# Reduction of Critical Resource Consumption through Second Life Applications of Lithium Ion Traction Batteries

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**Abstract:**

Based on the defined criticality screening procedure, especially cobalt, but also lithium, natural graphite and nickel are identified as critical raw materials in lithium ion traction batteries. By using the concept of the Substitutable Nominal Capacity, which is derived from battery ageing models, it is shown that an extension of a traction battery's life time can lead to a reduction of critical resource consumption. Due to different ageing processes and material compositions the amount of saved resources depends on the considered second life application (Photovoltaic Home Storage System and Primary Control Reserve) as well as the battery type (Nickel-Manganese-Cobalt and Lithium-Iron-Phosphate). Other determining factors for the reduction of critical material consumption are the collection rate and the recycling efficiencies of used lithium ion batteries.

**Keywords:** Critical resources, lithium ion batteries, electric mobility, circular economy, second life, battery ageing

## 1 Motivation

The energy transition ("Energiewende") – including the transformation of the mobility sector – requires new technologies, many of which come with an increasing demand for critical resources. As discussed in [1] approaches from the Circular Economy such as the extension of product life time through reuse can lead to increasing resource productivity as well as new opportunities for value creation. This paper shows how second life (SL) applications of lithium ion traction batteries can lead to a reduction of critical resource consumption.

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# 2 Resource Criticality of Lithium Ion Traction Batteries

Resource criticality is not limited to physical scarcity, but is defined as a combination of the vulnerability of the economic system and the supply risk or the environmental risk of a raw material [2]. Therefore, a criticality screening procedure is first defined, which is then applied so as to identify the critical raw materials in lithium ion batteries with Nickel-Manganese-Cobalt (NMC) and Lithium-Iron-Phosphate (LFP) cathodes.

## 2.1 Criticality Screening Procedure

The comparison of different criticality studies in [3] shows that – following the risk definition of ISO 31000 – the criticality of a raw material is often defined as the product of vulnerability of the economic system and supply risk. For instance, the criticality assessment in [4] and [5] is conducted by means of a criticality matrix, according to which a raw material is classified as critical, if it is characterised both by an economic importance as well as high supply risk.

As these two dimensions solely represent economic risks, an environmental dimension is added in [4] and [6]. Graedel et al. [6] for example set up a criticality space by adding an environmental axis to the criticality matrix. The criticality can then be derived from the length of the vector. According to the European Commission [2], however, a raw material is defined as critical, if the raw material is of economic importance and the access is either characterised by a supply or an environmental risk. Also Glöser und Faulstich [3] argument that other parameters such as environmental, price and social risk should be considered separately from the supply risk, because there is no additive relation between these risks.

Since, next to cost effectiveness and security of supply, environmental sustainability is another important goal of German energy policy [7], hereafter the economic importance, the supply risk as well as the environmental risk are taken into consideration. Meaning that an energy technology is rated as critical, if

- it plays a key role in the future energy system
- and leads to a relevant increase in demand of raw materials,
- whose recyclability and substitutability are limited
- and which either go along with a supply or an environmental risk.

From this the following procedure for a simplified criticality assessment of key technologies for future energy supply can be derived:

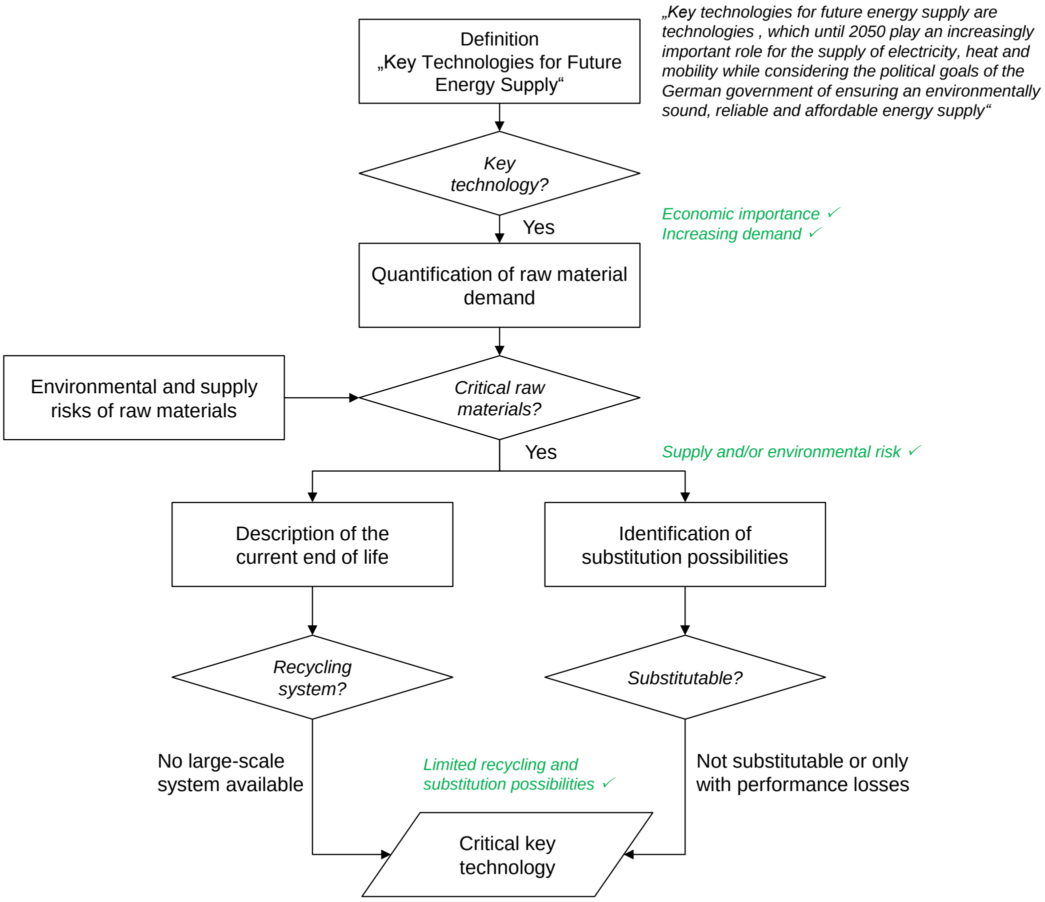

*Figure 1: Procedure for a criticality screening of key technologies for future energy supply*

It should be noted that the purpose of the defined criticality screening procedure is not the quantification and comparison of the absolute criticality of different raw materials. It should rather be understood as a guideline to identify critical technologies and to understand the reasons for the criticality of different raw materials based on existing resource criticality literature.

## 2.2 Critical Raw Materials in Lithium Ion Traction Batteries

When applying the described criticality screening procedure on lithium ion traction batteries, the technology is rated as critical, because all criteria of the criticality definition are fulfilled with regard to the cathode materials lithium, cobalt and nickel and the anode material natural graphite. First of all, lithium ion traction batteries meet the definition of a key technology for future energy supply because of the growing market for electric mobility as well as stationary applications in the energy sector. Furthermore, alternatives for lithium ion batteries in mobile applications are not foreseeable in the near future and recycling capacities are only recently being built up due to a lack of economies of scale [8].

One of the main reasons for the criticality of *cobalt* is the country of origin. With a share of 59 % in 2013 [9] the politically instable Democratic Republic of the Congo plays an important role in the mining of cobalt, while refining mainly takes place in China holding a market share of 42 % [9]. Furthermore, cobalt is primarily mined as a by-product of copper and nickel [8] and a large rise in demand is expected [10], both contributing to an increased supply risk.

With a “criticality environmental implications (EI) score” of 4.3 out of 100 the environmental risk is rated relatively low according to Graedel et al. [11], but cobalt can be harmful to the surrounding fauna in case of high concentrations at the mining and refining sites [7].

The raw material *lithium* goes along with a supply risk, because the demand for lithium is strongly increasing in the future and the production is focused on a limited amount of countries and companies. While in 2013 85 % of the mining took place in Australia, Chile and Argentina [9], the two largest companies own a market share of 70 % [12]. As the political risk of the countries of origin is rather low, the production rate can be seen as the main limitation due to a strongly increasing demand of lithium for batteries [8]. With an EI score of 6.5 out of 100 [11] the environmental risk is rather low, but lithium is corrosive and easily inflammable [8].

*Natural graphite* is being classified as critical in [12] because of a high concentration of mining in countries of origins with a political risk. In 2011 for example 80 % of the mining was covered by China and India. Still, it needs to be considered that technologies for a synthetic production of graphite based on oil as a feedstock are available [12].

The main reason for the criticality of *nickel* is the rising demand, which is amongst others induced by the increasing demand for steel in China [12]. The EI score of 10.5 [11] is only slightly higher than for cobalt and lithium, but nickel can constitute a health hazard when exposed to the skin or when being inhaled [8].

While cobalt, lithium, nickel and natural graphite are categorised as raw materials with a medium criticality according to [5], iron, phosphate and manganese are classified as raw materials with low criticality and are not further considered in the following. While there is a consensus when it comes to the criticality of cobalt, the degree of criticality of lithium, natural graphite and nickel varies between studies.

# 3 Accounting of Second Life Applications

In order to quantify the reduction of critical resource consumption through SL applications of lithium ion traction batteries, the concept of the Substitutable Nominal Capacity (SNC) from Kim et al. [13] is chosen. First, the methodological approach is described with regard to the functional unit, the system boundaries and the considered processes. Then the critical material demand and the recycling efficiencies of lithium ion battery systems are determined. Lastly, the SNC is quantified for both NMC and LFP battery systems for the two applications Photovoltaic Home Storage System (PV HSS) and Primary Control Reserve (PCR).

## 3.1 Methodological Approach

Following [14] the system boundaries as depicted in Figure 2 were defined. After its first life in the electric vehicle a traction battery with an original nominal capacity of 1 $kWh_{nom,EV}$ is repurposed and fed into a SL application, eliminating the need for production of a new battery system and thereby reducing resource consumption.

With an end of first life criterion of 80 % of the original nominal capacity as discussed in [14] the used traction battery is entering the SL system with a capacity of 0.8 $kWh_{nom,SL}$. After the repurposing process, entailing the disassembly of the battery system, the testing and sorting of the modules and the assembly of the new battery system [15], the repurposed battery system enters the stationary application. In this case the SL battery is deployed for PCR or as a PV HSS.

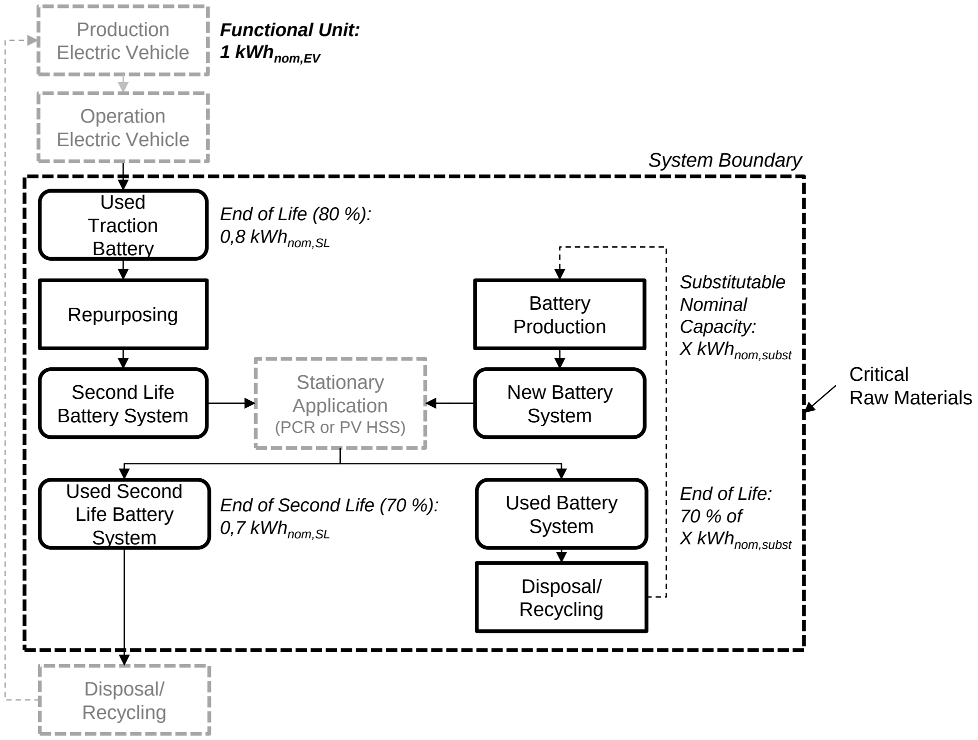

*Figure 2: System boundary for the assessment of second life applications*

Control reserve is needed for the event of an imbalance between power supply and demand in order to stabilise network frequency. As described in [16] *PCR* is automatically activated in the event of a frequency deviation in a non-selective manner, meaning that the deployment of PCR is directly controlled by the network frequency and not by a central entity. According to the German prequalification requirements an activation of the complete PCR has to be performed within 30 seconds. Thus, as large power gradients in both directions are required, batteries constitute a viable option for delivering PCR. The idea behind using batteries as *PV HSS* is the increase of on-site consumption from the PV system due to a temporal decoupling of PV generation and electricity demand. The increased on-site consumption leads to a decrease of electricity demand from the grid and potentially a decrease of electricity costs.

As the SL battery has already aged during its use in the vehicle, its ageing process and life time in the stationary application differ from those of a new battery. Hence, the SNC is quantified by building on battery ageing curves derived from [14, 17-20]. It constitutes the capacity of a new battery system, which over its life time delivers the same function (provide PCR or increase on-site consumption) as the SL battery.

In this case, the final end of life is defined as 70 % of the original nominal capacity, which corresponds to a typical end of life criterion of stationary battery systems. Once the final end of life is reached both the SL battery system and the new battery system are disposed or if possible recycled. As the disposal of the traction battery would have taken place independent of the SL application, it is not included in the system boundaries. The recycled materials of the avoided new battery system on the contrary need to be included when determining the reduction of resource consumption.

Finally, the reduction of critical resource consumption through SL applications can be quantified via the raw material consumption of the avoided battery production. The specific critical resource consumption of the new battery system results from the specific critical material demand of the battery system minus the recycled critical materials. When multiplying the specific critical resource consumption of the new battery system with the SNC the overall reduced critical resource consumption can be determined as illustrated in the following equation:

$$RCRC_{m,SLA,BT} = (CMD_{BT} - RCM_{BT}) \times SNC_{SLA,BT} \qquad (1)$$

| | |
|---|---|
| RCRC: | Reduced Critical Resource Consumption in kg/kWh$_{nom,EV}$ |
| m: | Material (Cobalt, Lithium, Graphite or Nickel) |
| SLA: | Second Life Application (PCR or PV Home Storage System) |
| BT: | Battery Type (NMC or LFP) |
| CMD: | Critical Material Demand of Battery System in kg/kWh$_{nom}$ |
| RCM: | Recycled Critical Materials from Battery System in kg/kWh$_{nom}$ |
| SNC: | Substitutable Nominal Capacity in kWh$_{nom,subst}$/kWh$_{nom,EV}$ |

In the following chapters, first the specific critical material demand and the recycling efficiencies are quantified for NMC and LFP battery systems. Then the substitutable nominal capacity for PCR and PV HSS is derived from NMC and LFP battery ageing models.

## 3.2 Demand and Recycling of Critical Materials

The specific critical raw material demand for both NMC and LFP battery systems according to Argonne National Laboratory [21, 22] and Öko-Institut [23] is depicted in Table 1. The raw material content in [21] and [22] is given per mass of cathode and anode and was translated into the specific critical material demand for a 28 kWh/80 kW-battery system containing a 51 kg cathode and a 43 kg anode. In case the material demand was only given for the metal oxides, the pure metal content was derived via stoichiometry. The values for LFP battery systems were directly taken from [23].

*Table 1: Specific critical material demand for NMC and LFP battery systems*

| Type | Unit | Cobalt | Lithium | Graphite | Nickel | References |
|---|---|---|---|---|---|---|
| NMC | g/kWh$_{nom}$ | 223 | 131 | 1214 | 444 | [21, 22] |
| LFP | g/kWh$_{nom}$ | – | 107 | 1563 | – | [23] |

Due to uncertainties with regard to current and future collection rates and recycling efficiencies, two scenarios are defined for the overall recycling efficiency of these materials. For the low scenario the legal collection rate of 45 % according to §15 of the German battery law [24] and recycling efficiencies of the LiBRi-process [25] are assumed. The high scenario is based on [23] and entails a theoretical collection rate of 100 % and recycling efficiencies of the Lithorec-process measured on a laboratory scale, thus, representing future technical potentials rather than the current state-of-the-art.

*Table 2: Scenarios for the overall recycling efficiency of NMC and LFP battery systems*

| | Type | Cobalt | Lithium | Graphite | Nickel | References |
|---|---|---|---|---|---|---|
| Low | Mix (NMC/NCA*/LFP) | 43 % | 23 % | 0 % | 40 % | [24, 25] |
| High | NMC | 100 % | 93 % | 0 % | 97 % | [23] |
| | LFP | – | 80 % | 0 % | – | |

*NCA=Nickel-Cobalt-Aluminium-Oxide

According to Moradi and Botte [26] the three main challenges of graphite recycling from lithium ion batteries for high quality applications are economic justification, purity and ageing mechanisms. Therefore in the considered hydro- and pyrometallurgical processes [23, 25] the material recycling efficiency of high quality graphite is still 0 %.

## 3.3 Substitutable Nominal Capacity

The SNC considers on the one hand the decrease in battery capacity due to the battery ageing process, which depends on the load profile and the battery type. On the other hand it takes into account the time period in which the battery system can be used in the stationary application until the final end of life criterion of 70 % of the original nominal capacity is reached. Considering these factors, first, the supplied function of the SL battery system, namely the provision of PCR or the increase of on-site consumption, is quantified. Then, the equivalent size of a new battery system providing the same function over its life time is determined.

Analogous to [14] the load profile for PCR is taken from the research project EEBatt [27, 28]. Thus, it is assumed that a 200 kWh/200 kW-storage system characterised by an overall system efficiency of 81 % provides PCR in a pool of several technical units making use of different operation strategies such as e.g. intraday trading. The load profile for the PV HSS originating from the project e-GAP [29] is derived from measurements of PV generation and household loads. A battery system with 10 kWh/3.6 kW and an efficiency of 86.5 % is chosen. A detailed description of the load profile characteristics can be found in [14].

These load profiles are then inserted into battery ageing models so as to determine the decrease in battery capacity and the final end of life. The ageing functions for the NMC battery system stem from a battery ageing model by the Technical University of Munich [17]. The resulting ageing process for the NMC battery system is described in [14] and is characterised by the following functions:

$$C_{PCR}(t) = 1 - 0.03599 \times t^{0.65} \tag{2}$$

$$C_{PV\ HSS}(t) = 1 - 0.05843 \times t^{0.88}$$

| | |
|---|---|
| C: | Battery capacity in kWh |
| PCR: | Primary Control Reserve |
| PV HSS: | Photovoltaic Home Storage System |
| t: | Time in years |

These functions show that due to deeper charging cycles the ageing of NMC batteries proceeds much faster in home storage than in PCR applications.

The LFP ageing model is based on [18-20]. The chosen model considers a loss of capacity due to calendar ageing ($SOH_t$) and cycling ageing ($SOH_c$) expressed by the following functions:

$$SOH_c = SOH_{start} - A \times e^{\frac{B}{R \times T}} \times Ah(SOH)^C \tag{3}$$
$$SOH_t = SOH_{start} \times (D + (E + t)^F)$$

| | |
|---|---|
| SOH: | State-Of-Health |
| T: | Temperature in Kelvin |
| A,B,C: | Parameter as f(C-Rate) |
| D,E,F: | Parameter as f(T, SOC) |
| t: | Time in days |
| Ah: | Ah-throughput as f(SOH) |
| R: | Universal gas constant |

In both models a constant temperature of 25 °C is assumed. Due to the numerous manufacturer-specific influences on the ageing of both cell technologies and the different approaches of the models, the results are not to be understood as an absolute comparison, but rather as a tendency of the different ageing characteristics of NMC and LFP cells. The examined LFP cells for example show higher cycle stability than the NMC cells, but on the other hand are characterised by a higher temperature and C-rate dependency.

The resulting ageing curves are depicted in Figure 3. It can be seen that the ageing model of the NMC cell shows a strong ageing process in case of the PV HSS profile. This is due to the deep charging and discharging cycles, which have a great influence on the ageing of the investigated NMC cell. In general, batteries for mobile applications are designed for different technical requirements than stationary batteries. While in mobile applications the most important design criterion is energy density, in stationary applications on the contrary cycle stability is the most relevant criterion.

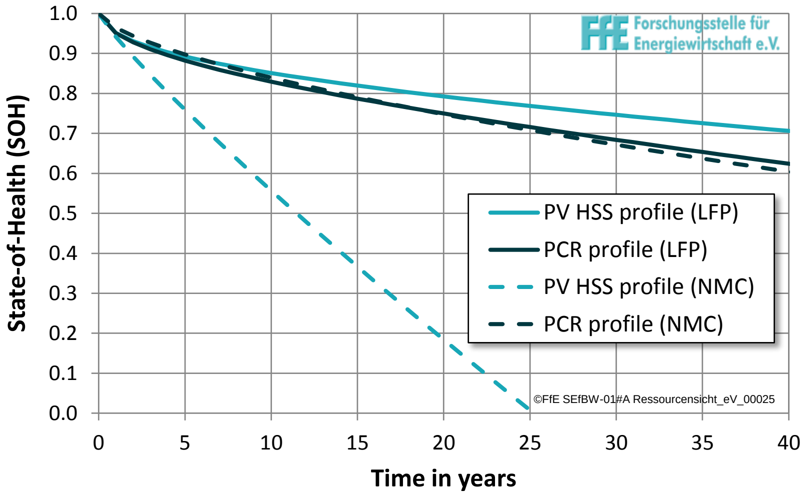

*Figure 3: Ageing curves for the PCR and PV HSS load profiles based on the ageing models for NMC and LFP cells*

On the basis of the described ageing curves for an NMC battery system a substitutable nominal capacity (related to 1 $kWh_{nom,EV}$ original nominal capacity of the traction battery) of 0.47 $kWh_{nom,subst}$ for the PCR and of 0.26 $kWh_{nom,subst}$ for the PV HSS application has been determined. For the LFP battery system the SNC amounts to 0.51 $kWh_{nom,subst}$ for PCR and 0.53 $kWh_{nom,subst}$ for PV HSS. The SNC is lower than the capacity of the SL battery system of 0.8 $kWh_{nom,SL}$ as the SL battery has already aged in the vehicle and the time period until it reaches its final end of life in the stationary application is lower than that of a new battery system. Furthermore, the resulting SNC values reflect that the considered NMC battery system ages faster in the PV HSS application.

# 4 Reduction of Critical Resource Consumption

The reduction of critical resource consumption through SL applications can then be calculated by inserting the calculated SNC, the specific material demand from Table 1 and the recycled materials from Table 2 into Equation 1. Figure 4 and 5 show the maximum reduction of critical resources for an NMC and an LFP battery system for the two SL applications PCR and PV HSS.

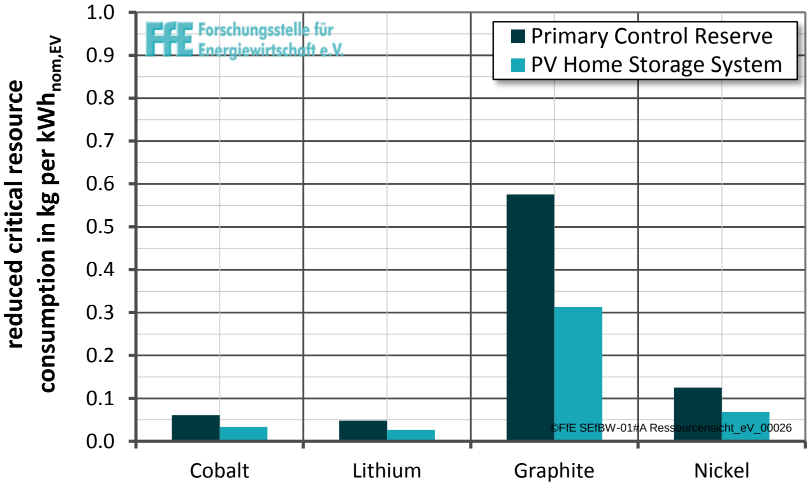

*Figure 4: Maximum reduction of critical resources through SL applications for an NMC battery system*

In the case of an NMC battery system the critical resource saving potential is lower in the PV HSS application. This is due to the fact that the considered NMC battery cells age faster when being cycled with the HSS load profile, thus resulting in a lower SNC. For the LFP battery system on the contrary the critical resource saving potential for PV HSS is exceeding that of PCR as the considered LFP battery cells show better ageing properties for the PV HSS load profile.

When comparing the two battery types it is obvious that NMC battery systems contain all four critical raw materials identified and LFP battery systems only entail lithium and graphite. While the capacity loss for the PCR application is similar both for LFP and NMC, the ageing process for the PV HSS application differs a lot between battery types. This is reflected in the SNC, which is around twice as large in case of LFP compared to NMC.

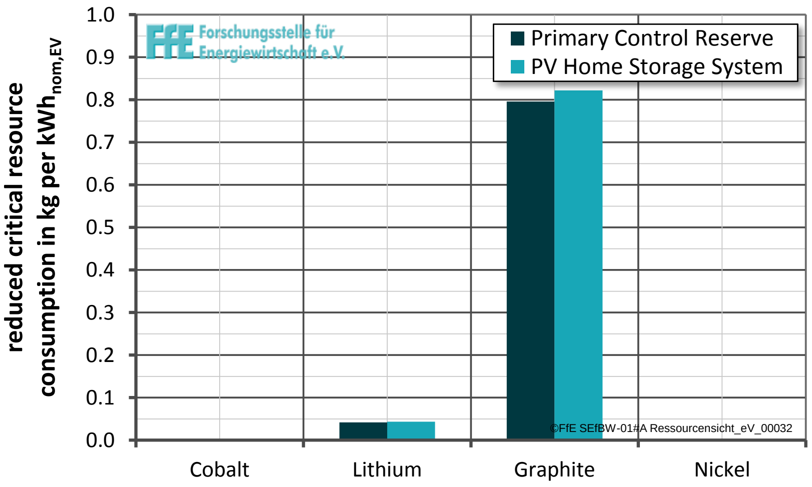

*Figure 5: Maximum reduction of critical resources through SL applications for an LFP battery system*

When looking at the minimum resource saving potential for an NMC battery system, the reduction of critical resources approaches zero for cobalt, nickel and lithium due to high recycling efficiencies between 93 and 100 %. For the LFP battery system the recycling efficiency of lithium is lower than for NMC, which results for the PV HSS application in a minimum saving potential of 11 g/kWh$_{nom,EV}$ for LFP compared to 2 g/kWh$_{nom,EV}$ for NMC. The reduced graphite consumption stays the same in the minimum case both for LFP and NMC as graphite material recycling is still being investigated.

These results show that the reduction of critical resource consumption is strongly dependent on the battery type as well as the SL application. In this context, several determining factors could be identified with the specific material demand, collection rate and recycling efficiencies having a large impact on the reduction potential. As lithium ion batteries are still subject to technological developments these parameters can be expected to undergo significant changes in the future. Other sensitive parameters, which are entailed in the SNC, are the considered load profiles, the modelled ageing processes and the chosen final end of life criterion. These parameters can vary strongly depending on the specific battery type, battery sizing and application. Thus, a thorough sizing and matching of the used traction batteries with the requirements of the SL application is needed. Furthermore, it needs to be considered that these results are derived from two battery ageing models with a different level of modelling complexity and for which a validation is difficult as there are no long-term measurement samples for battery ageing available.

## 5 Conclusions and Outlook

Based on the defined criticality screening procedure, especially cobalt, but also lithium, natural graphite and nickel are identified as critical raw materials. Furthermore, it is shown that an extension of a traction battery’s life time can lead to a reduction of critical resource consumption. Due to different ageing processes and material compositions the amount of saved resources depends on the considered second life application and battery type. Other determining factors for the reduction of critical material consumption are the achieved collection rate and recycling efficiencies of used lithium ion batteries.

In this paper an assessment on the technology level has been conducted. In a next step an expansion of the system boundaries is needed so as to analyse the impact of second life applications on resource availability and raw material markets. For example, in order to determine the overall potential of second life applications an analysis of the availability of second life storage systems and of the demand for second life applications would be necessary. It also needs to be considered that second life applications generally lead to a postponement of the recycling process. This could go along with better recycling efficiencies, but in the short-term leads to an increase of primary resource demand due to a later availability of the secondary materials. While the reduction of critical resource consumption has been in the focus of this paper, environmental and economic advantages are other important criteria, which need consideration in a holistic assessment of second life applications.

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