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Advances of 2nd Life Applications for Lithium Ion Batteries from Electric Vehicles Based on Energy Demand

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Abstract: Electromobility is a new approach to the reduction of CO_2 emissions and the deceleration of global warming. Its environmental impacts are often compared to traditional mobility solutions based on gasoline or diesel engines. The comparison pertains mostly to the single life cycle of a battery. The impact of multiple life cycles remains an important, and yet unanswered, question. The aim of this paper is to demonstrate advances of 2nd life applications for lithium ion batteries from electric vehicles based on their energy demand. Therefore, it highlights the limitations of a conventional life cycle analysis (LCA) and presents a supplementary method of analysis by providing the design and results of a meta study on the environmental impact of lithium ion batteries. The study focuses on energy demand, and investigates its total impact for different cases considering 2nd life applications such as (C1) material recycling, (C2) repurposing and (C3) reuse. Required reprocessing methods such as remanufacturing of batteries lie at the basis of these 2nd life applications. Batteries are used in their 2nd lives for stationary energy storage (C2, repurpose) and electric vehicles (C3, reuse). The study results confirm that both of these 2nd life applications require less energy than the recycling of batteries at the end of their first life and the production of new batteries. The paper concludes by identifying future research areas in order to generate precise forecasts for 2nd life applications and their industrial dissemination.

Keywords: circular economy; remanufacturing; multiple life cycles; electromobility; lithium ion battery

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1. Introduction

Electromobility is an approach that aims to reduce CO_2 emissions and to decelerate global warming. Scientific papers, reports and news often compare the environmental impacts of electromobility to traditional mobility solutions with gasoline or diesel engines [1–5]. Some of these investigations address the question of whether electromobility has, among others, a better CO_2 footprint. Regardless of whether it is better, the same or even worse than combustion technology, electromobility will be present in the future and continue to gain importance following a political urge and past investments. In any future case, large quantities of used batteries will occur that need to be treated. The total demand for batteries is estimated to be 200 GWh by the year 2025, four-fold more than in the year 2020 [6]. If the total impact can be robustly assessed, it can influence the decision for or against a specific 2nd and End of Life (EoL) strategy. The total environmental impact of a battery, considering multiple life cycles with various 2nd and EoL applications, remains an important, and yet an unanswered, question.

The aim of this paper is to demonstrate the advances of 2nd life applications for lithium ion batteries from electric vehicles based on their energy demand within various multiple life cycles. The total impact of a product consists of multiple factors including environmental, social and economic factors such as the production costs, supply and demand, which are influenced, among other things, by the customers' acceptance. This study is based on the impact of the energy demand in order to present the potential of 2nd Life applications in a comprehensible way. Economic factors such as the influence and costs of supply chain will be considered in further research activities and publications. For the demonstration, it presents the design and results of a meta study on the environmental impact of lithium ion batteries. The study focuses on energy demand, and investigates this demand for three different cases, namely (C1) material recycling, (C2) repurposing and (C3) reuse, as visualized in Figure 1 and described in Section 3.2 in detail.

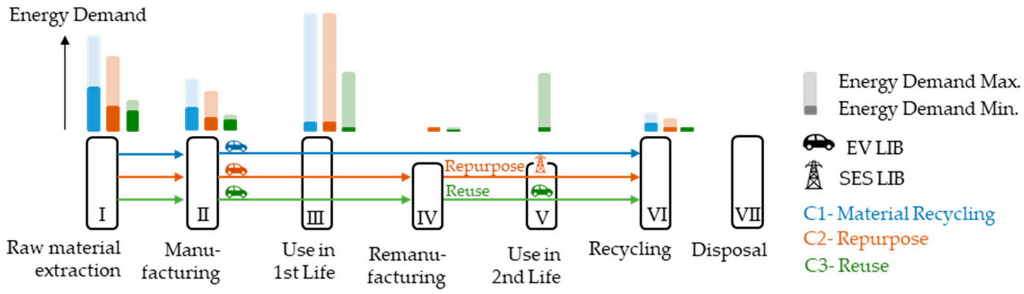

Figure 1. Exemplary cases: C1—material recycling, C2—repurposing, C3—reuse.

2. Method

A meta study is designed to create a data basis that allows the energy demand of the individual life cycle stages to be estimated in a generally valid manner, rather than just for a specific case. The results are described in detail in Section 2.1. Based on the results, a mathematical algorithm is presented in Section 2.2, which calculates the energy demand for multiple life cycles.

2.1. Meta Study

The environmental impact of a product is dependent on the processes used within the life cycle stages, but also on location-specific factors such as the available energy mix. Reporting of the environmental impact in units as for example the CO_2 equivalent allow the comparison of the total impact for a specific case, but hinders the analysis of the magnitude of the processes itself. In order to decide whether other processes, such as remanufacturing, should be pursued in the future, the influence of these processes must be estimated. Only subsequently should the location-specific impact be considered. This assumption is contrary to the way of presenting the results of analysis on environmental impact.

Within this meta study, 31 scientific articles on the environmental impact of lithium ion batteries were analyzed [1,2,7–35]. For the state of the art, a desktop research performed with Google Scholar using combinations of keywords such as life cycle assessment, LCA, lithium-ion-battery, electric vehicle, impact and emissions was conducted. The literature from the last decade and additionally the most cited publications, despite the publication date, were considered. The majority state their results in a variety of units, such as the $CO_{2eq.}$, which cannot be unambiguously converted into a process specific unit without further information. Other publications use secondary data. Only eight articles have reported primary data stated in the energy demand [7–14] and were selected to be considered in the further analysis.

The majority of comparisons regarding mobility solutions is based on LCA, including the following life cycle stages: (I) raw material extraction, (II) manufacturing, (III) use in 1st life, (IV) remanufacturing, (V) use in 2nd life, (VI) material recycling and (VII) disposal. Nevertheless, studies on LCA address all or only a few of these stages. Out of the eight selected articles, five consider (I) extraction of raw materials; eleven concentrate on (II) material, component production and/or on battery assembly. (III) The use stage is considered in two studies for a single case. Two studies focus on (VI) recycling. None of the evaluated studies consider the environmental impact of life cycle stages such as (IV) remanufacturing and (V) use in 2nd life applications or (VII) disposal. Table 1 summarizes the assumptions and the availability of data for the life cycle stages of the selected studies.

Table 1. Scope of the selected eight studies.

	Material	Capacity [kWh]	Weight [kg]	(I)	(II)	(III)	(IV)	(V)	(VI)	(VII)
[7]	$LiMn_2O_4$	34.2	300	-	Yes	-	-	-	-	-
	$LiMnO_2$	-	-	Yes	Yes	Yes	-	-	Yes	-
[8]	Li-NMC	-	-	Yes	Yes	-	-	-	Yes	-
	$LiFePO_4$	-	-	Yes	Yes	-	-	-	Yes	-
[9]	Li-NMC	26.6	253	-	Yes	-	-	-	-	-
	NiMH	-	-	-	Yes	Yes	-	-	-	-
[10]	Li-NMC	-	-	-	Yes	Yes	-	-	-	-
	LFP	-	-	-	Yes	Yes	-	-	-	-
[11]	LMO-graph.	24	290	Yes	Yes	-	-	-	-	-
[12]	NMC111	23.5	165	Yes	-	-	-	-	-	-
[13]	LMO/NMC	24	303	-	Yes	-	-	-	-	-
[14]	NMC	-	-	-	-	-	-	-	Yes	-
	LFP	-	-	-	-	-	-	-	Yes	-

The energy demand can be divided into the primary energy and process electrical energy. Within this meta study, we consider the measurable energy demand required for the process. For the life cycle stages (I) raw material extraction and (VI) material recycling, the primary energy demand is considered. The required energy for these processes cannot be precisely converted into electrical energy, as other types of energy are indispensable in addition to it. For the life cycle stages (II) to (V), the process electrical energy demand is considered, as it is directly measurable. For these processes, the primary energy demand is dependent on the available energy mix and is therefore location-dependent.

The available data of the studies are stated in different units as MJ/km, MJ/kg, MJ/kWh or kg oil eq/kg. Therefore, the data are converted into a consistent unit of kWh/kg. The exact conversion can be found in Appendix A. The available values for the life cycle stages are summarized in the Tables 2–4.

Table 2. Data on energy demand for (I) raw material extraction.

(I) Raw Material Extraction	[8]	[8]	[8]	[11]	[12]
	$LiMnO_2$	LI-NCM	$LiFePO_4$	LMO-gr.	NMC111
Primary Energy in kWh/kg	30.22	42.92	43.63	28.6	44.55

Table 3. Data on energy demand for (II) manufacturing.

(II) LIB Manufacturing	[7]	[8]	[8]	[8]	[9]	[10]	[10]	[10]	[11]	[13]
	$LiMn_2O_4$	$LiMnO_2$	Li-NCM	$LiFePO_4$	Li-NCM	NiMH	Li-NCM	LFP	LMO-gr.	LMO
Process Energy in kWh/kg	10.1	3.70	15.71	20.14	17.11 28.03 67.69	21.98	19.13	18.72	50.17	11.67

Table 4. Data on energy demand for (VI) recycling.

(VI) LIB Recycling		[8]	[8]	[8]	[14]	[14]
		$LiMnO_2$	LI-NCM	NMC	NMC	LFP
Primary Energy in kWh/kg	Total	−5.81	−12.05	−13.00	−4.49	−7.99
	Effort	-	-	-	10.50	4.55
	Benefit	-	-	-	−14.97	−12.55

Three studies provide values for "primary energy for material extraction", convertible into a comparable unit of kWh per kilogram of battery, as summarized in Table 2. The values vary considerably, the maximum value being more than 50% higher than the minimum. However, the distribution is symmetrical to the mean value and can be described as mean value +/−20%. Due to the small number of values, this description cannot be verified for its general validity.

Table 3 shows the process energy demand for the life cycle stage (II) battery manufacturing. Five studies provide values for this stage. The value varies considerably beginning at 3.70 kWh/kg and reaching up to 67.69 kWh/kg. The median of these values is 18.93 kWh/kg. Based on these values, no generally valid estimation of the average energy demand can be made. The study of Ellingsen et al. [9] provides an explanation that the values vary greatly even within the same process. This study is fundamental, as the actual energy consumption in a factory was measured over a period of 18 months, and not only mathematically calculated. The measured values vary greatly even for the same type of battery, with the value for the most energy efficient month being 17.11 kWh/kg and the average value being 67.69 kWh/kg.

Only two studies have published the energy needed for the life cycle stage (VI) recycling of a battery, as summarized in Table 4. The values are strongly dependent on the specific recycling process and can hardly be compared. Furthermore, on the one hand, the recycling process requires energy but, on the other hand, it saves energy in relation to the new production of the materials. This distinction was made in only one study [14].

In order to understand the environmental impact of batteries, on the one hand, the influence of all processes within the life cycle stages must be estimated. Yet, the results from the meta study provide information on the life cycle stages (I) raw material extraction, (II) manufacturing and (VI) recycling. On the other hand, different cases of a life cycle have to be considered in order to estimate the total environmental impact of the product and to provide sufficient information for its further development [36]. In the analyzed articles, only one case is considered for the (III) use stage. However, this does not correspond to the reality, in which a wide range of users, from rare to frequent users, coexist. Further, no information on optional life cycle stages such as (IV) remanufacturing and (V) use in 2nd life is provided. The consideration of several different cases within a conventional LCA is difficult due to its functional unit [37,38]. It means that a new LCA would have to be calculated for each case separately.

In contrast to an LCA, where the functional unit describes the amount of a defined use, for example a single targeted mileage [37,38], we extend the definition and set the functional unit as the combination of a continuously operating lithium ion battery of an electric vehicle (EV LIB) and a continuously operating lithium ion battery for a 2nd life application, where the use of 2nd life batteries is conceivable, in a defined time period; compare with Q4 from Figure 2. It allows the functionality to be variable. Further, it includes the influence of time, as asked in Q2, as well, it considers that more than one device has to be used to fulfill the requirements for use; compare with Q6. It shifts the perspective, as not only the impact during the use (value creation) is considered, but rather the impact during the life cycle of a product, where the product is often not used, but still in the possession of the user and therefore not available for others. In the calculated cases, we consider a stationary energy storage (SES LIB) as a conceivable 2nd life application. This approach allows easy variation of the parameters, to create different cases and to consider the optional life cycle stages. The results, however, do not calculate the exact valid values for the processes, but show the tendencies and the interrelation between the stages. Chapter 2.2 presents the proposed mathematical algorithm.

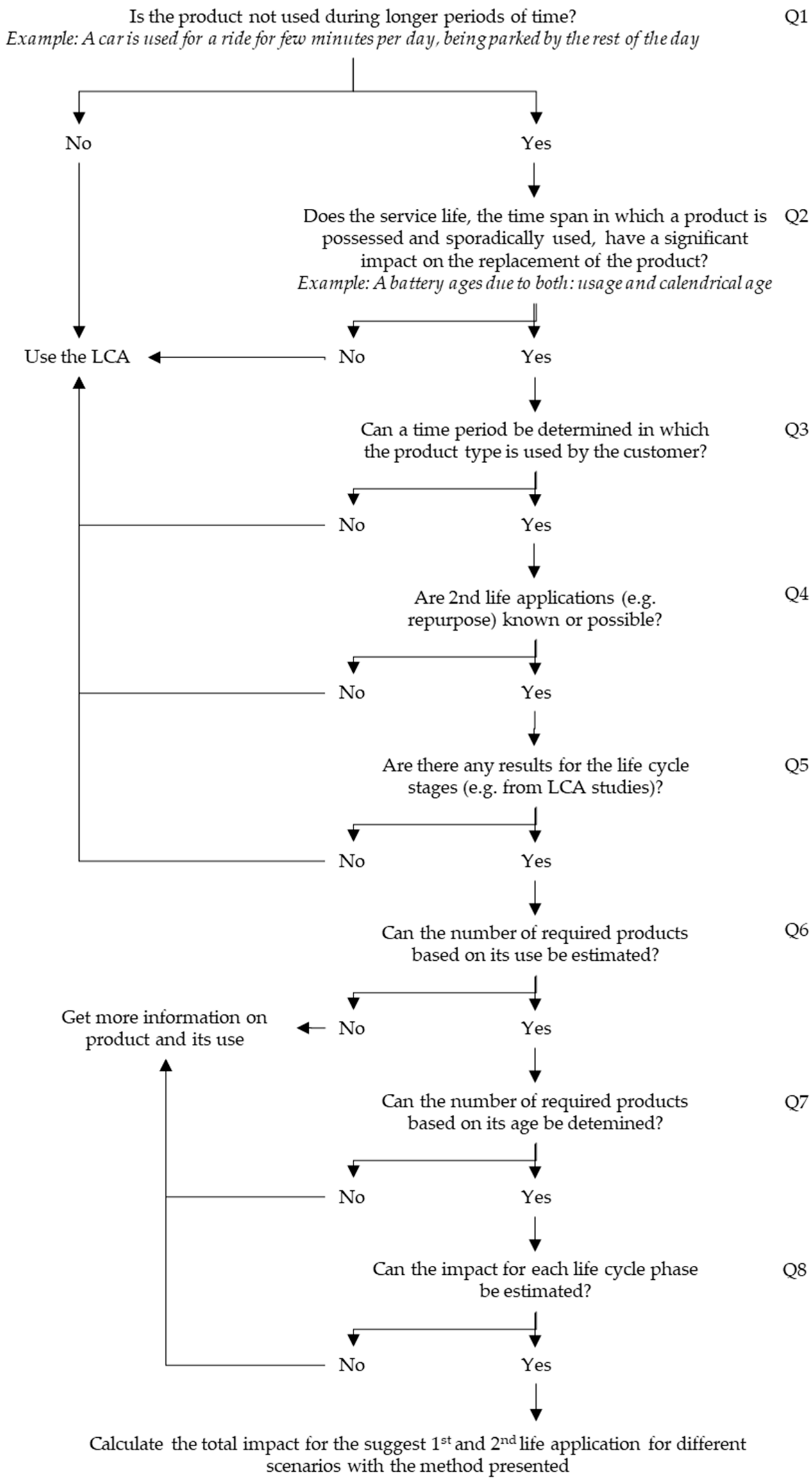

Figure 2. Flow chart for the proposed method with questions (Q).

The following flowchart (see Figure 2) presents the approach for the proposed method including the algorithm. The method provides the values for the variables in the algorithm by answering eight questions (Q1 to Q8). Figure 2 also presents the difference to LCA. If the answers from Q1 to Q5 are denied, LCA remains the only applicable method. In the case of denying any answers between Q6 and Q8, further information about a certain product and its use are required to continue with the proposed method.

2.2. Mathematical Algorithm

The total impact can be described as the sum of individual cases, as shown in the Equation (1):

$$z = x + y, \tag{1}$$

with z, the total environmental impact of the functional unit; where x describes the environmental impact of the life cycle of the EV LIB; where y describes the environmental impact of the life cycle of the SES LIB.

A total life cycle of electric vehicle lithium ion batteries includes the seven life cycle stages, described in Section 2.1. Each life cycle stage of a single battery causes an environmental impact, which is independent of the other. This means that the (II) manufacturing causes the same impact, whether a battery is (III) used or not. The presented method considers this aspect, as shown with Q1 in Figure 2. On the other hand, if the life cycle of several batteries over a defined time period is considered, especially the (III) use stage has a significant influence on the required number of repetitions of the other stages. Equations (2) and (3) show the described relationship:

$$x = \sum n_i \times (x_i + t_{xi}), \tag{2}$$

$$y = \sum m_i \times (y_i + t_{yi}), \tag{3}$$

where i, i = I, . . . , VII, describing the life cycle stage from (I) to (VII); n_i or m_i, describes the amount of EV LIB/SES LIB in the life cycle stage; x_i or y_i, describes the energy demand of the EV LIB/SES LIB life cycle stage, compare with Q5 and Q8; t_{xi} or t_{yi} describes the energy demand of transportation to each life cycle stage.

The use stage, both during the (III) 1st and (V) 2nd life application, is dependent on the energy consumption of the electric vehicle, the kilometers driven and the charging efficiency:

$$x_{i = 3 \text{ or } i = 5} = (v_i \times d_i)/e_i \tag{4}$$

where e_i, charging efficiency; v_i, energy consumption; d_i, kilometers driven;

The use stage, both during the (III) 1st and (V) 2nd life application, determines the demand for batteries. Their lifetime is limited either by calendrical age or the maximum total range, compare with Q6 and Q7:

$$n = n_3 + n_5 \tag{5}$$

with n, the total number of batteries required;

$$n_i = \max\,(n_a, n_d), \tag{6}$$

with n_a, the number of batteries resulting by their age; with n_d, the number of batteries resulting by their total driving range;

$$n_{ai} = \text{integer}\,(T/a_{bat}) \tag{7}$$

$$n_{di} = \text{integer}\,(d/d_{bat}) \tag{8}$$

with T, describing the considered time period, compare with Q3; a_{bat}, describing the maximum battery age, before reaching critical value of its original capacity; with d_{bat}, describing the maximum total range of a battery, before reaching the critical value of its original capacity.

The amount of reprocessed batteries is dependent on the production of new units:

$$n_3 = f \times n_5 \tag{9}$$

with f, a factor describing how many new batteries have to be produced in order to enable the remanufacturing of one battery for a 2nd life application.

The mathematical model allows a simple calculation of the total impact within a defined time period. The focus on the useful time and the definition of use of functionality as a variable enables the consideration of additional factors as the aging of a product. These allow the interpretation of the total impact from a new perspective.

Additionally, this model uses only process-related variables, which allows the comparison of the impact of the individual process steps, without the distortion of the values due to local influences.

3. Case Study

The values for the case studies are based on the results of the meta study and complemented by further assumptions in order to estimate the real situation in the best possible way. All assumptions are stated and explained in Section 3.1. In Section 3.2, the results of the case studies are presented, discussed and compared to one another.

3.1. Assumptions

To calculate the impact of the stated cases and estimate the real situation, assumption on the battery characteristics, the energy demand of the single life cycle stages and the use behavior have to be made. Table 5 summarizes the following assumptions on the product characteristics.

Table 5. Assumption for the case study—product characteristics.

	Weight	**Max. Mileage**	**Max. Age**	**Charging Efficiency**	**Energy Use [kWh/100 km]**	
EV LIB					Efficient	High
new	300 kg	150,000 km	10	0.8	10	16
reprocessed	300 kg	120,000 km	6	0.8	10	16
SES LIB						
new	240 kg	-	15	-	-	-
reprocessed	300 kg	-	10	-	-	-

In our calculation, the EV LIB weighs 300 kg and has a useful time of 150,000 km or 10 years, which corresponds to the most common assumptions for a real case. The electric vehicle requires optimistically, 10 kWh/100 km and, pessimistically, 16 kWh/100 km with a charge efficiency, both for new and reprocessed batteries, of 80%, based on the energy consumption stated in [22]. A new SES LIB weighs 240 kg, has 80% capacity compared to an EV LIB and has a useful time of 15 years.

In the case study, reprocessed batteries are used. The total capacity as well as the life time and total mileage of a reprocessed EV LIB must be lower than the equivalent new battery. The capacity is assumed to be 80% compared to a new one. For the application in SES, the life time is assumed to be ten years and, in EV, six years accordingly. The maximum total mileage for the EV application is assumed to be 120,000 km.

The energy demand is based on the findings of the meta study. For the first life cycle stage, (I) the raw material extraction, the energy demand is assumed to be 36 kWh/kg. For the sensibility analysis, this value will be varied by +/−20% corresponding to 43 kWh/kg and 29 kWh/kg.

As the energy demand for (II) the manufacturing varies strongly, the median of the available data, valued at 19 kWh/kg, is considered for the calculation. For the sensibility analysis, two further cases are considered. The future technological development may influence the demand for energy positively. In this case, the energy demand is assumed to be 10 kWh/kg. On the other hand, the study of Ellingsen et al. [9] shows that the average energy demand might be significantly higher than the theoretically possible value. In this case, the energy demand is assumed to be 68 kWh/kg.

In the meta study, no information on the energy demand for the remanufacturing process could be found. Therefore, this value is estimated based on the values for the production process. Remanufacturing describes a method to reprocess products to at least the same performance as that of the new device [39], reusing as many components of this product as possible [40].

The process of remanufacturing consists of a mix of subprocesses such as (a) identification, (b) condition check, (c) disassembly, (d) repair, (e) prophylactic treatment, (f) reassembly and (g) inspection.

(a) The identification of the product type is done manually and requires no process energy.
(b) The condition of the battery cannot usually be determined by its appearance, requiring energy-intensive charging tests. We assume that the condition of a battery can be determined after five charging cycles, corresponding approximately to 0.6 kWh per kg of a battery.
(c) & (f) Next, the battery is (c) disassembled. Precise values for a disassembly are not available, therefore the assembly of the batteries is considered in detail and equated with disassembly. According to [11], the process of assembly is not energy intensive and is estimated to account 0.03 kWh per kilogram of battery. As in our case, used and therefore possibly deformed batteries are disassembled and (f) reassembled. The process energy consumption of one process step is assumed as 0.05 kWh per kilogram of battery.
(d) & (e) In general, within these processes, only few components have to be replaced by new units. Thus, the calculation assumes for both processes that all components are reused, and no additional material extraction is needed. If the energy consumption during (d) the repair equals that of the production and, further, it is assumed that around 10% of the batteries have to be (e) treated, the energy expenditure of this process is estimated to be 3.6 kWh/kg.
(g) The final inspection requires repeated charging and discharging of the battery and is considered to cause energy expenditure in the amount of 0.6 kWh/kg.

In total, the energy consumption of the (IV) remanufacturing process is estimated to be around 5 kWh/kg, which corresponds to 26% of the energy demand for (I) manufacturing.

The meta study could not provide a sufficient database for the accurate estimation of the energy demand for (VI) recycling. For this calculation, it is assumed that the energy demand for the process is 7 kWh/kg and the benefit compared to new material production is 15 kWh/kg, corresponding to the mean value of the processes presented by the study of Buchert et al. [14].

Due to the objective that all stages should be considered location independent, the transport routes cannot be determined. We assume that in contrast to the production, remanufacturing as well as reuse and repurposing will be done locally, for example within the boundaries of a country. A study on the subject [41] shows that the recollection of used batteries within only one day is possible for Germany with a single recollection point. The exact values for the transportation are not calculated. However, their magnitude is discussed in relation to other results.

The influence of (VII) disposal was neither stated in any document found, nor could sufficient assumptions be made to estimate it. Therefore, it is disregarded and its value will be set to zero for the calculation of the cases. The assumptions on the energy demand in the life cycle stages are summarized in Table 6.

Table 6. Assumption for the case study—energy demand in the life cycle stages.

	Assumed Value	Min. Assumed Value	Max. Assumed Value
(I) Material extraction	36 kWh/kg	43 kWh/kg	29 kWh/kg
(II) Manufacturing	19 kWh/kg	10 kWh/kg	68 kWh/kg
(IV) Remanufacturing	5 kWh/kg	-	-
(VI) Recycling (effort)	7 kWh/kg	-	-
(VI) Recycling (benefit)	15 kWh/kg	-	-

3.2. Case Study-Results

Three cases based on the described assumptions are developed to demonstrate the results of the meta study, see Table 7 and Figure 3:

Table 7. Life cycle stages within the cases.

		Produce (I & II)	Use (III)	Reprocess (IV)	Reuse (V)	Recycle (VI)	Dispose (VII)
C1	EV LIB	Yes	Yes			Yes	
	SES LIB	Yes	Yes			Yes	
C2	EV LIB	Yes	Yes	Yes		Yes	
	SES LIB				Yes		
C3	EV LIB	Yes	Yes	Yes	Yes	Yes	
	SES LIB	Yes	Yes			Yes	

The colors are consistent with the cases visualized in the figures. These colors are the same as in Figures 1 and 3.

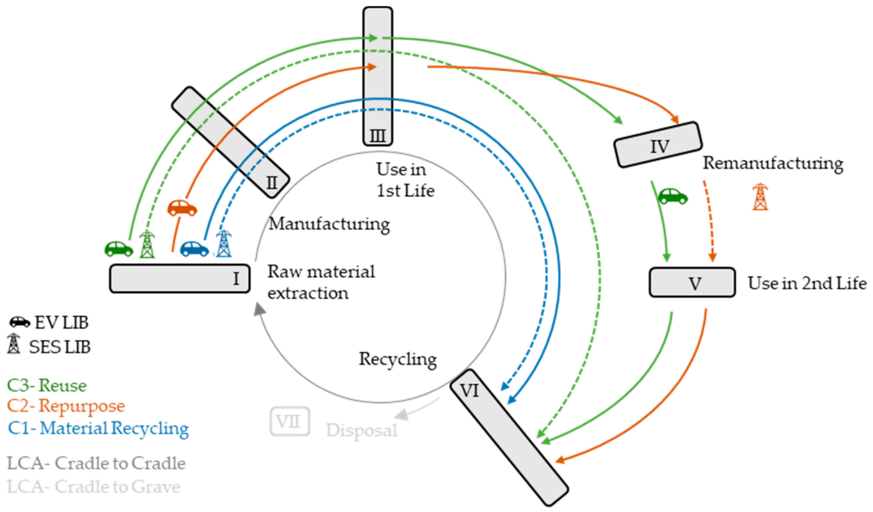

Figure 3. Product life cycle stages within the cases.

In the first case (C1, material recycling), all batteries are newly produced, used and recycled at the end of their 1st life.

In the second case (C2, repurposing), the electric vehicle batteries are newly produced. The electric vehicle batteries are reprocessed after their 1st life and repurposed as stationary energy storages.

In the third case (C3, reuse), the electric vehicle batteries are newly produced, reprocessed and reused as electric vehicle batteries.

Based on the extended definition of the functional unit, our approach considers the total energy demand over a period of time, rather than over a defined reputational use of a product function.

3.2.1. C1—Material Recycling

C1 describes the case where all batteries considered are newly manufactured and recycled at their EoL. The stages (I) material extraction, (II) manufacturing and (VI) recycling cause an energy demand for one EV LIB of around 18,600 kWh and for one SES LIB 14,900 kWh, accordingly. Extended by the energy demand during the use stage for a defined repetition of use, here the total mileage driven, and converted into comparable values such as $CO_{2\,eq.}$, this result can be directly compared with other LCAs. However, in contrast to these LCAs, the use during a time period of 20 years and not only the repetition of use is considered in this analysis. It means that also the amount of batteries needed is considered here.

For rarely used electric vehicles, two batteries are required due to their maximum assumed age (n_a). For frequently used vehicles, up to six batteries within the time span of 20 years are needed (n_d). This amount of batteries influences the total energy demand for their production and recycling. This means that a rarely used electric vehicle causes for the (I & II) production and (VI) recycling of its batteries around 37,200 kWh in energy demand, whereas a frequently used one requires around 111,600 kWh. This approach shifts the consideration from the battery as a product to the battery as a part of the car. This allows easier interpretation of the overall impact of the batteries required.

For the overall impact, the use stage has to be considered. Its impact is dependent on the distance driven. A calculation for only one case, as used in LCA, does not reflect the reality sufficiently, as a high variety of users exist. Here, we analyze the impact for the targeted mileage of 3000 km, 9000 km, 15,000 km, 25,000 km and 40,000 km per year. Rarely used cars, driven for 3000 km/year and with an assumed energy consumption of 10 kWh/100 km, cause within the considered time period of 20 years, 7500 kWh in energy demand. Frequently used cars, driven for 40,000 km/year, cause 100,000 kWh under the same assumptions. An x times higher distance causes an x times higher energy consumption. More interesting, however, is the question of how this use stage relates to the stages I, II and VI.

Driving a car for 3000 km per year require two batteries and the energy used for their production (I & II) and recycling (VI) is around 37,200 kWh. The use stage causes 7500 kWh, which corresponds to 20% of the stages I, II and VI. A frequently used car needs six batteries, causes 3-fold the energy demand for stages I, II and VI, and more than 13-fold for the use stage compared to the rarely used car. The ratio between the use stage and the stages I, II and VI are 90%. This example shows that the analysis of the impact per battery for a single case gives a basis to compare battery types or processes, but it is not sufficient to estimate the total impact during a real use. If multiple life cycles are considered, the combined impact of all the batteries used requires consideration, as enabled by the presented algorithm.

In our case study, additionally to the EV LIB, SES LIBs are considered. Hence, the total energy demand for this case, meaning the (I) raw material extraction, (II) manufacturing, (III) use and (VI) recycling of EV LIB and SES LIB amounts to around 74,500 kWh if rarely used vehicles are considered, and around 241,400 kWh in the case of frequently used vehicles. These values are the comparative values for the total energy demand of a case.

The uniqueness of this case is the calculation based on the measurable energy, resulting in the consideration of two different energy demands. While the primary energy is taken for the life cycle stages I and VI, the process energy is considered for the life cycle stages II and III. To make the result comparable with other studies, the primary energy is assumed for all processes. The conversion factor between primary and process energy is assumed to be 0.3 [42]. The exact calculation is described in detail in Appendix B. In the case of a rarely used car, the use stage makes around 39% of stages I, II and VI and, for the frequently used car, 174% accordingly. Also, this result confirms that the production (I & II) and recycling (VI) of the batteries have a significant influence on the total energy demand, even if the percentage share may vary.

The assumed energy consumption during the use stage may be accurate only for small cars. If a higher energy consumption of 16 kWh per 100 km is assumed, the use stage corresponds to around 32% of stages I, II and VI for rarely used cars and 143% for frequently used ones. Even if, for the stages I and II, very efficient processes are considered, the ratio between the use stage and these stages is 43% and 193% for the described examples. All presented results show that the ratio between the use stage and the stages I, II and VI vary strongly, dependent on the considered use stage. To lower the environmental impact of batteries in reality, both improvements of the processes as well the battery itself are needed. The results of the case C1 for the different assumptions are summarized in Table 8.

Table 8. C1—material recycling—summary.

	Basic Analysis	**Primary Energy**	**Sens. Analysis**
(I) Material extraction	36 kWh/kg	36 kWh/kg	29 kWh/kg
(II) Manufacturing	19 kWh/kg	63.3 kWh/kg	10 kWh/kg
(III) Use in 1st Life	10 kWh/100 km	33.3 kWh/100 km	16 kWh/100 km
(VI) Recycling (effort)	7 kWh/kg	7 kWh/kg	7 kWh/kg
Per SES LIB	14,900 kWh	31,900 kWh	11,000 kWh
Per EV LIB	18,600 kWh	25,500 kWh	13,800 kWh
$\frac{\text{Stage (III)}}{\text{Stages (I)+(II)+(VI effort)}}$			
For 3000 km/year	20%	39%	43%
For 40,000 km/year	90%	174%	193%
S1: Total energy demand for SES LIB and EV LIB within 20 years			
For 3000 km/year	74,460 kWh		
For 40,000 km/year	241,360 kWh		

3.2.2. C2—Repurposing

In C2, the EV LIBs are newly produced, then reprocessed and repurposed to SES LIB. This means that no SES LIBs were newly produced. The total energy demand of the EV LIB is slightly higher than in C1, as the batteries have to be remanufactured. On the other hand, the energy demand for the production and recycling of SES LIBs is saved. This means that around 13,400 kWh per battery are saved, which corresponds to a savings of 40%. For the cases of rarely used cars, the total energy consumption accounts for 47,700 kWh and, in the case of frequently used ones, 214,600 kWh. It is assumed that, as in C1, only two SES LIBs are required, despite how many EV LIBs are available for the remanufacturing. In comparison to C1 in the case of rarely used vehicles, around 36% of the total energy demand is saved and, in the case of frequently used vehicles, around 11%. The total energy demand for C2 is summarized in Table 9.

Table 9. C2—repurpose—summary.

Energy Demand per Battery	
Per SES LIB	0 kWh
Per EV LIB	20,100 kWh
C2: Total energy demand for SES LIB and EV LIB within 20 years	
For 3000 km/year	47,700 kWh
For 40,000 km/year	214,600 kWh

3.2.3. C3—Reuse

In the third case, the EV LIBs are reprocessed and used again in the electric vehicles. The SES LIBs are newly produced, used for this application and recycled. Remanufacturing is performed on used batteries. It requires spare parts. Therefore, the amount of reprocessed batteries is always lower than that of produced unitsAdditionally considering that not every battery can be collected, for example, due to sales abroad, the assumed amount of reprocessed batteries requires further reduction. In our calculation, we therefore assume that two used batteries are required for the remanufacturing of one battery.

For rarely used cars, however, no reprocessed battery would exist in the calculation, as during the time period considered only two batteries are needed. However, especially these customers are assumed to have a higher acceptance for used batteries, as their requirements of total mileage are lower. Therefore, we assume that a pool of batteries exists, so that batteries from frequently used vehicles are reprocessed and used in rarely used vehicles. Still, the impact of a shorter maximum age of the reprocessed battery has to be considered.

To calculate the energy demand per battery, as in C1 and C2, first, the total energy demand for a pool of batteries has to be calculated and divided by the total number of batteries. Therefore, we use the statistic of German car users classified according to their annual mileage [43]. The kilometer clusters in the statistics differ slightly from the clusters we used. The values are therefore adjusted manually. In the calculation, we assume a distribution, as summarized in Table 10.

Table 10. C3—reuse—amount of used and remanufactured batteries.

	Share	n_New	n_Repro.	n_Repro. Assumed (1)	n_Repro. Assumed (2)
3000 km/year	14%	14	28	28	0
9000 km/year	32%	32	64	64	0
15,000 km/year	30%	60	30	0	30
25,000 km/year	15%	45	15	0	15
45,000 km/year	9%	36	18	0	18
Total	100%	187	155	92	63

Based on the amount of newly produced batteries, the maximum amount of remanufactured batteries can be calculated. If two new batteries are needed to make a remanufactured one, the maximum number of remanufactured batteries is equal to half of the amount of new batteries. If this assumption is applied to the considered battery pool, it is shown that remanufactured batteries can only be used for the rarely used cars up to 9000 km per year (subcase 3.1) or for frequently used cars from 15,000 km per year (subcase 3.2).

An exact calculation of the energy demand over the considered time period for rarely or frequently used vehicles cannot be given, as the use of the remanufactured batteries was divided into two subcases. Based on the results per battery, however, it could be shown that the reuse of batteries might be desirable from the energy demand perspective, as summarized in Table 11.

Table 11. C3—reuse—summary.

Energy Demand per Battery (Rarely Used Cars—Subcase C3.1)	
Per SES LIB	14,900 kWh
Per EV LIB	19,300 kWh
Energy demand per battery (frequently used cars—subcase C3.2)	
Per SES LIB	14,900 kWh
Per EV LIB	13,800 kWh

On the one hand, the reuse of reprocessed batteries in rarely used cars is possible. Due to the low targeted mileage, the real requirement of the batteries is lower. The willingness to pay a high price for a new battery without taking advantage of all of its properties is expected to be low. However, due to the lower expected calendric life time of the battery, two remanufactured batteries are needed in our case. For this reason, the energy demand per battery in this subcase is higher than in C1. However, if the ageing behavior of batteries under different stresses is sufficiently understood, the results of our calculation can be positively influenced.

On the other hand, there is the opportunity to use reprocessed batteries in frequently used cars. Especially fleet vehicles with a high mileage per year but short driving distances might be an interesting application. The energy demand is lower than in C1, even though many new batteries have to be produced. The calendric life time is not significant in this case, as the battery has to be replaced often due to the targeted mileage.

The results of the case studies show that the use of remanufactured batteries leads to significant energy savings. Further, in the case studies, the influence of the transport was neglected. As remanufacturing would likely be performed locally, the energy demand for transportation is expected to be lower than the transport from China or Brazil. This effect strengthens the results positively. The ratio of the individual cases as compared to C1 is summarized in Table 12.

Table 12. Comparison of the cases C1, C2 and C3.

Energy Demand	C1	C2	C3.1	C3.2
per SES LIB	14,900 kWh	0 kWh	14,900 kWh	14,900 kWh
per EV LIB	18,600 kWh	20,100 kWh	19,300 kWh	13,800 kWh
Total	33,500 kWh	20,100 kWh	34,200 kWh	28,700 kWh
Cx/C1	100%	60%	102%	86%

4. Discussion and Conclusions

This section summarizes the key findings regarding the calculation with an emphasis on (i) the limitations and potentials, and (ii) the results and impacts of a lithium ion battery and its life cycle stages. Later, it concludes with a look at (iii) the future research agenda.

(i) Calculation of impact: limitations and potentials

Challenges of resource scarcity can be met by using products, components and materials in multiple life cycles instead of a single life cycle if EoL scenarios and life cycle extensions are environmentally and economically valuable. In order to estimate the environmental impact of a product, such as a lithium ion battery, an LCA can be conducted.

Within this paper, three limitations of LCA regarding multiple life cycles were identified. First, an LCA is valid for rigid system boundaries and for a single use case. In general, it accounts for a single life cycle of the product, neglecting the multiple uses, especially in different applications. Second, for the consideration of the overall environmental impact, it may be disadvantageous that a sensitivity analysis cannot simply be performed, due to the rigid system boundaries. Therefore, the analysis needs to be recalculated for the changed parameters. Especially, the variation in the use phase can strongly influence the overall result. In reality, however, products are used differently to satisfy the requirements of various customers. Third, concerning multiple life cycles, both the impact of the process as well as the location, where it is performed, should be possible to interpret: 2nd life loops are characterized by uncertainties about the amount, the location and the demand for products. Therefore, more cases, such as the type of 2nd life application, its market share or the locations for reprocessing and distribution, are possible compared to the forward oriented production and distribution. The results of the LCA are stated in units as the $CO_{2\,eq.}$, which combine the impact of both processes and location. On the one hand, it simplifies the interpretation of the impact for the calculated case. On the other hand, it limits the ability of the interpretation of the impact of processes and location to identify the main influence factors.

Resulting from the limitations of an LCA, three requirements have to be met: (A) in contrast to an LCA, the functional unit of the approach has to enable the comparison of multiple applications, as the function of a 1st and 2nd life application may differ; (B) the approach has to be easily adapted to different use cases to reflect reality as best as possible; (C) the results have to be location-independent in order to enable an impact analysis of the processes.

Based on the requirements from (A) to (C), a meta study is designed to demonstrate an LCA-complementing approach for 2nd life applications. A mathematical algorithm presents the calculation of energy demand for a case considering a product in multiple life cycles. It uses values from previous LCA studies, simplifying the effort of use and allows the estimation of the magnitude of the individual processes and to identify the main influencing factors.

The algorithm is based on LCA-values as inputs. However, LCA studies are not available yet for all life cycle stages of a lithium ion battery. LCA studies with primary data exist only for the stages (I) raw material extraction, (II) manufacturing or (VI) recycling. Each study uses unique assumptions, different process boundaries and a specific way to present values and results. Existing values are converted into comparable units and areas of application. For the stage (IV) remanufacturing, no quantitative data could be found. The value for remanufacturing is estimated based on the general definition of the remanufacturing process and the energy demand for the comparable subprocesses stated in the LCA studies on manufacturing processes. It accounts for approximately 26% of the energy demand for the manufacturing process, saving accordingly 74% of the energy. This value gives a first estimation of the energy demand for the remanufacturing process as no calculation, experimental or experience value, and an exact definition of the process for a lithium ion battery exists. Further research on the technical feasibility of the processes combined with statistics on the expected state of health and longevity of a used battery will enable the validation of the proposed algorithm.

The state of health is particularly important for the determination of the use stage. The maximum life time or range of a battery determines the demand on units over a time period for a defined use intensity. This demand determines the amount of batteries to be produced and the energy demand in the considered time period.

(ii) Impact of a lithium ion battery and its life cycle stages

The impact of a lithium ion battery was calculated based on three cases: C1—production and recycling on LIBs; C2—production of new batteries for electric vehicles (EV LIB) and repurposing them into stationary energy storages (SES LIB); C3—remanufacturing the EV LIB and reuse again in electric vehicles.

Case C1—recycling discusses the ratio between the (III) use stage and stages (I) raw material extraction, (II) manufacturing and (VI) recycling. The results show that, dependent on the use intensity, this ratio accounts from 20% to 90%. As there exist different car users in real life, both the product, influencing stage (III), as well as process efficiency, influencing stages (I, II and VI), should be improved and researched in more detail.

Case C2—repurpose estimates the energy savings for the case, where the EV LIBs are remanufactured and repurposed to SES LIBs. This case requires the least amount of energy, saving up to 40% compared to C1—recycling.

Case C3—reuse highlights the influence on the expected life time of a battery. In the calculation, the assumption for the calendrical lifetime of a remanufactured battery for the reuse in electric vehicles is approximately six years. In the considered time span of 20 years, this means that for rarely used vehicles three (one new and two remanufactured) instead of two (new) batteries are needed. This higher demand for batteries implies no savings in energy demand. Further, the calculation assumes the maximum range of a remanufactured battery to be 120,000 km. This value is considered to be constant, regardless of the intensity of use. However, as explained in Section 2, the use intensity has a significant influence on the ageing behavior of a battery. Nevertheless, this assumption simplifies the calculation. Adapting and specifying them for different areas of use intensity can provide new insights into whether and when reuse is appropriate. However, the aging behavior of 2nd life batteries remains insufficiently understood.

With the new method, the question of which treatment after the 1st life should be preferred, can be considered in more detail due to new findings. For example, in a certain case, the results of an LCA can indicate that the use of reprocessed products for the same application, meaning with the same function, is not reasonable. Then, the new method can be used to check to what extent the use in other applications, considering other functions, is reasonable. Further, by taking calendar aging into account, the results can be more closely adapted to real-life situations. This means that the method presented can additionally be used to check whether the frequency of the function assumed in the

LCA can also be realized by the product. One example described in the paper is the use of a car for a long period of time for very low ranges. The influence of calendric aging is higher than the influence of functionality. This relationship is not considered in an LCA and is complemented by the method presented here. The presented method adds new perspectives to the results of an LCA. It does not claim to replace them.

(iii) Future research agenda

The aging behavior and the corresponding state of health of a 2nd life battery can be determined by practical tests and theoretical considerations such as energy intensive tests, including multiple charging and discharging, or post mortem analysis. A continuous condition monitoring for batteries with a capacity lower than 80% of their original capacity, or for remanufactured batteries, which have a higher capacity due to the exchange of single cells, is not possible yet. Further, sufficient data for this case are missing.

Theoretical considerations may lessen the practical test intensity. One possible solution is the evaluation of the exact history of the battery, for example by means of a battery log or passport. However, due to the large number of stakeholders involved during the life cycle of the battery, data storage becomes a challenging task for 2nd life applications. Further, due to possible conflicts of interest, the free use of these data will hardly be possible in the near future. A battery passport or data storage with new technologies, such as the blockchain, offer possible solutions. Nevertheless, these data should be applicable down to the module or cell level in order to enable the continuation of the data in further life cycles.

However, if it is assumed that the exact history of the battery will not be freely available, further approaches can be considered. Service providers of overall equipment manufacturers (OEMs) such as remanufacturing companies or contracted logistics companies have, on the one hand, experience data on the state of health of their take-back products and, on the other hand, some information on the previous owners. These data do not refer to the specific characteristics of a single battery, but to the characteristics of the delivery from a particular customer. For example, the location, with its climatic parameters, can affect the condition of the battery. In order to determine a probability for the expected condition of the battery batch, for example based on its origin, methods of artificial intelligence such as machine learning can be used. This assessment can help to carry out the required practical tests in a more targeted manner and thus reduce the energy requirement for them. This would further lessen the impact of remanufactured batteries and increase the potential for a 2nd life.

As shown in the case C3—reuse, the expected life time and range of a battery have a significant influence on the total energy demand over a time period. In this context, it was considered that a battery is used until a specific state of health, which does not allow further use in this application. Neither the technical feasibility, nor the market characteristics, such as the availability of comparable battery types, was considered. These aspects must be investigated separately.

The availability of comparable battery types for their remanufacturing may be a challenging task as the technical progress of batteries is very fast. The exchange of new batteries, available in the market in large quantities, may reduce this problem. Nowadays, the majority of users lease electric vehicles from the OEMs or their third parties, and the batteries remain the property of the distributor. This ownership enables new business models, such as battery pooling. These can be implemented, among other things, thanks to a network of battery exchange stations, where an empty battery is exchanged against a fully charged one. The empty battery can be checked for its condition and, if necessary, remanufactured at an early stage. This application would combine the stages (IV) remanufacturing and (V) use in 2nd life in a new manner. On the one hand, the lifetime of a battery could be extended. However, it remains unclear whether the lifetime would be as durable as the conventional one. On the other hand, the remanufacturing would occur more often, increasing the energy demand. The interaction of these two factors should be investigated in more detail.

The results of the case studies demonstrate the high potential of energy savings by implementing multiple life cycles of batteries. It has been shown that both the repurposing of EV LIBs into SES LIBs, as well as the reuse of EV LIB in electric vehicles, can reduce the total energy demand. The calculation, however, is based on assumptions that have to be verified by real cases. Especially the characteristics of used or remanufactured batteries and their handling is insufficiently known.

Future research should verify and/or revise these conclusions. The research field on multiple life cycles of EV LIBs is untapped from various perspectives. There exist many topics to investigate in the future that range from required processes over the demand or availability of the batteries to real-life applications with their benefits and disadvantages. To fully explore the potential of multiple life cycles in a battery, a broader consideration of these research fields is needed, in parallel to investigations on optimization of single processes and life cycle stages.

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Appendix A

Reference [7] Data for battery production including battery assembly, cell production, component manufacturing and material processing Original data: 104 MJ_{eq}/kg Converted into: 10.1 kWh/kg with 0.35 for converion from primary energy to process energy. Reference [8].

Table A1. Original and converted data for $LIMNO_2$ [8].

$LIMNO_2$	Original Data	Converted Into	
Material extraction	0.169 MJ/km	30.22 kWh/kg	Primary Energy
Material Processing	0.0591 MJ/km	3.7 kWh/kg	Process Energy
EoL	−0.0325 MJ/km	−5.81 kWh/kg	Primary Energy

Table A2. Original and converted data for Li-NMC [8].

Li-NCM	Original Data	Converted Into	
Material extraction	0.24 MJ/km	42.92 kWh/kg	Primary Energy
Material Processing	0.251 MJ/km	15.71 kWh/kg	Process Energy
EoL	−0.0674 MJ/km	−12.05 kWh/kg	Primary Energy

Table A3. Original and converted data for $LiFePO_4$ [8].

$LiFePO_4$	Original Data	Converted Into	
Material extraction	0.244 MJ/Battery	43.63 kWh/kg	Primary Energy
Processing	0.322 MJ/Battery	20.14 kWh/kg	Process Energy
Material Processing	0.0531 MJ/Battery	3.32 kWh/kg	Process Energy
Component Manufacturing	0.0287 MJ/Battery	1.80 kWh/kg	Process Energy
Product Manufacturing	0.24 MJ/Battery	15.02 kWh/kg	Process Energy
EoL	−0.0727 MJ/Battery	13.00 kWh/kg	Primary Energy

Converted with 193,120 referred kilometers and 300 kg battery weight. Reference [9] Data for the energy demand for the production.

Table A4. Original and converted data for [9].

	Original Data	Converted Into
Lower-bound value	586 MJ/kWh	17.11 kWh/kg
Asymptotic value	960 MJ/kWh	28.04 kWh/kg
Average value	2318 MJ/kWh	67.70 kWh/kg

Converted with the produced battery capacity of 26.6 kWh and a weight of 253 kg. Reference [10] Data for the battery production

Table A5. Original and converted data for [10].

	Original Data		Converted Into	
NiMH	5.4 kg oil_{eq}/kg	Primary Energy	21.98 kWh/kg	Process Energy
Li-NMC	4.7 kg oil_{eq}/kg	Primary Energy	19.13 kWh/kg	Process Energy
LFP	4.6 kg oil_{eq}/kg	Primary Energy	18.72 kWh/kg	Process Energy

Converted with factor 11.63 for converion of kg oil_{eq} into kWh and 0.35 for converion from primary energy to process energy. Reference [11] Data for material extraction and battery manufacturing

Table A6. Original and converted data for [11].

	Original Data	Converted Into
Materiel extraction	29.9 GJ/Battery	28.64 kWh/kg
Manufacturing	50.17 kWh/kg	50.17 kWh/kg

Converted with the battery weight of 290 kg. Reference [12] Data for material extraction. Original data: 1126 MJ/kWh Converted into: 44.55 kWh/kg Converted with the battery capacity of 23.5 kWh and weight of 165 kg. Reference [14] Data for battery recycling

Table A7. Original and converted data for [14].

NMC	Original Data	Converted Into
DM-Last	3701 MJ/1000 kg	1.03 kWh/kg
DM-Gut	−29,324 MJ/1000 kg	−8.15 kWh/kg
zz_Last	4195 MJ/1000 kg	1.17 kWh/kg
zz_gut	−4823 MJ/1000 kg	−1.34 kWh/kg
KS-Last	3080 MJ/1000 kg	0.86 kWh/kg
KS_Gut	−3553 MJ/1000 kg	−0.99 kWh/kg
HA_Last	26,757 MJ/1000 kg	7.43 kWh/kg
HA_Gut	−16,206 MJ/1000 kg	−4.50 kWh/kg
Total	−16,173 MJ/100 kg	−4.49 kWh/kg
Effort	−53,906 MJ/1000 kg	−14.97 kWh/kg
Benefit	37,733 MJ/1000 kg	10.48 kWh/kg

Table A8. Original and converted data for [14].

LFP	Original Data	Converted Into
DM-Last	4552 MJ/1000 kg	1.26 kWh/kg
DM-Gut	−37,548 MJ/1000 kg	−10.43 kWh/kg
zz_Last	3668 MJ/1000 kg	1.02 kWh/kg
zz_gut	−4192 MJ/1000 kg	−1.16 kWh/kg
KS-Last	2786 MJ/1000 kg	0.77 kWh/kg
KS_Gut	−3075 MJ/1000 kg	−0.85 kWh/kg
HA_Last	5387 MJ/1000 kg	1.50 kWh/kg
HA_Gut	−375 MJ/1000 kg	−0.10 kWh/kg
Total	−28,797 MJ/1000 kg	−8.00 kWh/kg
Effort	−45,190 MJ/1000 kg	−12.55 kWh/kg
Benefit	16,393 MJ/1000 kg	4.55 kWh/kg

Appendix B

Assumptions for the case study

Table A9. Assumptions for EV LIB.

EV LIB		
New		
	Weight	300 kg
	Maximum mileage	150,000 km
	Maximum age	10 years
	Energy use	
	efficient	10 kWh/100 km
	high	16 kWh/100 km
	Charging efficiency	0.8
Remanufactured		
	Maximum mileage	120,000 km
	Maximum age	6 years

Table A10. Assumptions for SES LIB.

SES LIB		
New		
	Weight	240 kg
	Capacity	0.8 of EV LIB
	Maximum age	15 years
Remanufactured		
	Weight	300 kg
	Maximum mileage	0.8 of EV LIB
	Maximum age	10 years

Table A11. Assumptions for the energy demand for the processes.

Process		
(I) Material extraction		
	main value:	36 kWh/kg
	+20%	43 kWh/kg
	−20%	29 kWh/kg
(II) Production		
	main value	19 kWh/kg
	efficient	10 kWh/kg
	high value	68 kWh/kg
(V) Usage		
	Targeted mileage	
		3000 km/year
		9000 km/year
		15,000 km/year
		25,000 km/year
		40,000 km/year
(IV) Remanufacturing		
	main value	5 kWh/kg
(VI) Recycling		
	Effort	7 kWh/kg
	Benefit	15 kWh/kg
Time period		20 years

Results of the case studies C1: Recycling

Table A12. Battery amount for case C1.

Target Mileage	d [km]	$n_{d3/5}$	$n_{a3/5}$	$n_{3/5}$
3000 km/year	60,000	1	2	2
9000 km/year	180,000	2	2	2
15,000 km/year	300,000	2	2	2
25,000 km/year	500,000	4	2	4
40,000 km/year	800,000	6	2	6

Table A13. Energy demand for case C1 in [kWh].

	Material Extraction	Manufacturing	Usage (Efficient)	Remanufacturing	Recycling Effort	Recycling Benefit
EV LIB						
3000 km/year	21,600	11,400	7500	-	4200	9000
9000 km/year	21,600	11,400	22,500	-	4200	9000
15,000 km/year	21,600	11,400	37,500	-	4200	9000
25,000 km/year	43,200	22,800	62,500	-	8400	18,000
40,000 km/year	64,800	34,200	100,000	-	12,600	27,000
SES LIB	17,280	9120	-	-	3360	7200

C2: Repurposing

Table A14. Battery amount for case C2.

Target Mileage	d [km]	$n_{d3/5}$	$n_{a3/5}$	$n_{3/5}$
3000 km/year	60,000	1	2	2
9000 km/year	180,000	2	2	2
15,000 km/year	300,000	2	2	2
25,000 km/year	500,000	4	2	4
40,000 km/year	800,000	6	2	6

Table A15. Energy demand for case C2 in [kWh].

	Material Extraction	Manufacturing	Usage (Efficient)	Remanufacturing	Recycling Effort	Recycling Benefit
EV LIB						
3000 km/year	21,600	11,400	7500	3000	4200	9000
9000 km/year	21,600	11,400	22,500	3000	4200	9000
15,000 km/year	21,600	11,400	37,500	3000	4200	9000
25,000 km/year	43,200	22,800	62,500	3000	8400	18,000
40,000 km/year	64,800	34,200	100,000	3000	12,600	27,000
SES LIB	-	-	-	-	-	-

C3: Reuse

Table A16. Battery amount for case C3.

Target Mileage	d [km]	$n_{d\ total}$	$n_{d\ new.}$	$n_{d\ reman.}$	$n_{a\ new.}$	$n_{a\ reman.}$	$n_{new\ C3}$	$n_{reman.\ C3}$
3000 km/year	60,000	1	1	0	2	4	1	2
9000 km/year	180,000	2	2	0	2	4	1	2
15,000 km/year	300,000	3	2	1	2	4	2	1
25,000 km/year	500,000	4	3	1	2	4	3	1
40,000 km/year	800,000	6	4	2	2	4	4	2

Table A17. Types and amount of battery users.

Driven km per Year	Up to 3000 km	3000–9000 km	9000–15,000 km	15,000–25,000 km	25,000–40,000 km
	14%	32%	30%	15%	9%

Table A18. Battery amount for case C3 (battery pooling).

Pool of EV	n_{new}	n_{reman}
3000 km/year	14	28
9000 km/year	32	64
15,000 km/year	60	30
25,000 km/year	45	15
40,000 km/year	36	18
Total	187	-

Table A19. Energy demand for case C3.1 remanufacturing of frequently used batteries in [kWh].

	Material Extraction	Manufacturing	Usage (Efficient)	Remanufacturing	Recycling Effort	Recycling Benefit
EV LIB						
3000 km/year	151,200	79,800	7500	42,000	29,400	63,000
9000 km/year	345,600	182,400	22,500	96,000	67,200	144,000
15,000 km/year	648,000	342,000	37,500	0	126,000	270,000
25,000 km/year	486,000	256,500	62,500	0	94,500	202,500
40,000 km/year	388,800	205,200	100,000	0	75,600	162,000
SES LIB	17,280	9120	-	-	3360	7200

Table A20. Energy demand for case C3.2 remanufacturing of rarely used batteries in [kWh].

	Material Extraction	Manufacturing	Usage (Efficient)	Remanufacturing	Recycling Effort	Recycling Benefit
EV LIB						
3000 km/year	151,200	79,800	7500	0	29,400	63,000
9000 km/year	345,600	0	22,500	0	67,200	144,000
15,000 km/year	648,000	0	37,500	45,000	126,000	270,000
25,000 km/year	486,000	0	62,500	22,500	94,500	202,500
40,000 km/year	388,800	0	100,000	27,000	75,600	162,000
SES LIB	17,280	9120	-	-	3360	7200

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