Cost and Metal Savings through a Second-Life for Electric Vehicle Batteries

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1 Motivation

According to the application-related emissions balance in [1] in 2016 27 % of the energy-related CO_2 emissions can be attributed to mechanical energy for the transport sector. It is also outlined that the emissions for mechanical energy, mainly needed in the transport and industry sector, have been stagnating over the past decade. Against this background, the question of the role of electric vehicles (EV) as one option to meet climate targets in the transport sector have recently gained of importance.

Apart from preventing local emissions, one of the main advantage of EV, is the high efficiency in the use phase leading to lower operation-related greenhouse gas (GHG) emissions compared to internal combustion engine vehicles (ICEV). As described in [2] this advantage is currently reduced by the energy demand for the production of the EV battery. However, it is also shown that the carbon footprint of the battery production process can be largely reduced by efficiency measures and the use of renewable energy in the production process. Another issue of EV is the demand for metals such as lithium (Li) and cobalt (Co), which are classified as critical due to a geographical concentration, the environmental and social impacts associated with the mining process as well as a strong increase in demand [3], which in the short- to medium-term can lead to shortages on the supply side and therefore increasing prices.

Furthermore, despite decreasing battery prices, battery systems both for EV as well as for stationary applications are still characterized by large investments. While the prices for battery modules decreased by 15 % from 2015 to 2017 [4], the battery system still makes up 36 % of the EV's total costs [5]. Also for stationary battery systems the profitability is largely influenced by the investment [6], which in case of a home storage system (HSS) amounts to an average of 9 800 € per system in 2017 [7].

The circular economy (CE) (compare Figure 1) is often proposed as an option to reduce primary raw material demand, decrease environmental impacts and create new opportunities for value creation [8]. In this context, the question arises to what extent the remanufacturing or reuse of End-of-Life (EoL) batteries from EV in stationary application can reduce the disadvantages of EV with regard to critical metal demand. And another aspect of interest is the extent to which these so called Second-Life (SL) applications offer costs savings for stationary batteries. In [2] it is shown that the CE offers the potential to reduce the battery's carbon footprint. Furthermore, it is illustrated that approaches from the CE at the battery's EoL phase such as SL applications and recycling offer potential for metal savings. However, it is only briefly touched upon the fact that the actual saving potential of SL approaches depends on the boundary conditions. Therefore the aim of the present analysis is to quantify the potential of SL batteries to reduce costs for stationary batteries as well as to systematically identify critical parameters determining the metal and cost saving potential of SL batteries.

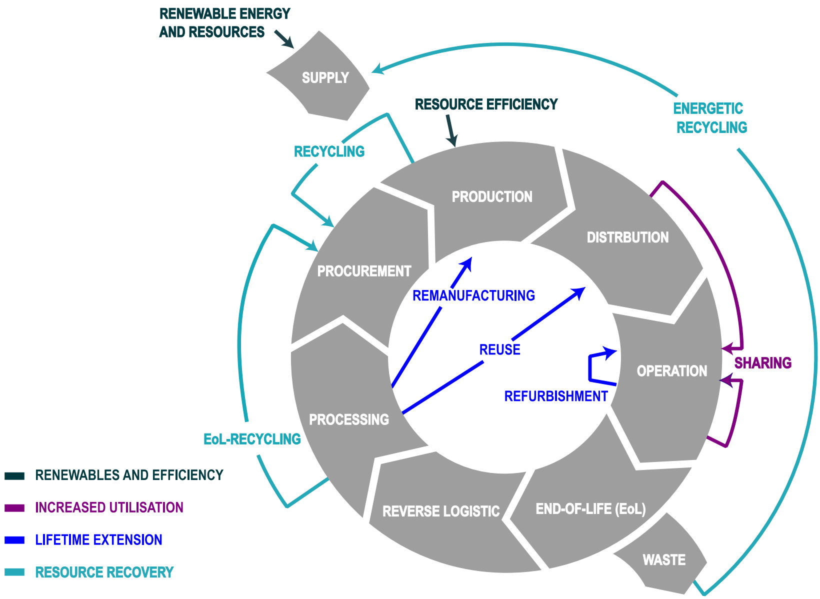

Figure 1: Overview of possible approaches from the CE in different life cycle phases (own illustration based on [9])

2 Methodological Procedure

The extension of the lifetime of EV batteries due to SL applications leads to time delays and substitution effects on stationary battery markets, which are met by a dynamic material flow analysis (MFA).

Starting Point

Starting point of this analysis is the stock-and-flow model described in [2]. This model covers traction batteries (TB) used in passenger cars and stationary batteries (SB) deployed as HSS and for Primary Control Reserve (PCR) in Germany from 2015 to 2050.

Model Extension

While for the quantification of critical metal savings in [2] the flows of battery production and recycling are linked to the specific stoichiometric Li and Co content per battery capacity, an extension of the model is required to determine the impact of SL applications on costs for SB. Therefore the model is modified and extended in the sense that the main components of SB are modelled separately. Next to battery modules a modelling of the periphery and power electronics is required because on the one hand different SL concepts (reuse or remanufacturing) require different components, and on the other hand different components are characterized by different lifetimes. This has an impact both on the time of replacement of these components and the annual costs which are determined by the annuity method described in [10]. By using this modelling approach in each year the simulated production of each SB component can be linked to the annuitized investments and the simulated capacity of repurposed SL batteries can be linked to the corresponding processing costs.

Scenario Comparison

The critical metal and costs savings through SL are determined by comparing a “recycling only” with a “recycling+SL” run of the model. As cost developments for battery recycling and changes in operations costs are not in the scope of the model, the stated cost savings refer to investments in SB systems including processing costs of SL batteries (SLB). This assessment is first conducted for the initial scenario, which is defined based on [2].

Sensitivity Analysis

In [2] it is shown that depending on the boundary conditions, SL can in the short- to medium-term even lead to an increase in demand of certain metals. Therefore in a next step, a systematic sensitivity analysis is conducted to identify critical parameters, which strongly impact the extent to which SL leads to metal and cost savings. Starting from the critical metal and cost saving of SL for the initial scenario, the development of one parameter is changed at a time and again a comparison of a “recycling only” and a “recycling+SL” simulation run takes place. The change in critical metal and cost savings due to SL for this modified sensitivity scenario is then compared to the change in the initial scenario to determine the influence of the changed parameter on the saving potential of SL applications.

In the following, in Chapter 3 the dynamic material flow and cost model as well as the input data for the initial scenario is described. Then in Chapter 4 the results, namely the cost and critical metals savings through SL for the initial scenario and the identified critical parameters from the sensitivity analysis, are shown. Finally, a conclusion is drawn in Chapter 5.

3 Dynamic Material Flow and Cost Modelling

As described in Chapter 2, the critical metal and cost saving potential of SL applications are determined by means of a stock-and-flow-model, which takes into account substitution effects on stationary battery markets and time dependencies. As the model is based on the dynamic material flow model, whose mathematical foundations are described in detail in [2], in Section 3.1 the basic principles of the model are only briefly summarised. Building on this, the further extension of the model with regard to costs is described in more detail in Section 3.2. Finally, in Section 3.3 the scenario and input data underlying the results in Chapter 4 are briefly summarized.

3.1 Model Overview

Figure 2 gives an overview of the stock-and-flow-model, describing the battery stock in the system and the battery flows into and out of the system over time. As mentioned in Chapter 2 this model covers TB used in electric passenger cars as well as SB used in HSS and PCR application in Germany from 2015 to 2050. From the annual stock for each battery type the annual production and EoL battery systems are determined using lifetime distribution functions. These battery flows are then connected to the corresponding Li and Co content to derive the demand for primary Li and Co, which results from the total metal demand less the available secondary metals from recycling. Because the Li and Co demand is determined based on stoichiometry a differentiation by cell type is made. The use phase of the batteries, on the contrary, is not in the scope of this analysis.

When assessing the reuse of TB in stationary applications the formerly separate automotive and stationary markets are now connected via processed SLB. While this leads to a decrease in production of new SB, the recycling process of the used TB is shifted in time due to the battery’s lifetime extension. By linking the production of new SB and the processing of SLB with their annual costs the assessment of SL applications can now be expanded to cost savings for SB.

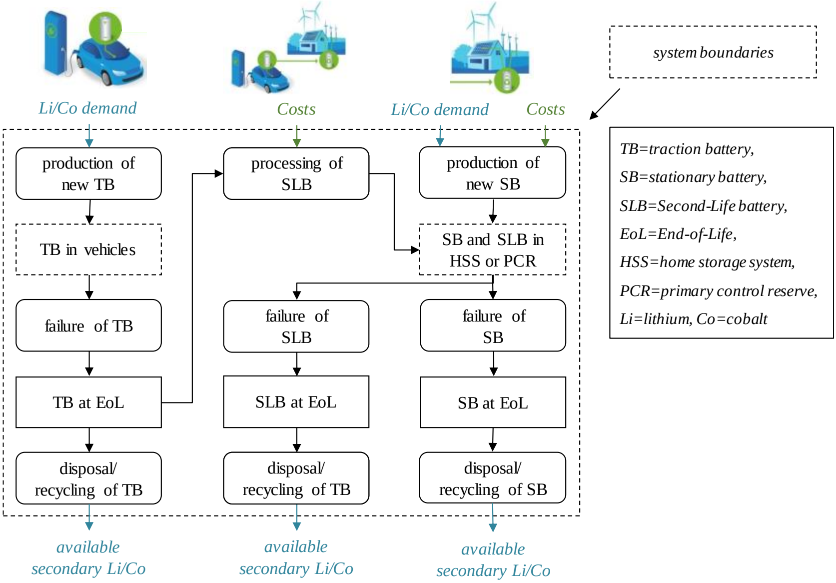

Figure 2: Overview of the dynamic material flow model to assess cost and critical metal savings of SL applications of EV batteries (based on [2])

3.2 Cost Modelling

In contrast to the quantification of critical metal demand, the cost assessment necessitates a separate modelling of the components of stationary batteries, because not only the modules, but also the costs of the periphery and power electronics need to be considered. The fact that these components have different lifetimes needs to be accounted for as the lifetime does not only determine the time of substitution, but also the battery's annuity a, which is used to evenly distribute the investment over the battery's lifetime. As described in [10] the annuity is quantified by

$$a = I \cdot ANF \tag{1}$$

where I is the investment and

$$ANF = \frac{(1+i)^n \cdot i}{(1+i)^n - 1} \tag{1}$$

with i being the interest rate and n being the lifetime.

When modelling costs, furthermore, a differentiation needs to be made between applications and SL concepts as they require different components as illustrated in Table 1. While ‘reuse’ means that the TB is used as a whole in the stationary application, ‘remanufacturing (reman)’ refers to the case that the TB is first broken down into modules before being remanufactured into a SB. This has also an impact on the amount of SB substituted by SLB as the substitution takes place on the basis of numbers of batteries in case of reuse and on the basis of capacity in case of remanufacturing.

Table 1: Demand for components depending on stationary application and SL concept

Component	HSS ‘new’	HSS ‘reuse’	HSS ‘reman’	PCR ‘new’	PCR ‘reuse’	PCR ‘reman’
Modules	X			X		
Processing		X	X		X	X
Power electronics	X	X	X	X	X	X
Periphery	X		X	X	X	X

For new battery systems *module costs* are considered, which take into account cell costs and the costs for their installation in the modules. In case of an SL system, instead of module costs the *costs for processing* of the used traction battery for stationary use are included. The amount of processing costs depends on the SL concept considered. The *power electronics costs* include the costs associated with the battery management system, the cell thermal management and the inverter. The *periphery costs* consist for HSS of the costs of the battery case, the mounting system and the isolation. In case of a large battery storage system for PCR, the peripheral costs primarily include the costs for the container, the fire management and protection system and the transformer for grid connection [11]. All of these costs only reflect the costs occurring due to the production of the battery system components and therefore include neither margins of the manufacturer nor costs for battery assembly and operation.

3.3 Initial Scenario and Input Data

As the starting point of the assessment an initial scenario is defined, which is described in detail in [2] and for which the input data is briefly summarised in Table 2. In this scenario, the lifetime of the TB in the vehicle corresponds to the EV’s lifetime. In the “recycling only” run the batteries at EoL are recovered with recycling rates according to Table 2. In case of the “recycling+SL” run the ‘reman’ concept is applied, meaning that SL batteries substitute stationary battery systems on capacity basis, and the PCR application is prioritised over the use as HSS.

Table 2: Summary of input data for initial scenario from [2]

Parameter	Traction Battery	Home Storage System	Primary Control Reserve
Battery stock	Results from transport model TraM [12] with scenario from [13]	Installed photovoltaic (PV) capacity from [14] and number of HSS depending on installed PV from [15][(a)]	Development according to [16] until the maximum PCR market potential of 600 MW [17] is reached
Capacity	From 34 kWh in 2015 to 44 kWh in 2050	~7 kWh	Historical: current projects Future: settle at 5 MWh
Lifetime[(b)]	In vehicle:12-13 years Second-Life: 8 years	20 years	
EoL criteria	70 % of original nominal capacity left at the battery's EoL in the vehicle ([18] and OEM warranties)	End-of-SL: 50 % of original nominal capacity [18]	
Cell technologies	NMC622: 56 % LFP: 2 % LMO-NMC333: 18 % NCA: 24 %	NMC622: 60 % LFP: 40 %	NMC622: 94 % LFP: 2 % LMO: 4 %
Metal content	NMC622: 0.115 kg Li and 0.177 kg Co per kWh LFP: 0.090 kg Li per kWh LMO: 0.109 kg Li per kWh LMO-NMC333: 0.127 kg Li and 0.168 kg Co per kWh NCA: 0.099 kg Li and 0.126 kg Co per kWh		
Collection rate	Maximum collection rate and SL feasibility: 100%	Maximum collection rate: 100%	
Recycling rate	Cobalt: 94% Lithium: 0% until 2020, 57% from 2020		

NMC: Lithium Nickel Cobalt Manganese Oxide, LFP: Lithium Iron Phosphate, LMO: Lithium Manganese Oxide,
NCA: Lithium Nickel Cobalt Aluminium Oxide, Co: Cobalt, Li: Lithium
(a) Probability of HSS equipment for PV stock: 0.6 % per year; probability of HSS for new PV systems: 42 %; PV systems, built before the time horizon under consideration, are also upgraded with an HSS with a probability of 42 % after 20 years of operation (due to expiring feed-in tariffs). These probabilities were derived based on the approach described in [15].
(b) Mean age of lifetime probability density function using a lognormal distribution with consideration of the manufacturer's warranty and failure before warranty expiry of 1%

In the following, the additionally required cost data is first described for each component and then all cost developments are compiled in Table 3.

Module Costs

The module costs of new lithium-ion batteries are based on the mean cost development for pouch/prismatic cells in [4]. To transfer these costs to the module level 10 % of the battery cell costs are added according to [19].

Processing Costs

The costs associated with the preparation of TB for stationary use are determined on the basis of the Tool 'b2u Repurposing Cost Calculator' [20], supplemented by data from [21] and [22] for a processing plant at a German location. The processing includes transport, storage and repurposing of the traction batteries for stationary use. In the initial scenario, a maximum utilization of the processing plants is assumed. As described above a distinction is made between processing at the system level ('reuse') and the module level ('reman').

While the costs for the transport and storage of the TB are independent of the processing concept and amount to 4.8 €/kWh, the repurposing costs depend on the level of processing. The calculated repurposing costs for the 'reuse' concept are 6.6 €/kWh and therefore lower than for the 'reman' concept, for which they add up to 17.3 €/kWh. The differences in costs are due to the greater amount of work involved in disassembling the TB down to the module level. Furthermore, the repurposing costs include additional material costs and costs for added elements, which arise due to different requirements of stationary applications. These additional costs are charged at 5.7 €/kWh for the 'reuse' concept and 32.3 €/kWh for the 'reman' concept. The higher additional costs of the 'reman' concept result from the need for new interfaces after dismantling down to the module level [22]. Thus, the repurposing costs sum up to 17.1 €/kWh for the 'reuse' concept and 54.4 €/kWh for the 'reman' concept, respectively. These are assumed to be constant over the considered time horizon.

Power Electronics Costs

The cost development for the power electronics depicted in Table 3 is taken from [11]. Here, a distinction is made between power electronics for small and large storage systems, so that different costs are assumed for HSS and PCR storage systems, respectively. Because the costs for power electronics refer to the battery's installed power, the battery flows on capacity basis are converted using the Energy-to-Power (E/P) ratios from [16].

Periphery Costs

As the cost development for the periphery is difficult to define, the cost development was calculated in relation to the module costs according to [23]. For HSS the periphery amounts to about 48 % of the module costs and for large storage systems, in this case PCR, to around 86 %. This assumption leads to the cost development described in Table 3.

Table 3: Cost development per component

Component	Unit	2015	2020	2025	2030	2035	2040	2045	2050
Modules	**€/kWh**	336	212	151	105	105	105	105	105
Processing 'reuse'	**€/kWh**	17							
Processing 'reman'	**€/kWh**	54							
Power electronics HSS	**€/kW**	169	136	97	70	53	39	29	21
Power electronic PCR	**€/kW**	112	95	74	57	46	37	29	23
Periphery HSS	**€/kWh**	161	101	72	50	50	50	50	50
Periphery PCR	**€/kWh**	288	182	130	90	90	90	90	90

4 Cost and Metal Saving Potential of Second-Life Applications

In Section 4.1, first, the critical metal and cost savings of SL application are described for the initial scenario. While the impact on critical metals has already been discussed in [2], additionally cost savings are determined. Then, in Section 4.2 critical parameters on the saving potential of SL applications are identified based on a systematic sensitivity analysis.

4.1 Impact of Second-Life for the Initial Scenario

STARTING POINT: "RECYCLING ONLY"

Figure 3 shows that the demand for primary metals increases due to an increasing stock of TB and SB. For Co, the primary demand decreases in the long-term once a large number of batteries reaches its EoL and enters the recycling process. This leads to an increasing availability of secondary Co, which is recovered with a high recycling rate, and therefore a reduction in demand for primary Co. This effect is less visible for Li because of a lower recycling rate.

A similar pattern can be observed for the costs associated with the investment in SB and processing of SLB. The peak in the mid-2030s can be explained by the PV systems built prior to 2015, which are upgraded with an HSS after 20 years of operation as a result of expiring feed-in tariffs. The cost curve then flattens as battery prices stabilize.

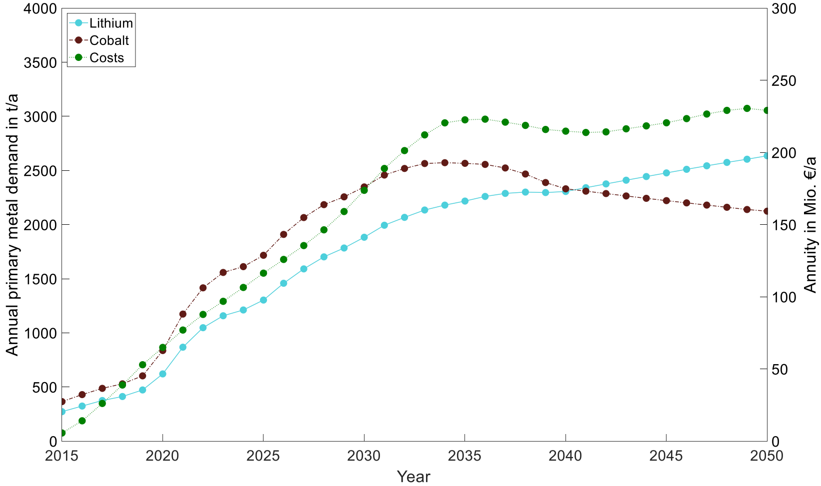

Figure 3: Primary Li and Co demand for TB and SB as well as annual costs for SB (investment) for the “recycling only” run of the initial scenario

Overall it can be seen that despite high recycling rates and a conservative EV scenario, the demand for primary Li and Co is still significant in 2050 (around 2 100 t Co correspond to about 2 % of current Co production [24]). Thus, the question of a further reduction through SL applications becomes relevant.

Lithium and Cobalt Savings through Second-Life applications

By comparing the “recycling only” with the “recycling+SL” simulation run the Li and Co savings through SL applications can be determined. From the results in Figure 4 it can be seen that for Li in each year of simulation a reduction in Li demand takes place in case batteries from EV are reused in stationary applications. For Co, on the contrary, an increase in Co demand (negative savings) is observed in the time horizon under consideration.

For Li the savings increase until 2020 due to an increasing availability of SLB, substituting the production of new Li-containing SB. In 2020 a decrease in savings can be observed because the Li recycling rate rises from 0 to 57 %. This has a negative effect on the saving potential as the Li contained in the used SLB reaches the recycling system at a later point of time, corresponding to a later availability of secondary Li. The peak in Li savings in the early 2030s results from the large demand in SLB due to the upgrade of old PV systems with an HSS. The increasing Li savings in the long-term can be explained by a still increasing stock of HSS as well as the fact that a large number of SLB gradually reaches the recycling system and is replaced by new SLB. In total, for Li the effect resulting from the substitution of new SB always outweighs the temporal shift of the recycling process leading to positive savings in every year of investigation.

For Co, on the contrary, the demand for primary Co increases in case of SL applications, which can mainly be traced back to three effects. First of all, due to the ageing in the vehicle the available capacity of a SLB is lower (EoL criterion: 70 % of original capacity) than the original capacity of a new SB. This results in the substitution of a smaller SB, while an oversized SLB (factor 1.4) is bound in the stationary market. This effect is independent of the metal and therefore also reduces the saving potential for Li. Second, Co-rich TB replace less Co-containing SB because the share of Co-free cell types (such as LFP) is larger for SB than for TB due to less stringent requirements with regard to energy density. Third, Co is characterized by a high recycling rate so that the extension of the TB's lifetime leads to a temporal shift of large amounts of secondary Co available from recycling. In the long-term, the increase in annual Co demand is reduced as Co-intensive SLB reach their EoL, leading to a large availability of secondary Co.

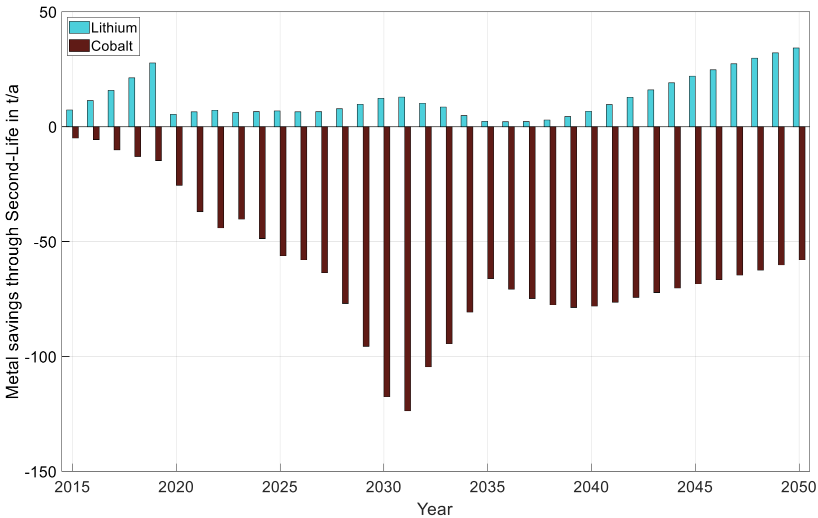

Figure 4: Critical metal savings through SL applications compared to "recycling only"

In general, the costs savings through SL are determined by several developments. One decisive factor is the difference in costs between the production of new SB and the processing of SLB. In the initial scenario the differential costs are decreasing because prices for new modules are falling while processing costs are assumed to stay constant. The decreasing module prices and the smaller lifetime of SLB lead to a tipping point in 2027, in which the annuity of a new HSS is smaller than the annuity of an SLB. Furthermore, the cost savings are determined by the availability of SLB, which in this case can cover the total demand of SB from 2021 on. And finally, the saving potential is strongly influenced by the demand for SB, which is not only dependent on the stock, but also on the lifetime of the deployed SB or SLB, respectively.

For the described scenario these developments lead to the annual cost savings for SB depicted in Figure 5. With the increasing use of SLB in stationary applications, first, growing cost savings can be observed. In 2027 the annuity of new HSS is smaller than the annuity of SLB leading to a decrease in cost savings. These savings eventually become negative once the SLB deployed prior to 2027 have reached their EoL.

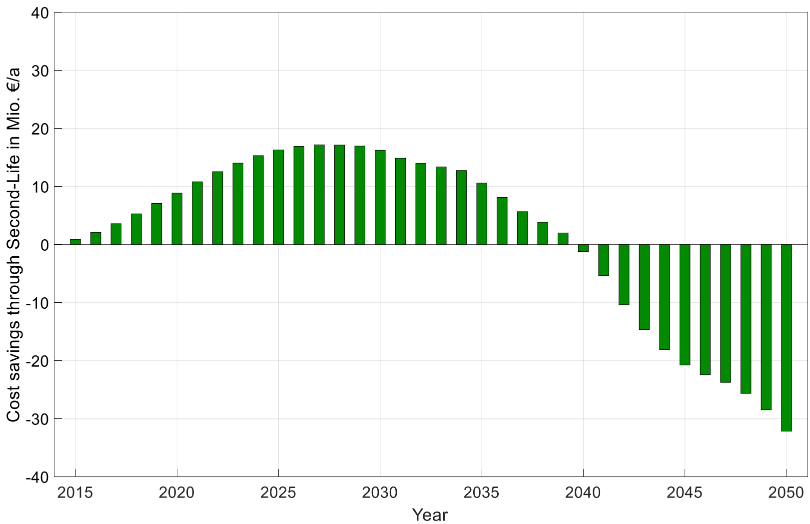

Figure 5: Cost savings (SB investment and SLB processing) through SL applications compared to “recycling only”

4.2 Identification of Critical Parameters on Second-Life

From the results of the initial scenario it can be concluded that there are several mechanism affecting the critical metal and cost saving potential. As these mechanism are influenced by the selected boundary conditions, in the following, a sensitivity analysis is conduced to identify critical parameters on the saving potential. Table 4 gives an overview of the defined sensitivity scenarios. For each of these scenarios one or two parameters are changed compared to the initial scenario. Then for each of these scenarios again the "recycling only" calculation run is compared to the "recycling+SL" run.

LITHIUM AND COBALT

Reducing the *SL feasibility* to 50 % leads to a decrease in saving potential because less SLB are deployed (full stationary market coverage by SLB only in 2025), resulting in lower positive savings for Li, but also lower negative savings for Co. However, once the market is fully covered by SLB, the course of the saving potential is the same as for the initial scenario in Figure 4. The smaller *collection rate* of 17 % does not only reduce the number of available SLB (full market coverage in 2034), but also reduces the availability of secondary materials in the "recycling only" case. This leads, on the one hand, to a shift of savings through SL to a later point of time and, on the other hand, to smaller relative savings for Li and to a smaller relative increase for Co than for the initial scenario.

At this point it must be mentioned that, if the changed parameter influences the "recycling only" run of the respective sensitivity scenario, the basis for the evaluation of SL applications is changed. In this case, comparing the absolute savings of the sensitivity scenario with the absolute savings of the initial scenario is not meaningful, but instead the relative savings of "recycling+SL" compared to the corresponding "recycling only" run need to be compared for the two scenarios.

Table 4: Overview of sensitivity scenarios

Name	Changed parameter	Motivation
"SL feasibility"	SL feasibility: 50 %	Considering restrictions for technical feasibility of SL applications
"Collection rate"	Collection rate: 17 %	Assuming an equally low collection rate for EV as for conventional vehicles due to vehicle export [25]
"Recycling efficiency min"	Recycling efficiency for Li und Co: 0 %	Illustrating the impact of the recycling efficiency by an extreme scenario
"Recycling efficiency max"	Recycling efficiency for Li und Co: 100 %	Illustrating the impact of the recycling efficiency by an extreme scenario
"EoL criterion"	EoL criterion: 100 %	Showing the impact of the EoL criterion by an extreme scenario
"Same technology"	Share of SB cell technologies: same shares as for TB	Eliminating the substitution effect resulting from different shares of cell technologies for TB and SB
"Constant stock"	Stock of HSS and PCR: stagnating from 2020 on	Illustrating the effects of SL in a saturated market
"Constant stock+half lifetime"	Stock of HSS and PCR: stagnating from 2020 on; Mean age SB and SLB: halved	To establish a "closed" system, in which the SB market is continuously covered by SLB, lifetimes need to be reduced
"Reuse"	SL concept: reuse	Determining the impact of the SL concept (processing on system instead of module level)
"Reuse only PCR"	SL concept: reuse; Chosen SL application: only PCR	Exploring whether the favourable SL concept depends on the application
"Processing costs"	Utilisation of processing plant: 2015 10%, 2020 40%, 2025 70%, 2030 100%	Outlining the impact of SLB availability, which affects the utilisation of processing plants and therefore costs
"Lifetime"	Mean age SLB: 4 years (halved)	Demonstrating the effect of shorter lifetimes of SLB because of strong uncertainties with regard to battery ageing

The sensitivity of the saving potential on the recycling efficiency has already been briefly discussed for the initial scenario in Section 4.1. In Figure 6 this effect is clarified by showing the relative Li savings through SL for the initial scenario (Li recycling rate: 57 % from 2020 on) and the two sensitivity scenario *"Recycling efficiency min"* and *"Recycling efficiency max"*. It can be seen that under the chosen boundary conditions the recycling rate decides whether Li savings through SL become positive or negative. Also for Co, the saving potential becomes positive if the minimum recycling efficiency is assumed. This shows that, from a critical metal perspective, SL is a more useful approach for metals with low recycling rates, because for these metals the temporal shift of the recycling process does not lead to binding large amounts of valuable secondary materials in stationary applications. This effect is reinforced by the oversize of SLB due to the previous ageing in the vehicle. If an hypothetical *EoL criterion* of 100 % is assumed, Li savings are more than doubled compared to the initial scenario and the increase in primary Co demand is more than halved.

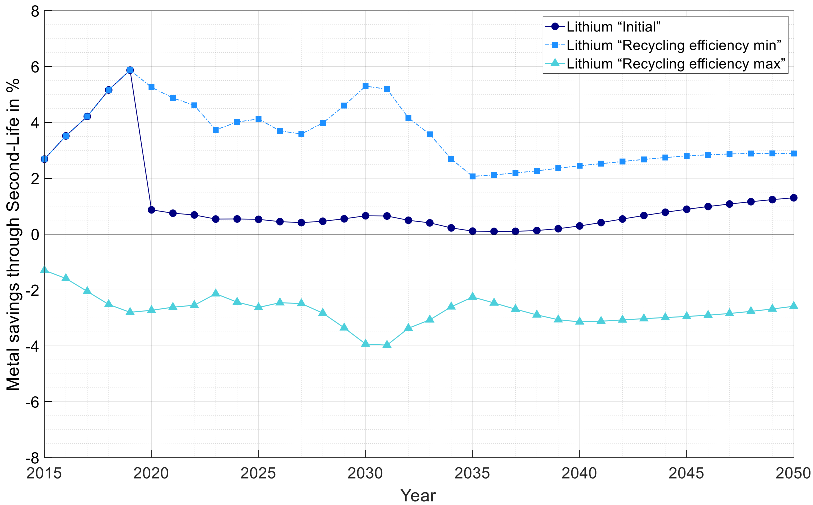

Figure 6: Li savings through SL – impact of the recycling efficiency

Furthermore, as described for the initial scenario, the share of cell technologies for TB and SB has an impact on the substitution effect of SLB. If for SB the *same technology* (same market shares of cell technologies) is assumed than for TB, relative Li savings through SL are increased in the medium- and long-term by a factor of about 1.5–2.5 and the relative increase in Co demand is about halved compared to the initial scenario.

The course of savings through SL described in Section 4.1 are also strongly influenced by the fact that battery markets are still growing in the time horizon under consideration. Therefore in Figure 7 it is illustrated how critical metal savings develop, if a saturated market (no stock increase from 2020 on) is assumed. Here, the scenario *“constant stock+half lifetime”* is depicted as lifetimes need to be reduced to actually reach a “closed” system until 2050, in which the SB market is continuously covered by SLB. It can be seen that once this type of system is established in the long-term, SL leads to positive savings for both Li and Co. In a system, for which only the existing stock needs to be renewed by the same type of battery, SL leads to an increase in the time period between recycling processes and therefore a decrease in recycling losses. As recycling losses are higher for Li than for Co, for Li larger savings are observed.

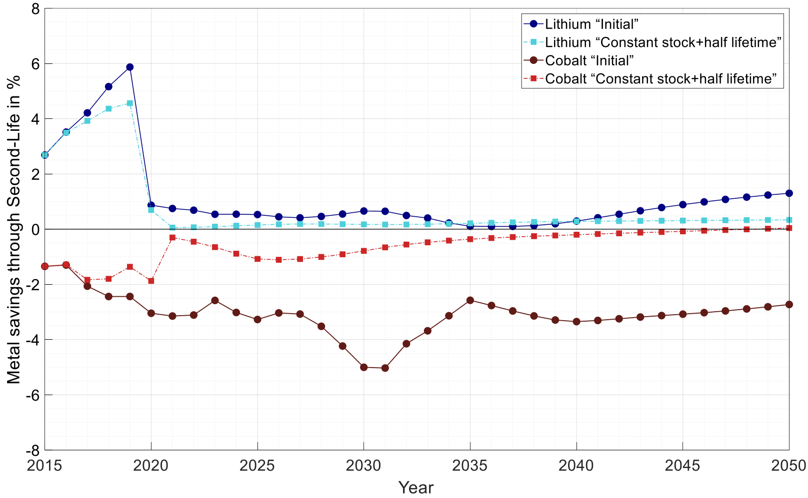

Figure 7: Critical metal savings through SL – impact of a market saturation

Figure 8 shows that the choice of the ‘reuse’ instead of the ‘reman’ concept, leads to a strong increase in primary metal demand. This is due to the substitution of small HSS (7 kWh) by large SLB (around 34–44 kWh) leading to a reinforcement of the substitution effects described above. Thus, large amounts of Li and Co from TB are bound in stationary applications and are available for recycling at a later point of time.

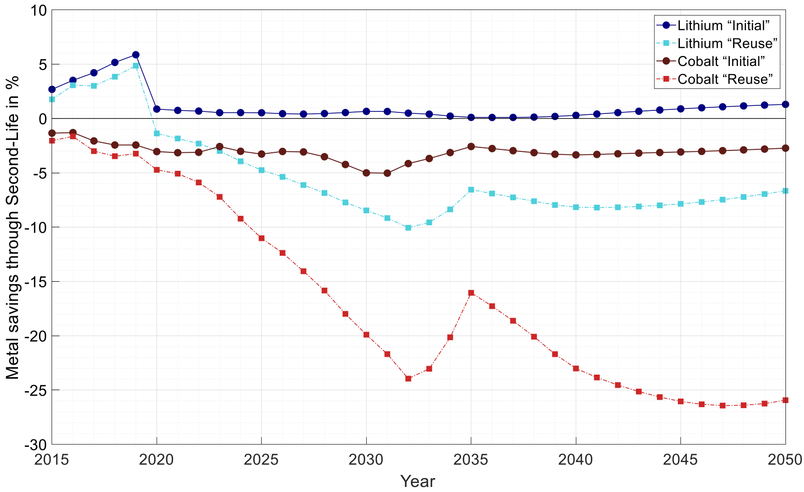

Figure 8: Critical metal savings through SL – impact of the SL concept

COSTS

The choice of SL concept also influences the cost saving potential as illustrated in Figure 9. In case ‘reuse’ is applied for both applications (HSS and PCR) cost savings turn negative in 2025. If, however, only the PCR application is considered in the assessment, cost savings stay positive over the whole time horizon. This is due to the fact, that for PCR the ‘reuse’ concept leads to lower annuities for SLB because of lower processing costs compared to the ‘reman’ case. Furthermore, in contrast to HSS, for large PCR storages several SLB are required, which means that for PCR the choice of SL concept does not lead to the oversizing issue described above. Thus, if in both applications SLB are being reused instead of remanufactured, cost savings turn negative as soon as the positive cost savings of the prioritised PCR application are balanced out by the negative savings for the HSS application.

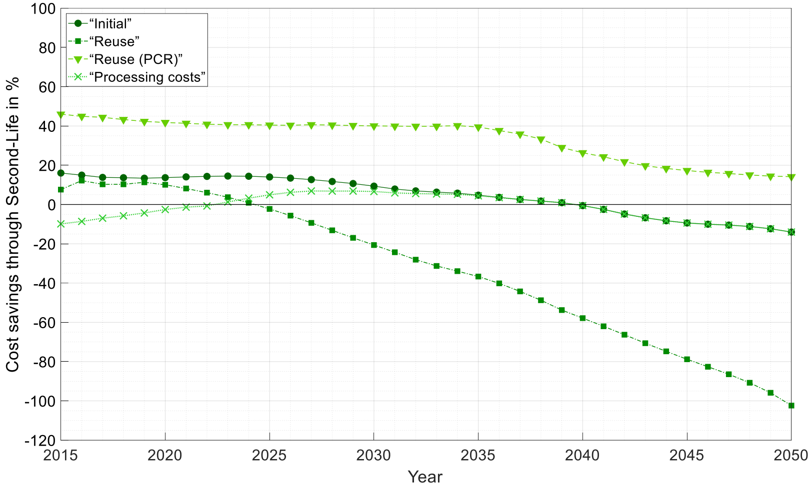

Figure 9: Cost savings (SB investment and SLB processing) through SL – impact of SL concept and utilisation of SL processing plant

Apart from the SL concept, also the development of *processing costs* affect the cost savings as depicted in Figure 9. If instead of a 100 % utilization an increasing utilization of the SL processing plant over time is assumed, first negative cost savings occur as the annuity of SLB is larger than the annuity of new HSS. With an increasing utilization the cost savings eventually turn positive. Once a 100 % utilization is reached in 2030 the same course of savings as for the initial scenario can bes observed.

Finally, the *lifetime* of SLB has an impact on the cost savings. In case the lifetime is halved, e.g. due to strong ageing processes in the SL application, the annuity for SLB increases. This would lead to a tipping point compared to the annuity of a new HSS as early as 2025 and therefore negative savings already from 2030 on.

5 Conclusion

It is often taken for granted that the CE leads to resource savings and new business opportunities. The present analysis shows that the reuse of TB in stationary applications can offer cost and critical metal savings. However, it is clearly outlined that this is not the case under all circumstances and that there are trade-offs for different indicators such as Li, Co and cost savings. Furthermore, it is shown that the savings through SL are strongly dependent on the considered time horizon as they vary over time. Thus, when pushing forward SL approaches for EV batteries, the potential negative effects and trade-offs over the course of time need to be considered.

In the analysed scenario the reuse of EV batteries leads to savings for Li and an increase in primary Co demand. By using a dynamic modelling approach it is shown that the time delay of the recycling process and the substitution effects on stationary markets have a strong impact on the critical metal saving potential. As SL leads to a postponement of the recycling process and therefore a delay of secondary metal availability, SL applications are more effective for metals with low recycling rates. When substituting the production of new SB by SLB both the oversizing as well as the share of cell technologies affect the saving potential. Because of the ageing in the vehicle an SLB is always oversized compared to a new battery as only a certain share of the original capacity is available. However, this effect is enhanced in case the ‘reuse’ concept is chosen for HSS as largely oversized TB substitute smaller HSS. This reinforces the effect resulting from the temporal shift of the recycling process because even larger amounts of secondary materials are bound in stationary applications. As TB and SB have different requirements with regard to energy density, SB markets are dominated by less Co-intensive batteries. Thus, in case of a substitution of a new SB by an SLB always more Co is bound than being displaced.

The absolute saving potential depends both on the availability of SLB and on the battery demand. It is shown that the availability of SLB is not only dependent on the available EoL batteries from EV, but that the collection rate and the technical feasibility also have a strong impact on the actual potential of SL. In case SL is applied in a saturated market, in which battery demand is stagnating, also Co savings would eventually become positive due to a decrease in recycling losses resulting from the establishment of longer cycles.

Finally, the development of battery prices, the utilisation of SL processing plants and the chosen SL concept are identified as critical parameters for cost savings. While the relative development of module prices and SL processing costs need to be included when assessing SL business cases, the present analysis also shows that is important to choose the right SL concept depending on the application. While for PCR reuse is economically more attractive, for HSS remanufacturing is the right option both from a critical metal and a cost perspective.

Furthermore, next to critical metal demand and costs the impact of SL application on greenhouse gas (GHG) emissions need to be considered. [26] indicates that the reuse of EV batteries holds the potential to decrease energy-related GHG emissions associated with battery production because of an increased time period between recycling processes. While the carbon footprint of battery production is described in detail in [2], a detailed assessment of the emission saving potential of SL applications by coupling life cycle assessment (LCA) methods with the described model is the subject of ongoing research.

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