Availability of Mineral Resources and Impact for Electric Vehicle Recycling in Europe

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Abstract Lithium-ion battery technology is a key component of vehicle electrification and its end-of-life recovery is an important factor in lifting barriers towards increased Electromobility, such as battery cost, environmental impact, mandatory recycling rates of more than 50% battery weight (European Union) and, finally, the availability of constituent elements such as lithium and cobalt. This chapter focuses on the availability of constituent materials, in order to assess the potential for critical shortages due to a scaling up of Electromobility. To account for the complexity and long-term horizon of our study, we combine the use of System Dynamics with the Stanford Research Institute Matrix for scenario planning. We find that for lithium-ion battery needs, only cobalt is likely to see its reserves depleted. Other materials such as nickel, manganese, copper, graphite and iron are at risk of depletion due to developments unrelated to Electromobility. In all cases, we show that recycling significantly reduces the consumption of materials for lithium-ion batteries.

Keywords Lithium-ion · Battery · Electric vehicle · Recycling · Criticality

1 Introduction

In this twenty-first century, our planet is facing unprecedented challenges for its preservation; this is especially true of our energy model which must be redesigned to meet growing demand, establish more democratic access worldwide, while minimizing the environmental impact of its production and use (WEC 2013). The transportation sector as a whole, road transport in particular, has a strong impact

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on our energy model due to its dependence on oil and its contribution to greenhouse gas (EEA 2015; European Commission 2014a; IEA 2012). Making it Greener is therefore a priority.

Measures have been taken at the EU and global levels to reduce these emissions. European commitments call for a transport sector emission reduction of 60% in 2050 compared to emission levels in 1990 (European Commission 2011). European Regulation No. 443/2009 was introduced as part of the climate package. It defined emissions thresholds for new light vehicles up to 130 g of C02 per km by 2015 and 95 g per km in 2020 (European Commission 2009) and was completed in 2014 by the European Regulation No 333/2014 (European Commission 2014b). Today, the 2015 goal is attainable by various car manufacturers (EEA 2015). The 2020 goal remains however, a challenge that requires radical innovation.

Fuel cells and other promising technologies being less mature in terms of technology and infrastructure, the industry has tended to turn towards electric vehicles (hybrid, plug-in hybrid and battery-electric) in order to comply with this regulation and thus reduce European energy dependence and emissions. According to Idjis and Da Costa (2017): “These electric vehicles (EV) mainly use lithium-ion batteries (LIB)”, which “give them greater autonomy. However, they crystallize some of the barriers preventing widespread use, such as the cost of the battery, its impact on the overall life cycle assessment of the EV and the availability of constituent materials”. It is the latter barrier that we are investigating in this chapter.

EV engines and batteries consume rare soil and strategic materials. Concerns are regularly expressed on dependence, potential depletion and environmental consequences of mining some raw materials such as lithium, cobalt or graphite. According to the USGS (U.S. Geological Survey), 85% of the world’s cobalt and lithium production comes from only seven countries (USGS 2010). Among the latter, there are countries in Latin America and sub-Saharan Africa, with unstable political regimes. Thus, the first concern is dependence on producer countries.

The second issue concerns the physical availability of resources, or what we call geological criticality, although for lithium the problem of its availability seems to be solved. Many studies show that there are enough reserves (economically exploitable resources) for the most optimistic EV scenarios (Grosjean et al. 2012; Gruber et al. 2011).

Finally, the third concern is on the ability of producing countries to meet demand in the years to come, given that it takes 5–10 years for a new mine to become exploitable (Miedema and Moll 2013; Novinsky et al. 2014).

Through all these elements of context, we conclude that the battery is the central technological element accompanying vehicle electrification, and that its valorization at the end-of-life is an important lever to lift the brakes on the deployment of Electromobility. In this work, we position ourselves on the battery’s end-of-life perimeter, where we will be interested in the effect of recycling on the raw materials consumption and criticality.

Section 2 now introduces the technical scope of battery and recovery technologies: these concepts are necessary for understanding the subsequent analysis. Our approach and results will be detailed in Sects. 3 and 4 respectively. Section 5 concludes this chapter.

2 Battery and Recovery Technologies

2.1 Battery

Several battery technologies are available for electrifying vehicles such as: nickel cadmium (Ni-Cd), nickel metal hydride (Ni-MH) and lithium-ion (LIB). This latter is more adapted and used for automotive applications, given its performances (energy density, voltage of cells, lifespan and memory effect). A LIB is made up of two principal parts: the electrical/support part (battery management system, connecting cables and cooling system), and the electrochemical one (set of modules, which are composed primarily of cells) (see Fig. 1).

Therefore the basic component of a battery is the cell, which gives it its name. A cell consists of an electrolyte, a separator, a cathode (positive electrode) and an anode (negative electrode). Each one of these electrodes is composed of a conductor and an active material. For the anode, the active material is usually graphite. For the cathode, the positive active material is a combination of **lithium and a metal oxide**, which varies from one technology to another. The properties of the LIB are defined by the latter (lifespan, safety, capacity, and cost). In this study, we selected two families of key technologies:

- Nickel-Manganese-Cobalt based batteries (NMC) with the average composition $Li(Ni_{1/3}Mn_{1/3}Co_{1/3})O_2$ (ADEME 2013; Hoyer et al. 2014);
- Iron phosphate based batteries (LFP) with the composition $LiFePO_4$.

In terms of materials contained in a LIB, Fig. 2 shows the average proportions in a pack (Idjis and Da Costa 2017):

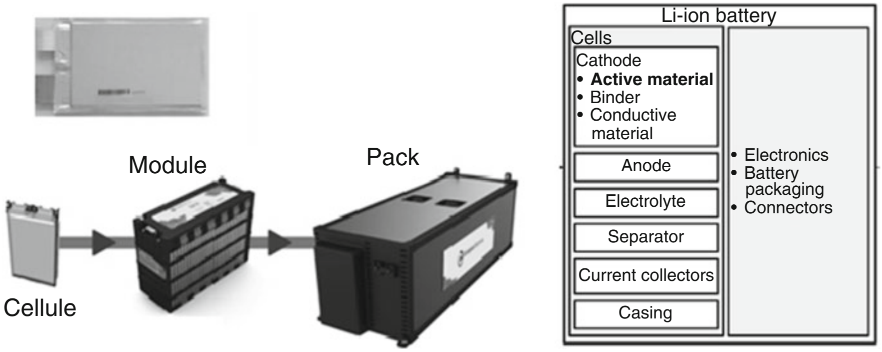

Fig. 1 Composition and decomposition of a battery. (Swart et al. 2014; Väyrynen and Salminen 2012)

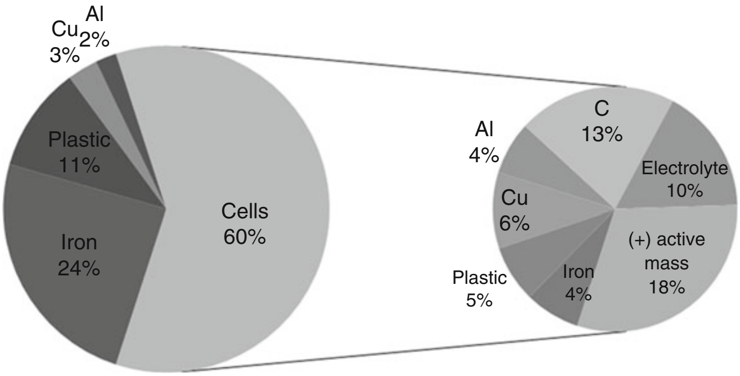

Fig. 2 Analytical decomposition of an EV pack (Idjis and Da Costa 2017)

- Steel and iron: casing of the battery cells, bolts;
- Aluminum and copper: electrode conductors, cables, electronic boards;
- Plastics: casing of the battery, cables, separator;
- Graphite: negative active material of the anode;
- Lithium: electrolyte and positive active material of the cathode;
- Cobalt, Nickel, Manganese, iron, phosphorus: positive active material of the cathode;
- And solvents.

Depending on the level of vehicle electrification, the LIB capacity defines its mass. For hybrid vehicles “HEV”, the capacity is between 1 kWh and 2 kWh, which result in a mass of about 30 kg. For plug-in hybrid ones “PHEV”, the capacity is between 5 kWh and 15 kWh, which result in an average mass of 150 kg. Last of all, for battery-electric vehicles “BEV”, with a capacity over 15 kWh, the average mass is about 250 kg.

2.2 *Recovery Options*

Two main LIB recovery options need to be considered: recycling (as required by EU regulation) and repurposing for reuse in 2nd life applications. In this work, we are interested in the first one in order to quantify the effect of recycling on the consumption of the constituent materials.

In Idjis and Da Costa (2017), the EU directive 2006/66/EC sets the regulatory framework for the treatment of batteries and accumulators at end-of-life. It imposes for EV batteries: (1) The establishment of a collection and a recycling system; and (2) The requirement to recycle at least 50% of the battery weight. Therefore, the recycling objective is the achievement of these regulatory targets, while recovering the value contained in the LIB materials.

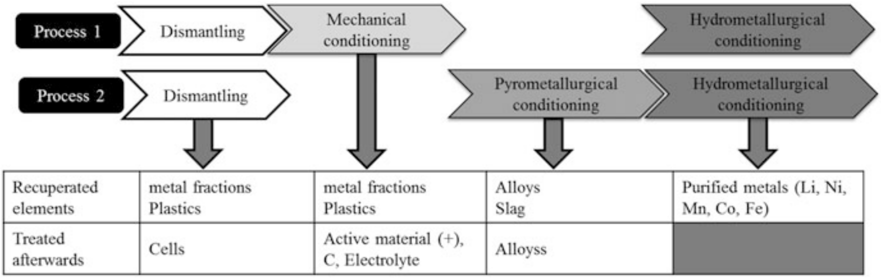

Fig. 3 Considered recycling processes

These materials are found at different levels in the battery (electrode, cell, pack), in varying proportions (remember Figs. 1 and 2), as well as with a different contribution to the recovered value. Operations of extraction, separation and purification are required consequently. Kwade (2010) identifies four possible basic processing operations: Dismantling; Mechanical conditioning; Pyrometallurgical conditioning; and hydrometallurgical conditioning. These operations could be combined in several ways to form five recycling alternatives. The scientific and industrial state of the art by Idjis (2015) considers two recycling processes as shown in Fig. 3. Each process is a succession of three operations, the recovered materials at each operation are described in the bottom. We denote Process 1 by P1 and Process 2 by P2.

Idjis and Da Costa (2017) notice that the recovery of materials contained in the positive active material (which are difficult to access) requires an elaborate recycling process, therefore a high cost. This is why materials such as lithium are not recycled today.

In the future, with the development of EVs, the level of criticality for any material will certainly justify the economic benefit of its recycling, which will reduce this initial criticality. We have highlighted above the so-called System Dynamics methodology (Sterman 2000) i.e. a feedback loop. The concept of feedback loops can be explained using the analogy of vicious or virtuous circles, wherein an influence spreads among several factors and returns back to the factor that initially generated it.

Due to the presence of these feedback loops, we have used System Dynamics Modeling in our approach, which is explained in the next section.

3 Approach

System Dynamics (SD) is a suitable methodology for the analysis of large-scale complex systems wherein heterogeneous factors interact, stemming from systems thinking theory. "The objective is to analyze, understand and predict the behavior of this system over time by analyzing its changing factors" (Sterman 2000). For our study and Idjis and Da Costa (2017), this means identifying the factors that create the dynamics of minerals consumption, modeling of internal laws of behavior between these factors and their time simulations in several scenarios. This was done in a much broader study by Idjis (2015), in which other objectives such as recovery profitability and compliance with recycling targets were investigated (Fig. 4).

As shown in Fig. 4, a SD model is a set of factors related by links of causalities. The Fig. 5 shows a simplified diagram of the SD model developed in (Idjis 2015), regarding the mineral consumption for LIBs in Europe.

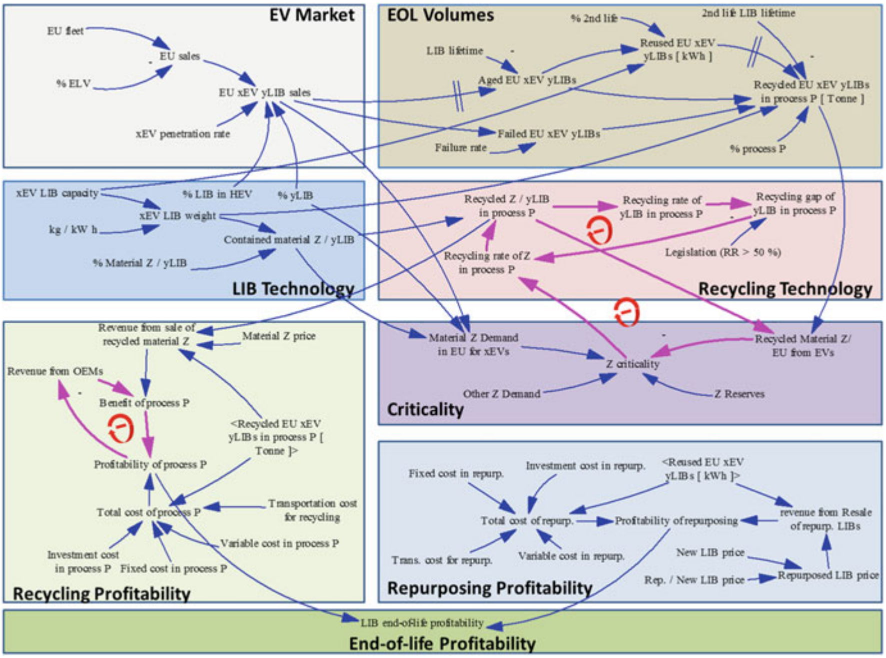

Fig. 4 Overview of the LIB recovery network SD model (Idjis 2015)

Fig. 5 Simplified SD diagram regarding the dynamic of minerals consumption for LIBs in Europe

Table 1 SRI matrix of scenarios

		80%	0%	% 2nd life
		80%	20%	% NMC
12.5–30 (kWh)	ETP_2DS	S1	S2	
10–24 (kWh)	Mean 2DS—4DS	S3	S4	
LIB capacity PHEV—EV	Penetration rate EV			

The Fig. 5 is as follows: the criticality of any material 'Z' is dictated by its reserves, its consumption in other markets, its consumption for EVs and the recycled amount of this material. The consumption for EVs is calculated based on the EVs market and LIB technologies developments, while the recycled amount is induced by end-of-life volumes and recycling technologies. Finally, we find the feedback loop (red arrow) explained above (criticality—increasing the recycled amount—decreasing criticality).

Being in a prospective study, we have combined the use of SD with scenarios. The choice of the Stanford Research Institute (SRI) matrix is justified given its suitability with the our SD model characteristics: complexity, heterogeneous factors and emergence (Acosta and Idjis 2014; Idjis and Da Costa 2017).

The SRI matrix is a crossing of two dimensions of factors that dictate primarily the dynamic evolution of the SD model. The scenarios introduced in Table 1 are derived from (Idjis 2015).

For example in the S1 scenario, 80% of end-of-life automotive LIBs undergo 2nd life reuse before recycling and the main technology is based on nickel, manganese and cobalt (NMC). For Idjis and Da Costa (2017), the electric vehicles sales volume is from the IEA's 2DS energy scenario (IEA 2012). This latter is based on proactive environmental policies to contain global warming to 2° (2DS) in 2050, unlike the 4° scenario (4DS). These vehicles have a capacity of 30 kWh and 12.5 kWh for EVs and PHEVs respectively. We notice that the most minerals consuming scenarios (pessimistic) are S1 for minerals: Li, Ni, Co, Mn, Cu, Al, C, and S2 for minerals: Fe, P.

The model is simulated from 2010 (first sales of electric vehicles with LIBs) until 2050. This is consistent with the literature on EV sales and minerals consumption (IEA 2012; Miedema and Moll 2013; Pasaoglu et al. 2012). In this timeframe, the LIBs will be the reference technology to be recovered at least until 2040 and beyond with post LIB batteries. As a reminder, we are considering here a European geographical area.

4 Results and Discussions

We begin with a preliminary analysis of geological criticality before the development of Electromobility. To do so, we calculated the number of years remaining for the mining of each material at its 2010 fixed level (Table 2).

Table 2 Number of years remaining for reserves consumption

	Li	Ni	Mn	Co	Cu	Al	C	Fe	P
Reserves (millions t)	13.5	81	570	7.3	700	28,000	110	87,000	67,000
Prod_2010 (millions t)	0.028	1.59	13.9	0.09	15.9	40.8	0.925	1140	181
Nb years (prod_2010)	482	51	41	81	44	686	119	76	370

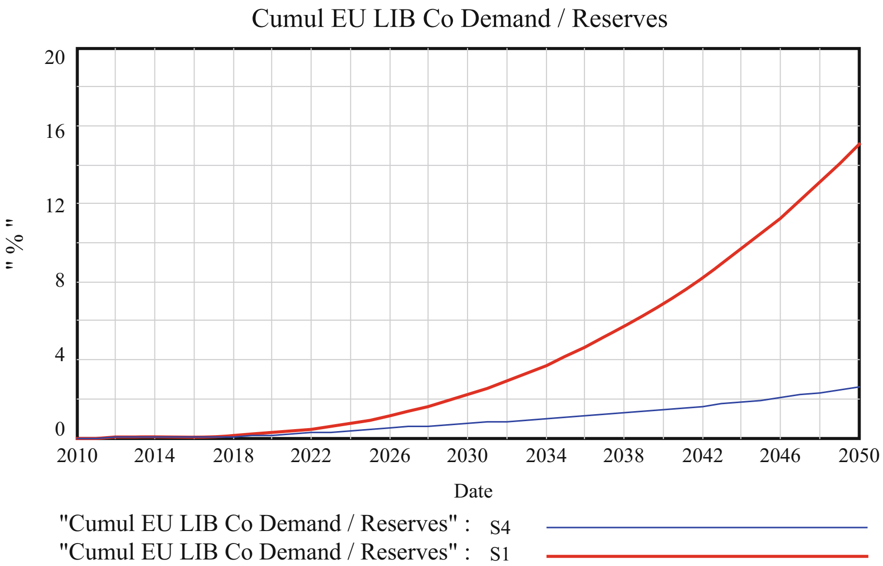

Fig. 6 Cobalt reserves consumption for EU LIBs in S1/S4 scenarios

We note that there are materials for which there is less than a hundred years of exploitation, even before the marketing of electrified vehicles based on LIBs. This is the case of Ni, Mn, Co, Cu and Fe, which present a potential geological criticality before the development of Electromobility. To determine whether this geological criticality is effective and possibly induced by Electromobility, it is necessary to integrate, using the SD model, future demand for LIBs, recycling and future demand in other markets.

Initially, we analyze the effect of LIBs in Europe, without recycling. To do this, we consider the extreme cases. The pessimistic scenarios (consumers of material)/ optimistic (not consumers of materials) are represented by S1/S4 (for materials: Li, Ni, Co, Mn, Cu, Al, C) and S2/S3 (for Fe, P). For example, the Fig. 6 illustrates the result obtained in the DS model on the consumption of cobalt reserves for EU LIBs. The rest of the results are summarized in Fig. 7.

These columns show the ratio between the cumulative demand (2010–2050) of a material for the LIBs needs in Europe and its current reserves. Except for cobalt in S1, no other material presents a risk of geological criticality due to the development of EVs (less than 4%).

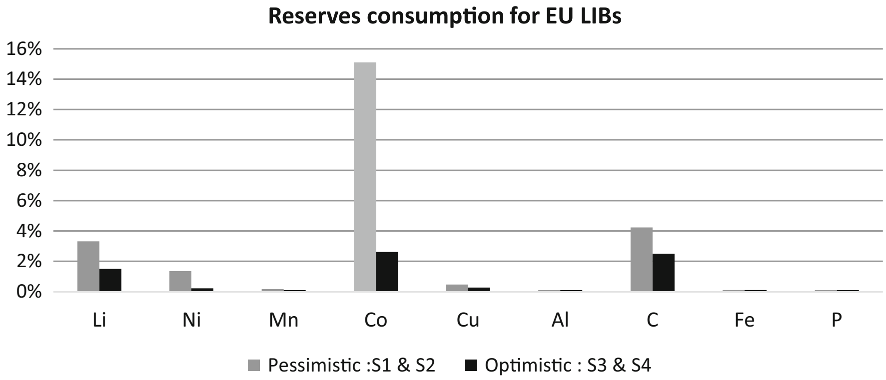

Fig. 7 Consumption of material reserves for electromobility needs in Europe

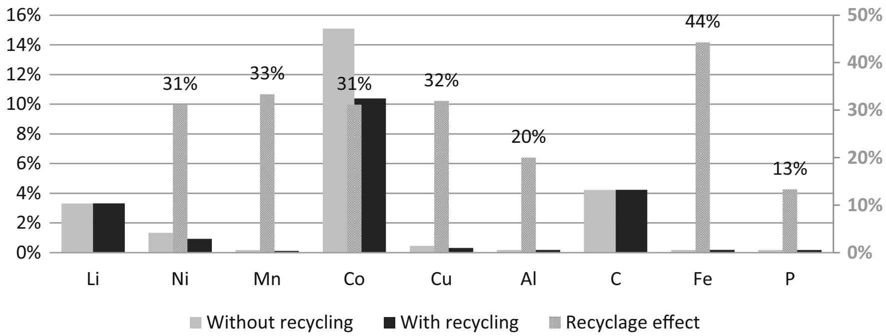

Fig. 8 Recycling effect on reserves consumption for EU LIBs

The Fig. 7 does not consider the recycling of LIBs in Europe, which has the effect of reducing the consumption of reserves. To analyze this effect, we considered the pessimistic case (S1 and S2), it was in this latter that we detected a potential geological criticality of cobalt, as shown in the Fig. 8.

We note that recycling significantly reduces the consumption of some materials (Ni, Mn, Cu, Al, Fe) for LIBs in Europe, although these do not present a risk of geological criticality, due to EVs development. In the case of Cobalt, even with recycling, 10% of the reserves will have been consumed by 2050. To sum up the demand for cobalt for the LIBs in the rest of the world and the demand for the other industrial sectors, one can expect a higher consumption of reserves. This is the purpose of the next section.

At present, we will combine the effect of demand for LIBs with the rest of the demands, including LIBs outside Europe. To do this, we consider only S1 and S2 for the demand from Electromobility. For the other applications, we consider three situations, stagnation (+ 0%/year), moderate increase (+ 2%/year) and strong increase (+ 5%/year). Recycling is included in all cases. The stagnation in demand

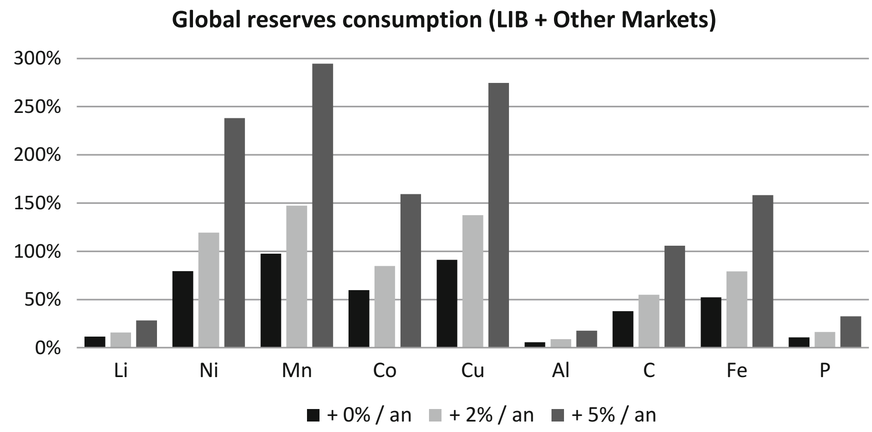

Fig. 9 Global reserves consumption

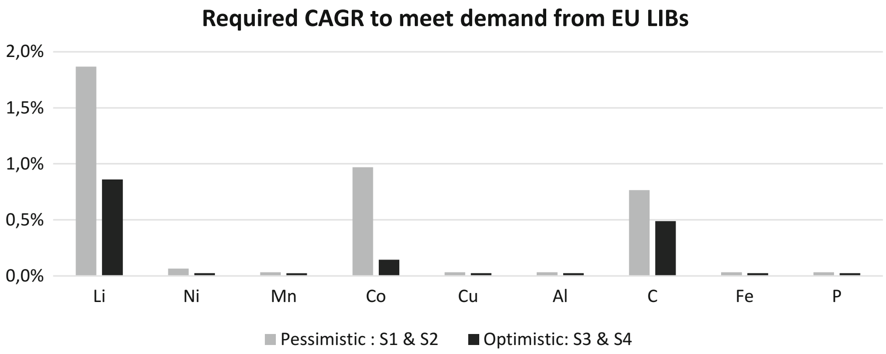

Fig. 10 Necessary production levels needed for electromobility in Europe

(+ 0%/year) is a rather optimistic situation, considering the history of the last 5 years (USGS 2015, 2014, 2013, 2012, 2011, 2010).

By analyzing the three demands profiles, we conclude that materials (Li, Al, and P) do not present a risk of geological criticality. The remaining materials (Ni, Mn, Co, Cu, C, Fe) present this risk and require mitigation strategies. Cobalt is the only material contributing to this risk through the development of Electromobility (Figs. 8 and 9). Mitigation strategies are therefore to be developed outside the automotive sector (increase in the recycling rate, substitution, exploration of new reserves and such).

Before concluding on the geological criticality of materials, we present a final analysis concerning the ability of production to meet future demand, especially in the event of a sudden increase induced by the deployment of EVs. We are interested in this because of the slow process, of the order of 5–10 years for the opening of a new mine (Miedema and Moll 2013; Novinsky et al. 2014). The Fig. 10 shows the required *Compound annual growth rate* (CAGR) in relation to 2010 production to meet the needs of LIBs in Europe, considering recycling.

The demands for materials (Ni, Mn, Cu, Al, Fe and P) for EU LIBs represent a negligible proportion of their production in 2010, even in the pessimistic case. The required annual increase in production to meet EU LIB requirements is less than 0.07% per year. Consequently, it is not the development of LIBs which will lead to a risk of deficit in the production of these materials.

Lithium, cobalt and graphite are the only materials requiring efforts to open new mines. For example, lithium production should be increased by almost 2%/year (1%/year) for LIBs in Europe, in the pessimistic (optimistic) case. By adding the demand for LIBs in the rest of the world and the demand from other industrial sectors, we can expect a necessary increase of up to 10%/year.

The increase in the production of these materials must therefore be anticipated. It will be necessary to ensure that the required production levels in 2020 and 2025 are currently under development. However, we do not have information on the prospective capabilities of mining companies to conduct such an audit.

5 Conclusion

In this chapter, we investigated the effect of the Electromobility market development in Europe on the consumption of materials, especially on the perimeter of the lithium-ion battery, which is the central technological element accompanying the electrification of vehicles. We have also analyzed the effect of recycling to reduce the consumption of these materials and their criticality.

We conclude that for the purposes of the LIBs, only the use of cobalt is likely to exhaust a large part of the reserves. Other materials such as nickel, manganese, copper, graphite and iron present a risk of depletion due to developments beyond the scope of Electromobility. Therefore, in-depth analyzes considering other sectors of use (future demand, substitutability, etc.) are necessary. In all cases, we have shown that recycling can significantly reduce material consumption for LIBs.

Regarding lithium, we have shown, contrary to what is expected of the public, that it does not present a risk of exhaustion even in the most optimistic scenarios of EVs deployment. However, its supply may be disrupted by other risk factors, such as geographic concentration of deposits and associated geopolitical risks, which calls for a multi-criteria approach of criticality estimation.

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