigments (10%) and for catalysts (9%) [32]. Its price is rather high at a level between 35,000 and 40,000 US$/t in 2011 [33].

e) Iron

With a concentration of 4.7%, iron is the most abundant metal in the earth's crust after aluminum [30]. It is the world's most important metal and has innumerable uses both in industrial and for private applications. The crude ore reserves are estimated to be 170 billion tons worldwide (with an iron content of 80 billion tons) [4] and the annual production comprises 3 billion tons of iron ore, 1.1 billion tons of pig iron and 1.5 billion tons of raw steel [4, 31]. Hence, the static lifetime of iron ore is about 55 years. The iron resources total 800 billion tons of crude ore containing 230 billion tons of iron [4]. The material is cheap: iron ore is sold for prices of 50 – 200 US$/t depending on the grade [33]. Pig iron has a price of about 550 US$/t [34] and hot rolled steel sheets cost between 700 and 1,000 US$/t in the US [33].

f) Phosphorus

Phosphorus is a relatively abundant element with a concentration of about 0.1% in the earth's crust [32]. Metallic phosphorus is produced in a reduction process which uses phosphate rock as the raw material. The global reserves of phosphate rock are around 67 billion tons and its resources are more than 300 billion tons [4]. As its production is about 208 million tons per year [4, 31] – which represents around 27 million tons of phosphorus [30] – the static lifetime of its reserves is about 320 years. It is predominantly used as fertilizer in agriculture (90%) whereas industrial use only plays a minor role (10%) [32]. The price level of phosphate rock is quite low at around 100 US$/t and elemental phosphorus costs around 3,740 US$/t [33].

g) Natural graphite

Graphite is the "standard material" for the anode in many battery technologies relevant for electric vehicles. It is a soft, electrically conducting material consisting of sheets of carbon atoms. Two different types of graphite can be used in batteries: The first one is synthetic graphite which can be produced by petrochemical processing [35]. The result is a very pure graphite structure but as its production requires large amounts of energy, the material is quite expensive with a price of between 7,000 and 20,000 US$/t [33]. In recent years, however, cheaper, natural graphite with its lower quality has been increasingly used in batteries (natural graphite with 90 – 95% carbon costs about 1,000 - 2,000 US$/t [32] and spherical graphite for batteries made from natural flake costs about 6,000 – 10,000 US$/t [36]). The reserves are estimated at 77 million tons of which ca. 85% are located in China and India. The annual production totals around 1.6 million tons [4, 31] which results in a static lifetime of about 50 years. The natural graphite resources exceed 800 million tons [4]. Natural graphite finds use in foundries (24%), in the steel industry (24%), in crucible production (15%), and in electrical applications (12%). The use in batteries represents only a minor share (4%) [37].

3) Assumed properties and composition of the batteries

The precise composition of a battery is usually a well-kept secret of the manufacturer. Thus, we have only been to use published data to determine typical masses of the relevant elements within a vehicle battery. The raw data used can be found in Annex C and the values derived are shown in Table II.

TABLE II. REQUIRED AMOUNT OF ELEMENTS IN GRAMMS PER KILOWATTHOUR OF BATTERY CAPACITY (SEE ANNEX C)

Li(NMC) batteries		**LiFeP batteries**	
lithium	177 g	lithium	119 g
nickel	459 g	iron	1030 g
manganese	432 g	phosphorus	478 g
cobalt	467 g	graphite	1,560 g
graphite	1,626 g		

For the estimation of the necessary battery capacity which is typically installed in the individual types of vehicles, we use data reported in the literature. Table III shows typical values for the various types of powertrains according to [1]. As we want to make conservative estimates, we decided to use the values of the upper range limits for the hybrids and 25 kWh for BEVs.

TABLE III. TYPICAL BATTERY CAPACITIES (IN KILOWATTHOURS) ACCORDING TO [1]

Powertrain technology	**Typical battery capacity**
Micro, Mild, and Full Hybrids	0.6 - 2
Plug-In Hybrids	3 - 10
BEV	10 - 30

With these assumptions as to the installed battery capacity, we can calculate the amount of material which is required for a certain type of vehicle. Obviously, the battery performance will improve in the coming decades and the amount of necessary material for a certain energy capacity of the battery might decrease. Nevertheless, we assume that these improvements will be compensated by the tendency to increase the battery capacity and thus the total amount of required material is expected to remain approximately constant.

D. *Assessment of the current and future recycling situation with regard to vehicle batteries*

The efficiency of a recycling scheme is determined by a number of factors: The first is the collection rate which expresses how much of a produced material is collected at the end-of-life of the products containing this material. Several further efficiency factors express various types of material losses during the individual steps of the recycling process. The overall recycling efficiency is the product of these individual rates and efficiencies.

As the collection rate for lead acid vehicle batteries is already almost 100% today [8, 38], we assume that all lithium-ion vehicle batteries will be collected in future and therefore focus on the achievable efficiency of the recycling process.

Several recycling processes for lithium-ion batteries have been developed. They can be grouped into two subgroups: pyrometallurgical and hydrometallurgical processes. Many treatments also combine these two types and use in addition a mechanical treatment. In pyrometallurgical processes organic and carbon compounds, i.e. the electrolyte and the graphite anode, are usually lost, as they are used as reducing agents and energy source in the high temperature process. Further, ignoble metals as well as lithium are usually slagged and hence cannot be recovered. However, pyrometallurgical processes are able to recover cobalt and nickel from the battery cells [10, 39]. On the other hand, hydrometallurgical processes aim at the recovery of more materials, including organic materials. In this chemical treatment certain materials can be recovered from the bulk element specifically. Hence, the recovery of cobalt, nickel, manganese and also lithium is possible. [11, 39]

However, since present recycling processes are economically driven, they tend to recover only the sufficiently valuable metals i.e. cobalt and nickel. The company Umicore runs a pilot facility with an annual capacity of 7,000 tons of NiMH and lithium-ion batteries, which primarily produces a cobalt-nickel-copper alloy but also provides the option to recover lithium [40]. The industrial-scale processes existing today only extract copper, nickel, and cobalt from Li(NMC) batteries and iron from Li(NMC) and LiFeP batteries, whereas manganese is usually not recovered [41]. As the recycling efficiency is reported to be quite low (< 30% for Li(NMC) and <10% for LiFeP [59]), we assume - rather arbitrarily - a present recycling rate of nickel and cobalt of 85%.

Two detailed studies analyze the future recovery potential of the relevant metals from lithium-ion batteries within specifically developed recycling processes: the first assesses the recovery of lithium, nickel, and cobalt in a combined pyrometallurgical and hydrometallurgical process from a mixture of Li(NMC), lithium nickel cobalt aluminum (Li(NCA)) and LiFeP batteries [10]. The second addresses a purely hydrometallurgical process which additionally recovers manganese from Li(NMC) and is also applied to LiFeP batteries [11]. Neither process recovers graphite from the batteries, nor iron or phosphorous from the LiFeP batteries. Table IV shows the reported recovery rates of metals according to the recycling processes presented in these studies. It must be mentioned that these results were obtained partially in laboratory experiments and that the processes do not yet exist on an industrial scale. Moreover, no data regarding their economic performance are given.

TABLE IV. RECOVERY RATES ACCORDING TO [10, 11] IN %

Material	LiBri [10]	LithoRec: Li(NMC) [11]	LithoRec: LiFeP [11]
Li	57	94	81
Ni	95	97	n/a
Mn	0	~100	n/a
Co	94	~100	n/a
Fe	0	n/a	0
P	0	n/a	0
graphite	0	0	0

For our study, we assume that recovery rates for the materials concerned will be according to the maximum values reported by these studies, but not before 2025. For the period until then, we interpolate linearly between the recovery rates estimated for the future and those of today. Furthermore, as the recycling rates will be less in an industrial-scale plant than in the laboratory test, we decrease the values to 95% if the given recovery rates exceed this threshold.

Regarding the lifetime of the automotive lithium-ion batteries we use the distribution given in [41] which is summarized in Table V.

TABLE V. CUMULATIVE SHARE OF END-OF-LIFE BATTERIES AFTER A CERTAIN USE TIME (IN %) [41]

Cumulative share of end of life batteries (in %)								
2 yrs.	*3 yrs.*	*4 yrs.*	*5 yrs.*	*6 yrs.*	*7 yrs.*	*8 yrs.*	*9 yrs.*	*10 yrs.*
0	10	20	30	40	50	60	80	100

For the market share between Li(NMC) and LiFeP batteries we assume a distribution of 70:30 in the automotive sector [41].

E. *Assessment of the current and future recycling situation and the future material requirements for other uses*

In this section we highlight the recycling of the materials in products other than vehicle batteries. We estimate that the demand of the assessed materials for other uses grows at the same rate as global economic growth. This is estimated to be 2.8% until 2030 in the OECD Environmental Outlook [42] and we assume that the material demand for non-battery uses will grow accordingly within our assessed time period.

Obviously, every product that contains a certain material influences the collection rate of this material. Also, the individual lifetime of products influences the time when a flow of recycled material occurs. Iron used in the structure of an automobile can be recycled after maybe ten years whereas the iron contained in the reinforced concrete of a building might be used for several decades. Most probably, the recycling efficiencies of these two products also differ. A detailed list of uses and products containing the materials assessed in this study and an estimation of the individual lifetime and recycling efficiency would exceed the scope of this study and induce too high uncertainties. Nevertheless, the recycling from non-battery uses needs to be modeled for a complete picture of the relevant material flows.

To overcome this problem, we decided to use current figures for the recycled content in global material production. Table VI shows the average values of the recycled content in the production of lithium, nickel, manganese, cobalt, and iron [43]. Although the proportion of recycled material is likely to rise in future, we use these values consistently throughout the chosen time period as a basis for our worst-case estimate.

TABLE VI. RECYCLED CONTENT IN FIVE METALS TODAY (%) [43]

Recycled content (%)				
lithium	***nickel***	***manganese***	***cobalt***	***iron***
< 1	38	37	32	42

Lithium is sometimes recovered after being used in batteries and in absorption cooling – a minor use for lithium within the air treatment sector [8]. As these usages are quite small and all other applications lead to the dissipative use of lithium, the recycling is only considered for batteries in our assessment.

The recovery of graphite from steelmaking is reported to be technically feasible [37], but due to its abundance in the market it is not practiced. Unfortunately, we could not find any further information on the recycling of graphite, for which reason we neglect it in our assessment.

As phosphorus is mainly used as a fertilizer in agriculture, its use is highly dissipative. It is mostly taken up by plants or washed away [32]. Hence, we also neglect the recycling of phosphorous in our analysis.

III. SIMPLE MATERIAL FLOW ANALYSIS

A. *Assessment of the baseline scenario*

With the data and assumptions presented in the previous section, we can simulate a very simple material flow analysis (see [44]). First, we consider the baseline scenario in which we assume a growth of the global vehicle production as shown in Fig. 4.

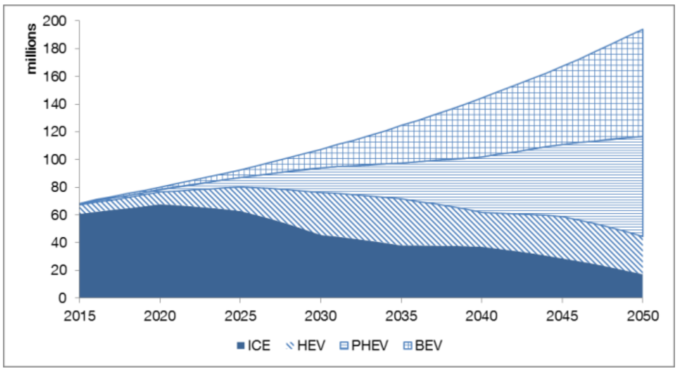


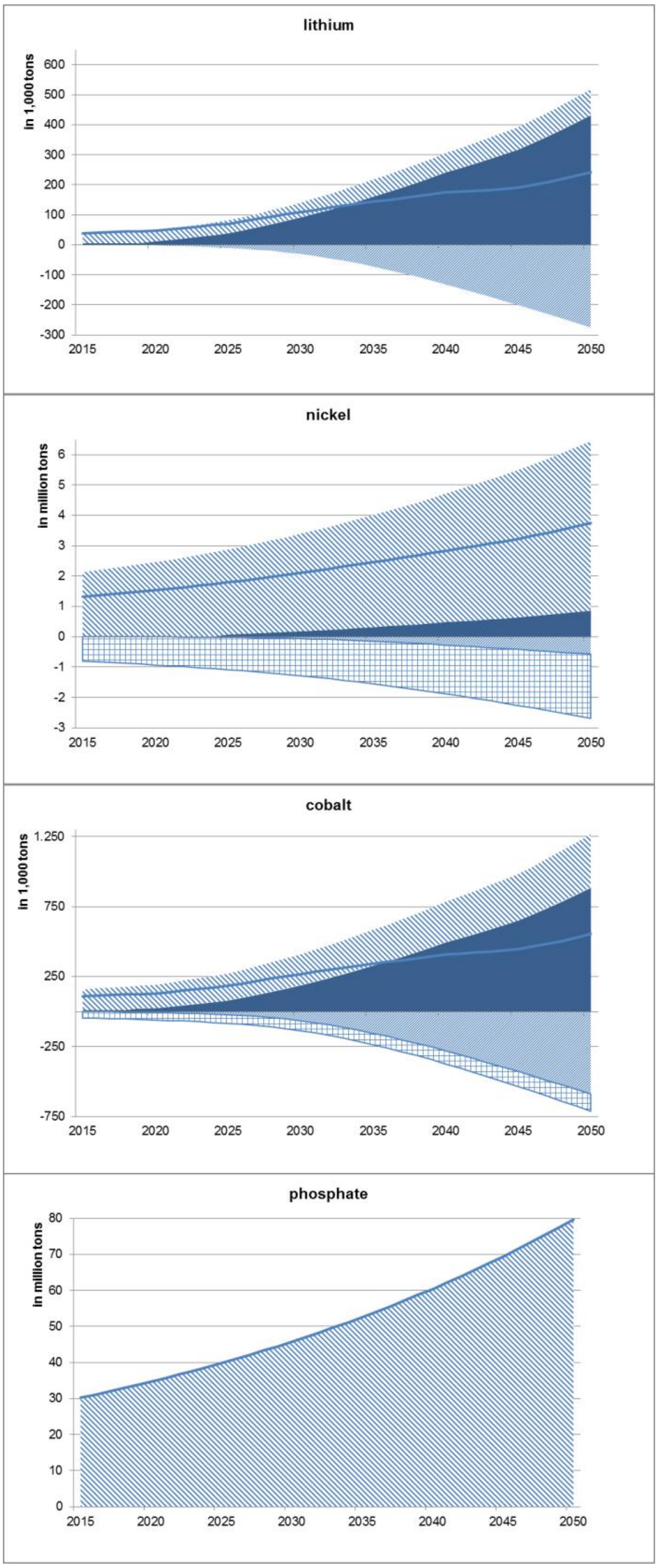
Fig. 4. Growth of the assumed global vehicle production per year

Fig. 5 – 11 show the demand for the assessed materials in the automotive sector and in other applications. It is obvious that the material demand caused by hybrid and electric vehicles is of negligible impact for nickel, manganese, iron, and phosphate. Hence, the quantities obtained from the recycling of automotive batteryies are negligible.

Regarding the elements lithium, cobalt, and natural graphite, however, the production of lithium-ion batteries contributes significantly to the global demand for these elements. In our baseline scenario, this accounts for shares of 83% for lithium, of 48% for natural graphite and of 70% for cobalt in 2050. Whereas no recycling for natural graphite occurs, the recycling of lithium and cobalt considerably decreases the necessary primary production. However, despite this mitigating factor, the primary production still needs to be increased significantly: For lithium, our simulation results show an average growth of 5.4% p.a. from 2013 to 2050 with a maximum increase between successive years of 11.5%. The production of natural graphite needs to be increased at an average of 4.5% p.a. and with a maximum value of 5.9%, and the production of cobalt is required to grow at an average of 4.7% p.a. and with a maximum of 9.5%. Although these rates seem quite high, the growth rates in the production of many other minerals have been of similar magnitude within the last few decades [45].

A more serious issue than the necessary expansion of production capacities is the natural availability of an element in deposits where it is economically mineable. As mentioned in the Introduction, there are two key concepts regarding such deposits globally. Reserves comprise all known deposits which can be mined economically with the technology already available today. Resources comprise the reserves but also deposits for which material extraction is currently sub-economic, but which might be feasible in the future.

To compare the results of our study with the existing reserves and resources of the assessed materials, we calculate the cumulative demand resulting from the demand for the automotive sector and for other uses considering the amount of available recycled material.



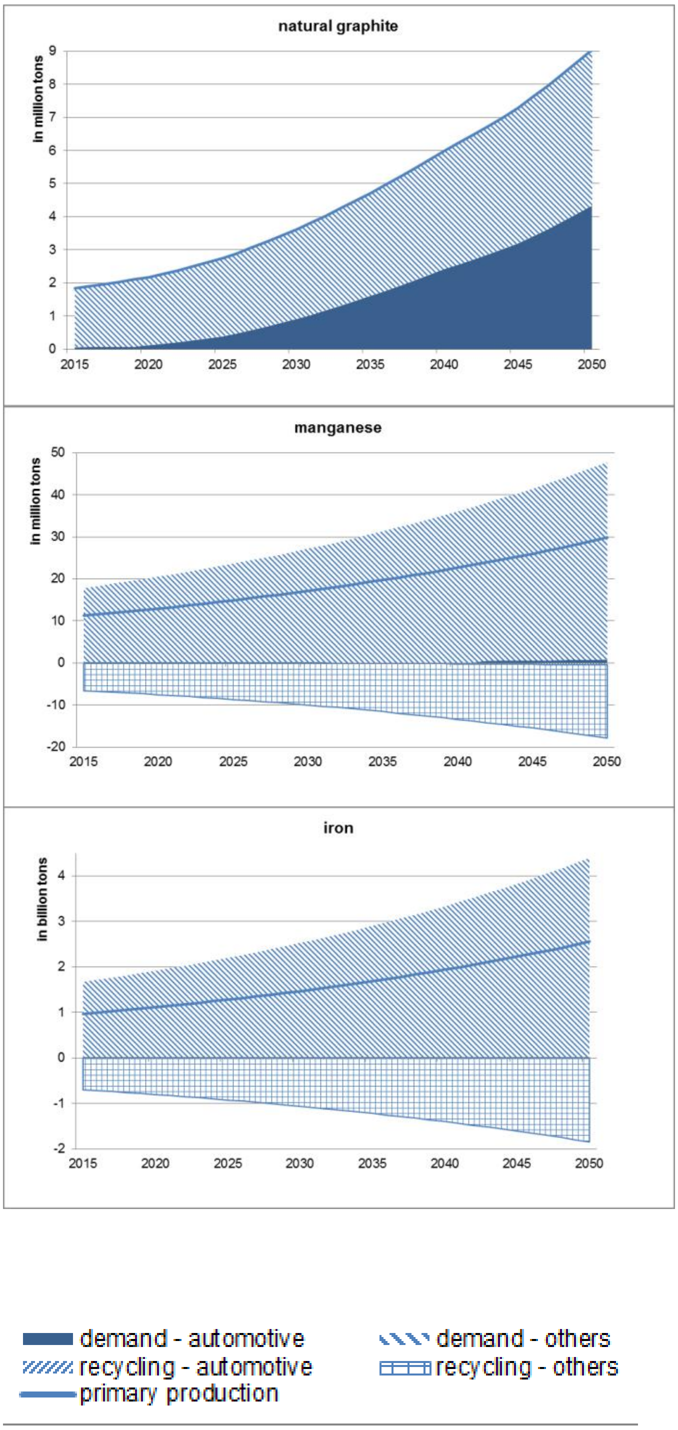


Fig. 5 – 11. Demand and recycling for the automotive sector and other uses

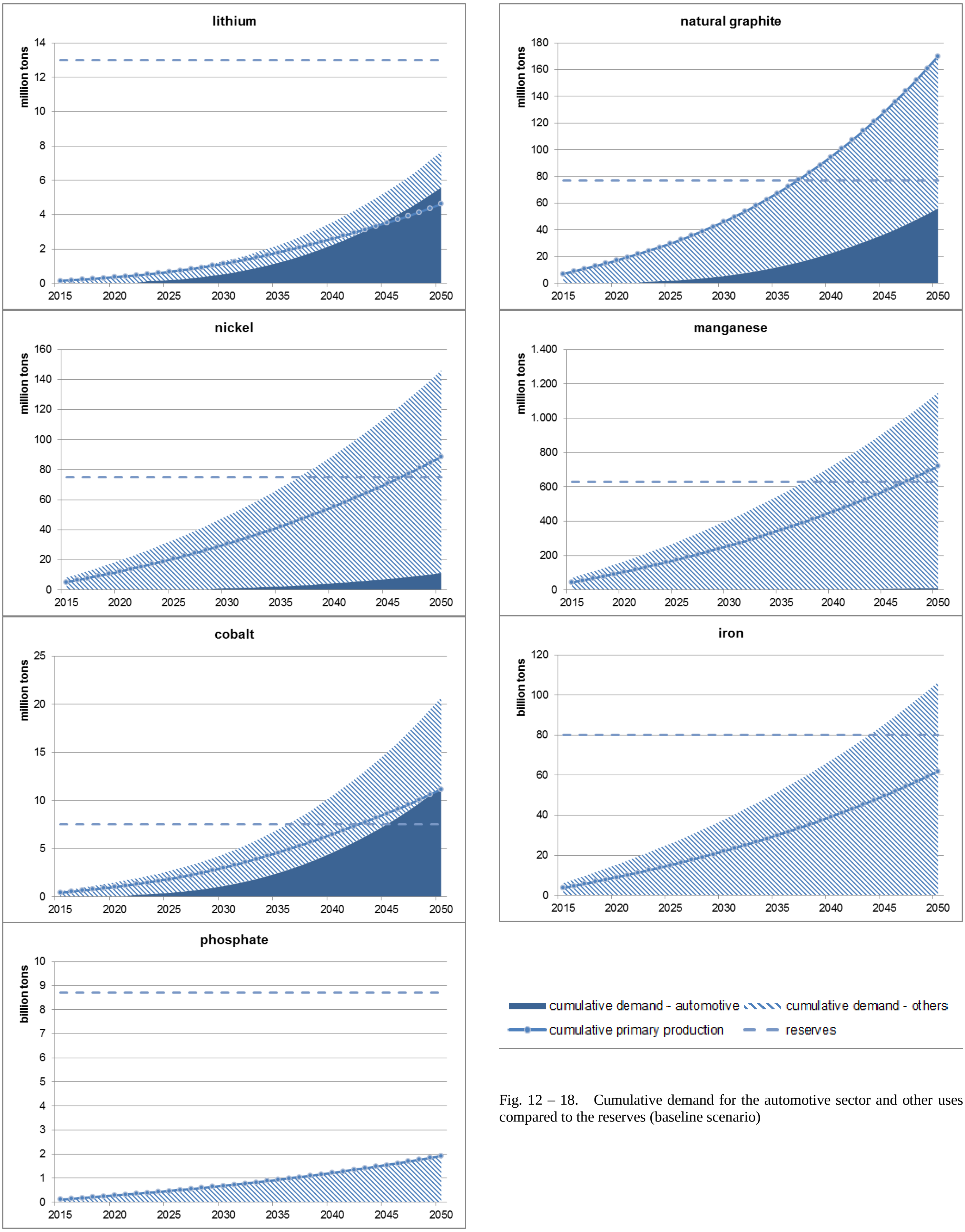


Fig. 12 – 18. Cumulative demand for the automotive sector and other uses compared to the reserves (baseline scenario)

The results of these calculations according to our baseline scenario are presented in Fig. 12 - 18. Although the use of lithium-ion batteries leads to a significant increase in future lithium production, current reserves will not be exhausted according to the results of our analysis. In fact, only about 35% of the reserves would need to be used by 2050.

In contrast, the cumulative demand for natural graphite – which we assume to be the only source for the graphite anode of lithium batteries in our assessment – reaches the “limit” of the reserves already in 2037. However, it must be kept in mind that synthetic graphite can also be used for the battery anode and that the amount of natural graphite reserves might rise when its price increases in the future.

Although the use of lithium-ion batteries hardly affects the overall consumption of nickel and manganese, current reserves will be exhausted between 2045 and 2050 in our simulation. As we assume that the recycling of these materials will improve and since the amount of resources known at present is quite large, we do not see a serious threat of scarcity for these materials in the short or medium term.

The availabilty of cobalt, especially at moderate price levels, can be questioned, however. Although we assume a good recycling scheme for the cobalt used in lithium batteries, currently known reserves will be exhausted by 2043 according to our simulation results. As the known cobalt resources are only double the reserves, the risk of scarcity leading to a substantial price increase exists.

With both iron and phosphorus reserves there appears to be no problem in the period under consideration; in any case the level of their consumption is determined almost entirely by other applications. Moreover, since the known resources of iron ore are a tenfold of the reserves, there is no risk of scarcity in coming decades. The same is true for phosphorous, which is mainly used as a fertilizer and cannot be recovered after its use (incidentally still a highly non-sustainable situation!).

B. Assessment of the economic prosperity and the ICT scenario

In this section we want to focus on lithium, cobalt, and natural graphite and assess the effect on our simulation results for different scenarios. To recapitulate: in the economic prosperity scenario, we use the assumption that the vehicle density per capita in 2050 will be on the same level globally, as it already is in developed countries today. This assumption leads to an average growth rate of vehicle production of 5.5% p.a instead of 3.0% p.a. which was used in the baseline scenario. Our third scenario considers that fewer vehicles will be required in the future, as ICTs will increase the average occupancy and the utilazation of vehicles. Hence, fewer vehicles will be necessary per capita which leads to an average growth in vehicle production of only 4.5 % p.a.

The results for the cumulative material demand are shown in Figures 19 – 21 for the economic prosperitiy scenario and in Figures 22 – 24 for the ICT scenario. For both scenarios, the reserves of lithium are sufficient to provide enough material to allow even the production of an extremely large number of batteries for hybrid and electric vehicles in the economic prosperity scenario.

For cobalt, the situation looks different: in both scenarios the reserves of today will fully be depleted around 2040. Even the identified cobalt resources which total about 15 million tons might not be enough to cover the global demand until 2050.

Similar to the results of the baseline scenario, the reserves of natural graphite would be depleted as early as 2035. However, as the resources of natural graphite are estimated to be about 800 million tons, the risk of global demand not being satisfied is rather small.

C. Influence of the share of each battery technology

In all three scenarios, we assumed a ratio of 70:30 for the use of Li(NMC) and LiFeP batteries. However, it is assumed that more LiFeP batteries will be used in electric vehicles than Li(NMC) batteries in the future [41]. For this reason, we change the ratio to 30:70 favoring the spread of LiFeP batteries.

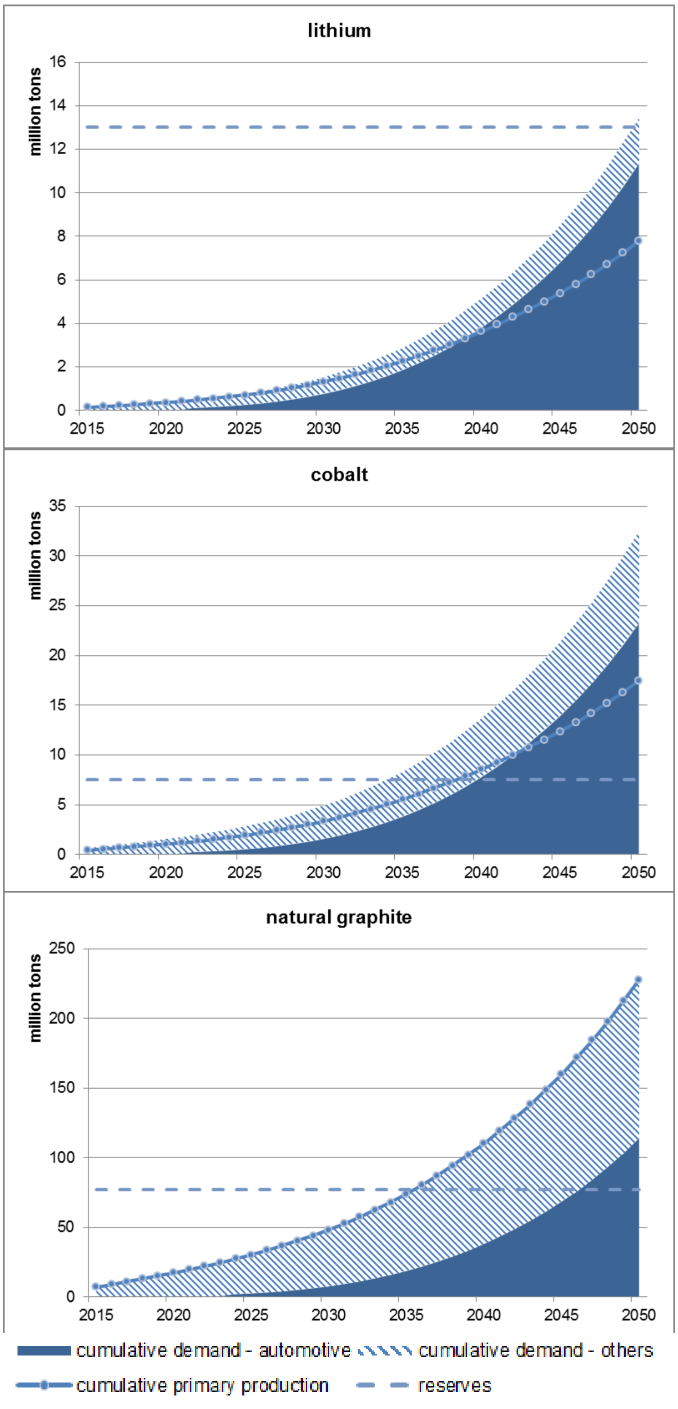
Fig 25 – 27 show the simulation results for cobalt according to all three scenarios. Even in the baseline scenario with a relative low vehicle production, all cobalt reserves known today are exploited in our time period. Only if we assume a share of 9% for the Li(NMC) batteries, would the cobalt reserves known today not be exhausted by 2050.

With respect to the supply situation of lithium and natural graphite, the share of the two assessed battery technologies has a minor impact.

D. Influence of the economic growth rate

We have assumed that the material demand for other uses besides vehicle batteries will grow with the global economic growth rate. Hence, this rate has a large impact on our simulation results, especially for those materials which are used predominantly for non-battery products e.g. manganese and iron.

An economic growth rate of 2.8% p.a. according to a prognosis of [42] was used in our baseline scenario. Nevertheless, other predictions may be used as well. Economic data of the International Monetary Fund [46] and the World Bank [47] show that the global gross domestic product has been increasing with an average rate of 5.5% p.a in the last two decades. Nevertheless, when we use such a high growth rate for the future material demand development for products besides vehicle batteries, the simulation results do not change much. Naturally, the year in which the cumulative material demand for natural graphite, nickel, manganese and cobalt reaches the present level of known reserves, is brought forward to an earlier point in time. The reserves of lithium, however, are sufficient for the total cumulative demand - even in the



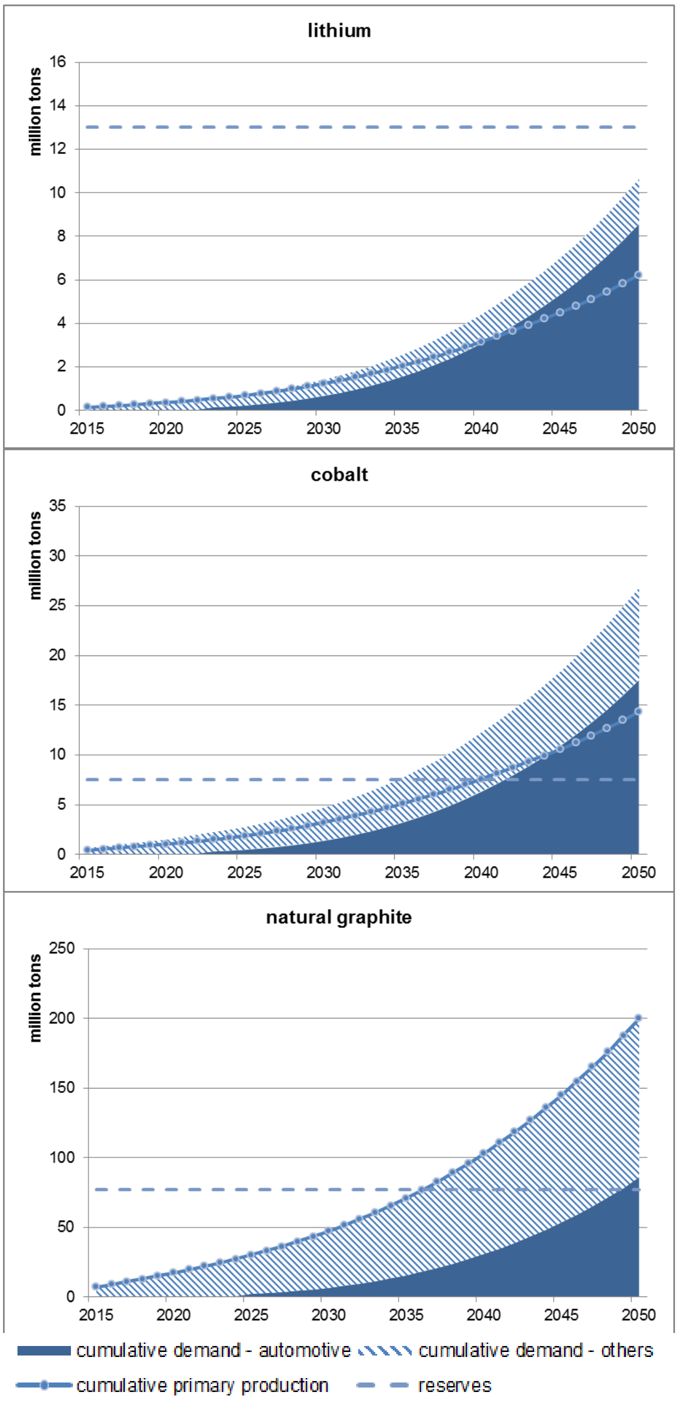


Fig. 19 – 21. Cumulative demand for the automotive sector and other uses compared to the reserves (economic prosperity scenario)

Fig. 22 – 24. Cumulative demand for the automotive sector and other uses compared to the reserves (ICT scenario)

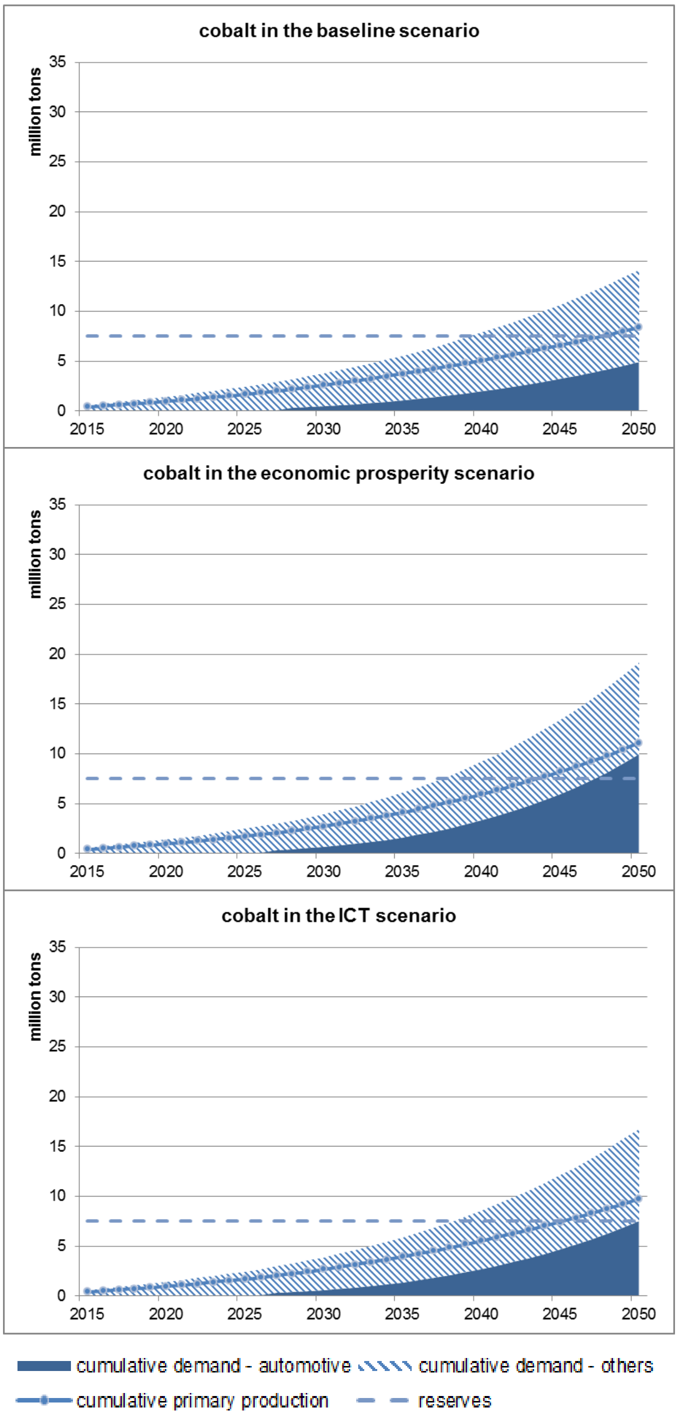


Fig. 25 – 27. Cumulative demand of cobalt for the baseline, the economic prosperity, and the ICT scenario assuming a ratio between Li(NMC) and LiFeP batteries of 30:70.

economic prosperity scenario - generated by battery production and other uses. Whereas also the phosphorus reserves are larger than the cumulative demand in all assessed simulations, it is only iron which might exceed its reserves due to a higher economic growth rate of more than 5% p.a. However, as the resources of iron ore are abundant, this would not necessarily imply scarcity.

IV. Summary and Discussion

In this paper, we have estimated the future demand and supply situation for materials which are used in the cells of lithium-ion batteries. The analysis included batteries with lithium nickel manganese cobalt (Li(NMC)) and lithium iron phosphate (LiFeP) cathodes. We have not only considered the future production of vehicle batteries, but also estimated the demand due to other uses of these materials. Moreover, we have addressed the recycling of vehicle batteries and modelled the recycling of other products. The results show that for almost all the materials assessed a serious risk of physical depletion of the known deposits (both reserves and resources) in the short and mid-term future does not exist. In particular, the known lithium reserves seem to be sufficient to cope with the substantial future increase in demand.

The recovery of lithium from automotive batteries is already technically feasible today, but has not yet been implemented. In the absence of environmental directives (which are for example in place in the EU for batteries containing lead, mercury and cadmium) the future price development of lithium will decide whether, or to what extent, the recovery of this element will be put into practice.

The cumulative production of the two elements cobalt and natural graphite, however, might exhaust the present known reserves by 2050. Further, the material demand for automotive batteries contributes significantly to the total demand for these two elements in our analysis. Nevertheless, the corresponding resources are much higher than the known reserves and thus sufficient to cover the demand until 2050.

A risk which is more serious than the physical depletion of the known reserves and resources is a potential supply shortage due to geopolitical factors: about 75% of global lithium production takes place in two countries, i.e. Australia and Chile; in the latter more than half of the global lithium reserves are situated. Political instability in Chile, for example, could therefore affect the security of supply. On the other hand, large, as yet undiscovered deposits are expected in salars in other parts of the Andes and in the Himalayas. The potential of sea water which contains 0.17 ppm lithium, corresponding to 200 billion tons, should also not be forgotten [48]! The situation with regard to cobalt gives some cause for concern. Much of the cobalt produced globally comes from the eastern region of the Democratic Republic of the Congo (DR Congo), where almost half of the world reserves are to be found. Not only do political unrest and armed rebellion produce a difficult "security of supply" situation, but they also give rise to justifiable ethical concerns, because of the fact that various guerilla groups have been financed in the past from mining profits. The reader is referred to the report on so-called “conflict minerals” by the Öko-Institut in Freiburg, Germany [49]. China dominates the global production of natural graphite and most of the global reserves (both about 70%) are found on its territory [4]. The recent price bubble for rare earth oxides was caused by Chinese export restrictions that were thought to be politically motivated. China was for some years a monopoly supplier of these elements.

For this reason, price increases and a certain degree of price volatility must be expected for the strategically important materials which are essential for the production of Li(NMC) and LiFeP batteries.

Nevertheless, there are several measures that can be taken to reduce the risk of a supply shortage in the production of vehicle batteries. Regarding lithium, the processes for its recovery during battery recycling can actually be implemented and, of course, improved. Similarly, recycling of the graphite anode can reduce the dependence on natural graphite supply. New, particularly energy-efficient technologies for the production of synthetic graphite could also help to provide enough material to satisfy future demand. As no cobalt is used in LiFeP batteries, the increased use of this battery technology reduces the security of supply risk. It should be noted that LiFeP cells have a lower voltage (so more must be connected to each other inside a battery pack) and their energy density is lower than for Li(NMC) batteries. This results in a higher vehicle weight and an increased energy consumption of the vehicle. However, as this increase in consumption is only a few percent, it can be neglected. Nevertheless, in contrast to the risk of exhaustion of the known cobalt reserves and resources, all of these disadvantages can be overcome by engineering measures.

It must be kept in mind that the results of the present analysis do not represent predictions of future production and demand for these elements. Instead, it has been our aim to derive rough estimates in order to be able to answer the question as to whether physical depletion is an inevitable threat that comes with electric vehicles. Within this focus, we have used various assumptions and estimates, which obviously cannot form the basis for a sound prognosis. This is especially true for the modelling of the recycling of both automotive battery cells and other applications, both of which we have had to simplify considerably. The use of the materials in products other than batteries was also only modelled in a rudimentary way. A more detailed approach could improve the reliability of the results obtained. This is particularly true of graphite, for which its characterstics could be modelled in a more detailed way, e.g. by changing the relative proportions of synthetic and natural graphite as well as by varying the percentage of natural graphite that is suitable for the production of batteries.

Furthermore, similar assessments can be performed for other technologies and other materials. The focus of this analysis was the production of batteries for hybrid and electric vehicles, since they might become one of the key technologies of the future. However, in all analyses of this sort, it is not possible to estimate the role that might be played in future by new technologies. These may be deemed unimportant at present or, indeed, they may perhaps not even have been identified! The possible wisespread construction of nuclear fusion reactors in the second half of this century would, for example, change the supply and demand situation for lithium in a complex way [48]. For this reason, analyses like the present one, need to be conducted regularly with updated assumptions and should comprise as many facets as possible. This might help to prevent a rude awakening occurring after too many expectations have been placed in one technology to solve a problem only to discover that another has been generated.

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Annex A.1: Literature survey regarding future vehicle sales (cars and commercial vehicles together) and the annual increase per year

Year	[50]		[51]	
2007	73,226,000			
2008	70,520,000	-3.7%		
2009	61,792,000	-12.4%		
2010	77,704,000	25.8%		
2011	80,045,000	3.0%		
2012	84,100,000	5.1%		
2013	87,094,000[1]	(3.6%)	83,300,000	
2020			105,200,000	2.4%
Average		**2.8 %**		**2.4 %**

Annex A.2: Literature survey regarding future car sales and the annual increase per year

Year	[9]		[18]		[19]		[50]	
2007							53,201,000	
2008							52,726,000	-0.9%
2009							47,773,000	-9.4%
2010			61,000,000				58,342,000	22.1%
2011							59,897,000	2.7%
2012							63,075,000	5.3%
2013							65,149,000[2]	(3.3%)
2020	78,522,000		75,000,000	2.1%	91,000,000			
2025	91,338,000	3.1%						
2030	106,246,000	3.1%	90,000,000	1.8%	125,000,000	3.2%		
Average		**3.1 %**		**2.0 %**		**3.2%**		**3.5 %**

[1] The production of the first six months was doubled
[2] The production of the first six months was doubled

Annex B: Estimated share of powertrain technologies in total car production. (Values with * are interpolated linearly between values given in the source)

year	2010	2015	2020	2025	2030	2035	2040	2045	2050	Source
HEV + FCEV	7.3 %	19.4%	27.8 %	29.2 %	31.0%	28.2%	22.7%	18.0%	14.1%	[8] Scenario: „Dominanz“[3]
			14.0%	27.0%*	40.1 %	25.7%*	11.2%			[16] Data for Germany[4]
		5.1%	22.5%	37.2%						[17] using data of Annex A.2
	0.0%	9.0 %*	18.0%	23.0%*	28.0%					[18] Scenario: „Hybrid and electric“
			12.0%	13.6%*	15.1 %					[19] Scenario II+III (Triad + BRICS)
	3.7%	**11.2%**	**16.6%**	**26.0%**	**28.6%**	**27.0%**	**17.0%**	**18.0%**	**14.1%**	**Average, used for the assessment**
PHEV	0.0 %	1.3 %	3.4 %	8.0%	15.2%	19.7%	23.5%	31.1%	37.2%	[8] Scenario: „Dominanz“
			0.7%	5.9%*	11.2%	21.7%*	32.2%			[16] Data for Germany
		1.0%	4.9%	18.9%						[17] using data of Annex A.2
	0.0%	3.0%*	6.0%	15.0%*	24.0%					[18] Scenario: „Hybrid and electric“
			2.4%	9.2%*	16.0%					[19] Scenario II+III (Triad + BRICS)
	0.0%	**1.8%**	**3.5%**	**11.4%**	**16.6%**	**20.7%**	**27.9%**	**31.1%**	**37.2%**	**Average, used for the assessment**
BEV	0.0 %	1.3%	3.4 %	8.9%	16.4%	22.0%	26.6%	33.7%	39.8%	[8] Scenario: „Dominanz“
			0.7%	6.0%*	11.2%	21.7%*	32.2%			[16] Data for Germany
		0.4%	2.9%	4.8%						[17] using data of Annex A.2
	0.0%	1.0%*	2.0%	5.0%*	8.0%					[18] Scenario: „Hybrid and electric“
			5.2 %	9.5%*	13.9 %					[19] Scenario II+III (Triad + BRICS)
	0.0%	**0.9%**	**2.7%**	**6.8%**	**12.4%**	**21.9%**	**29.4%**	**33.7%**	**39.8%**	**Average, used for the assessment**

[3] Assumption: PHEV and BEV each 50%
[4] Assumption: PHEV and BEV each 50%

Annex C.1: Properties of the battery technologies assessed

	Li(NMC) batteries		LiFeP batteries	
Energy density of battery pack (Wh/kg)	86	[11]	71	[11]
Ratio of cell weight to total battery weight (g/kg)	630	[11]	530	[11]

Annex C.2: Amount of each element in a vehicle battery

Li(NMC) batteries									
lithium	source	nickel	source	manganese	source	cobalt	source	graphite	source
2.2 m% (cell level)	[11]	6.2 m% (cell level)	[11]	5.7 m% (cell level)	[11]	6.2 m% (cell level)	[11]	22.2 m% (cell level)	[11]
2.0 m% (cell level)	[52]	3.2 m% (cell level)	[52]	3.2 m% (cell level)	[52]	3.2 m% (cell level)	[52]		
3.3 m% (cell level)	[53]	9.4 m% (cell level)	[53]	8.8 m% (cell level)	[53]	9.4 m% (cell level)	[53]		
180 g/kWh	[9]								
157 g/kWh	[12]					490 g/kWh	[12]		
177 g/kWh	**Final**	**459 g/kWh**	**Final**	**432 g/kWh**	**Final**	**467 g/kWh**	**Final**	**1626 g/kWh**	**Final**

LiFeP batteries							
lithium	source	iron	source	phosphorous	source	graphite	source
1.4 m% (cell level)	[11]	11.3 m% (cell level)	[11]	6.4 m% (cell level)	[11]	20.9 m% (cell level)	[11]
2.0 m% (cell level)	[53]	16.3 m% (cell level)	[53]				
120 g/kWh	[9]						
101 g/kWh	[12]						
119 g/kWh	**Final**	**1030 g/kWh**	**Final**	**478 g/kWh**	**Final**	**1560 g/kWh**	**Final**