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Economic Potentials of Ecologically Attractive Multi-Life Products—The Example of Lithium-Ion Batteries

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Abstract: The growth of the electric vehicle market is increasing the demand for batteries. The production of vehicle batteries has a high environmental impact and at the same time represents a high cost factor in the production of electric vehicles. Both the raw materials and the production capacity required for vehicle batteries are very limited. Driven by the increasing scarcity of resources and the rising internalization of external environmental costs, as well as by policy regulations, this paper shows a possibility of life cycle extension that goes beyond the circular economy approach and opens up additional economic and ecological potentials. In contrast to the current end-of-life strategies and the circular economy approach, a new innovation philosophy and business models for sustainable multi-life products are developed. To this end, we first conducted an economic analysis in three steps and developed a multi-life indicator in the process. Based on this, we integrated the influence of political regulations in a fourth step and elaborated on their effects in five scenarios. Our results show a savings potential of 5–30% (multi-life indicator M 0.95–0.70) compared to single-life batteries. This savings potential shows the importance of the new strategic multi-life approach and justifies the need for further research in this field.

Keywords: lithium-ion batteries; multi-life-products; circular economy; ecosystem; product life cycle

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1. Introduction

If the sustainability of products is to be increased, it is helpful to extend product life cycles [1,2]. This will lead to the economical consumption of resources and accelerate the market ramp-up of new technologies as a result of improved cost distribution together with a longer life cycle (ibid.). The volume-based linear development and production models prevalent today are therefore reaching their limits due to increasing shortages of resources and the rising internalization of external environmental costs into the products [3] via government regulations (see e.g., [4]).

For this reason, a variety of end-of-life strategies has been developed [5–7] to increase products' eco-efficiency, such as remanufacturing, refurbishment, and recycling [8,9]. However, new second and third lives in new markets with greatly changed or new business models for multi-life applications are rarely sought. Some reasons are that the dominant innovation philosophy is based on new product development, the required knowledge and incentives for continued use are not in place, and customers prefer new products and until now will pay more for them [6].

However, business models have to be realigned [10] because customers' purchasing decisions are no longer being made purely on the basis of economic aspects: ecological aspects are becoming more and more decisive [11], and these factors increase the costs of resources such as energy [10]. One approach to such realignment is multi-life products [1], which can be used over several life cycles in multiple applications.

An example here is batteries from electric vehicles which can be re-used as electricity storage devices in the home connected to a photo-voltaic system (second life, e.g., [12] and then re-used again in fork-lift trucks (third life). Such multi-life batteries can increase sustainability because batteries are considered to be the main green technology selected to decarbonize transport. They reduce CO_2 emissions in electric vehicles, thereby improving the air in urban areas in particular [5], even though they are also highly pollutant industrial products whose greening properties are contested [5]. However, because alternatives such as fuel cells are still too expensive and not yet technologically mature enough for passenger cars [13], and e-fuels are regarded as a transitional technology [14], it is possible to assume that multi-life products, and specifically multi-life batteries, have an ecological advantage (see also [15]).

Because extending product life will significantly increase product and process complexity in product development and in the supply chain, it is important for suppliers to collaborate on platforms where the cost-efficiency of the first life cycle will be improved by the second and third life cycles [16]. This is now becoming possible due to digitalization, which enables interfirm collaboration in networks on a necessary scale via digital platforms [17], including in the automotive industry [18]. However, these approaches still lack the basis for developing business models [19,20]. For this to emerge, it needs a precise assessment of the potential that can arise from the multiple uses of batteries Economic Potential [21–27]. In addition, the development of business models, especially for batteries and in the recycling sector, depends very much on policy and external factors [28–31].

Therefore, the research questions here are: will batteries as an example of multi-life products, with multiple applications and therefore several life cycles over the duration of use, offer economic potential? And what impact do political framework conditions have on this potential?

This assessment of the potential of new multi-life business opportunities in uncertain environments is in line with "narrowing the future" [32] through an estimation of the possible economic value. More specifically, it relates to joint value creation by partner companies [33–35] through collaboration on digital platforms, as a preliminary step towards the development of a blueprint for a network of partners (ecosystem, e.g., [36]. This requires new business models of the partners [17], connected in a "multiple business model" with different business model cores that are interconnected and mutually reinforcing via an overarching business logic [37]. After all, if such linked business models of the partners which enable a new form of synergy utilization are to make sense, multi-life products need their own economic logic and cannot be enforced e.g., solely by state regulations.

The remainder of the article is structured as follows: Section 2 first provides a literature review. In Section 3, a model for estimating the costs and potentials of multi-life solutions is presented, which we use for the empirical examination in Section 4, the potential assessment of multi-life batteries. Following this, Section 5 discusses the implications for research and management. The paper ends with a discussion of the study's limitations and an outlook for future research.

2. Literature Review

2.1. Development of the Market for Lithium-Ion Batteries

The transformation of drive technology is in full swing. In Germany alone, the goal of the federal government for 2030 is a stock of 15 million fully electric vehicles [38], which appears possible [39], at least if accompanied by extended regular support measures. These could include an extension of the purchase and innovation premium for pure electric vehicles, a disproportionate increase in fuel and taxes for motor vehicles with internal combustion engines (ICE and PHEV), the introduction of graduated inner-city charges for vehicles with internal ICE and PHEV or state subsidies for electricity costs for purely electric vehicles.

According to [40,41], the demand for lithium-ion batteries will increase sharply by 2030. A requirement of around 8800 GWh per annum will probably face a supply of only around 2450 GWh per annum (see Figure 1), which cannot cover demand due to limited raw materials.

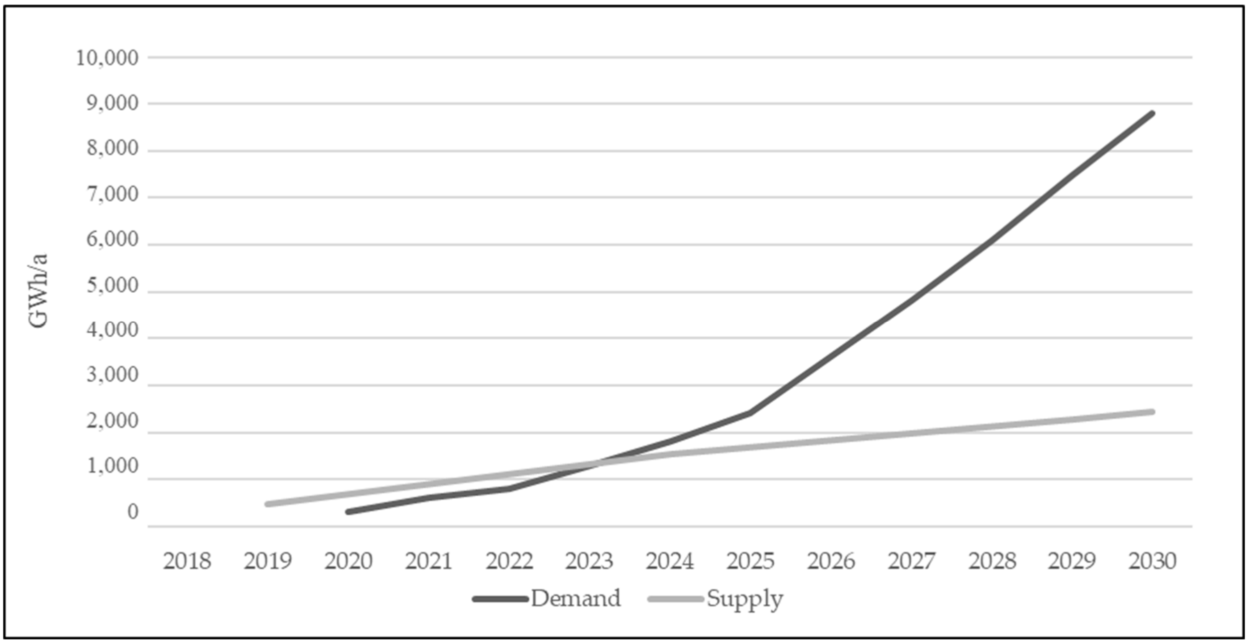

Figure 1. Differences between demand and supply for lithium-ion batteries by 2030 [40,41].

Because the development of new raw material mines and refining capacities will take a long time and is limited [42] and alternative drive technologies under discussion, such as fuel cells or e-fuels, do not match the efficiency of batteries [43], it is important to save resources (graphite, cobalt, copper, lithium, manganese and nickel) by remanufacturing, refurbishment and recycling and–preferably–by the development of multi-life products.

2.2. *Product Life Cycle Extension and Its Economic Importance*

So far, many companies are still strongly focused on developing, producing, and marketing new products with a dominant business model. There are also individual applications of remanufacturing, refurbishing, and recycling of their products for an existing market A ([8,9] and Figure 2). New second or third uses in new markets B and C with greatly changed or new, i.e., multiple, business models [37] for multi-life products are rarely sought, for the reasons stated in the introduction (a dominant innovation philosophy based on new product development, lack of knowledge and incentives for further use, customers who prefer new products and pay more for them, [44]).

As mentioned above, extending the product life cycle will also significantly increase product and process complexity in product development and in the supply chain [15]. Therefore, companies often prefer to remain in their traditional business and not become service providers, as BMW CEO Zipse (quoted from [45]) emphasizes in analogy to the aviation business: "BMW is an aircraft manufacturer and not an airline".

However, considering only one application (the first life) from an isolated perspective [1] is not sufficient [46]. Ecological potentials will be increased if the product life cycle is extended, because fewer products will be needed for the same performance.

By extending the product life cycle to multiple life cycles, the number of products needed and thus also resources per time unit can be reduced, in the case of lithium-ion batteries by 12 percent (based on [47]). This means that 12 percent fewer batteries will need to be produced compared to a single-life approach, immediately leading to a significant improvement in sustainability.

Multi-life batteries are therefore ecologically attractive. If they are also economically attractive, ecological and economic goals can be achieved at the same time [48]. This will be further examined below.

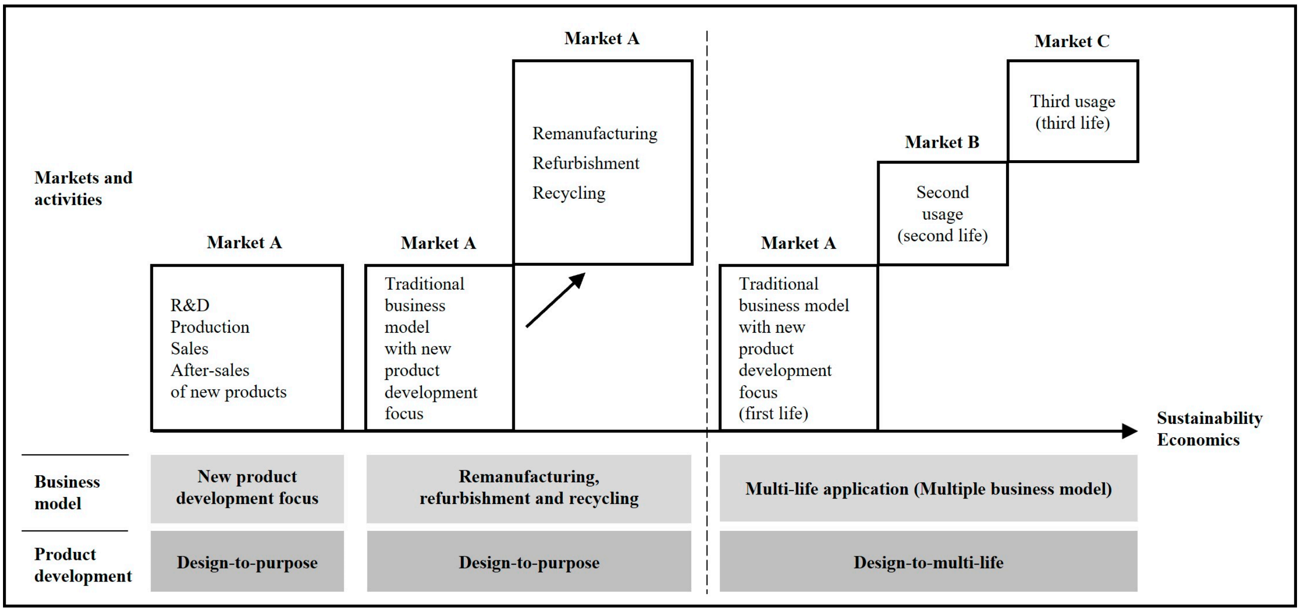

Figure 2. Product development and design of business models over the life cycle (Source: own design).

2.3. Previous Explanations for Estimating the Economic Potential of Ecologically Attractive Multi-Life Products

When making decisions about several product life cycles and thus over a long period of time, both technological uncertainty and market uncertainty [49] are very high. As a result, there are information deficits [50]. However, mathematical models for decision-making under uncertainty [51,52] are too abstract for the purpose of calculating the economic potential of multi-life products [53,54]. This also applies to the mathematical decision-making model to demonstrate the advantages of selling versus leasing batteries by Agawal et al. [55].

Alternatives are simulations under uncertainty with multi-period investment pathways [56] or the use of an AI crunch base, i.e., a digital platform for finding business information [57] to derive elements for a multi-life network. For this, however, an economically viable core (a minimum viable solution, similar to [58], pp. 25–26) of multi-life products must first be developed, which can then be refined iteratively using the models. Therefore, a rough (minimum viable) approach for estimating the economic potential of ecologically attractive products has to be found here.

3. A Model for Estimating the Economic Potentials of Ecologically Attractive Multi-Life Products

To model the economic potential of ecologically attractive multi-life products, the economically minimum viable core (similar to [58], pp. 25–26) of such a multi-life product must first be found. An analysis of the total costs of ownership (TCO) of multi-life products in comparison with single-life products helps. Therefore, the TCO calculation ([59] or [60]) will be briefly outlined here (Section 3.1) and is extended to multi-life products (Section 3.2) to calculate the economic potentials of ecologically attractive multi-life products (Section 3.3). The calculation of the minimum viable core of these products takes place around a digital platform. Further economic potentials (“upsides”) are likely to arise, if the partners involved align themselves even more strongly via the platform, because then they create an overarching value proposition through multilateral interaction ([61]) and thus also an added value through joint value creation.

3.1. Justification of the Economically Viable Core of a Multi-Life Product with the Help of a TCO-Model

The total costs of ownership ([59] or [60] as well as [62,63], specifically for application in the automotive industry) should be considered in order to calculate the total costs over one life cycle and the residual value. For this purpose, all costs are summed up over the duration of use, starting from the purchasing costs of the new product [62], which shows the typical development of the TCO over time (see Figure 3). The residual value–starting with the purchase price at the beginning of the life cycle–falls as the product ages [64]. The difference between TCO and the residual value divided by the duration in use, for example, shows the monthly payment requirements and falls over time as the purchase price is spread over a longer period and the residual value declines well above the average in the early years.

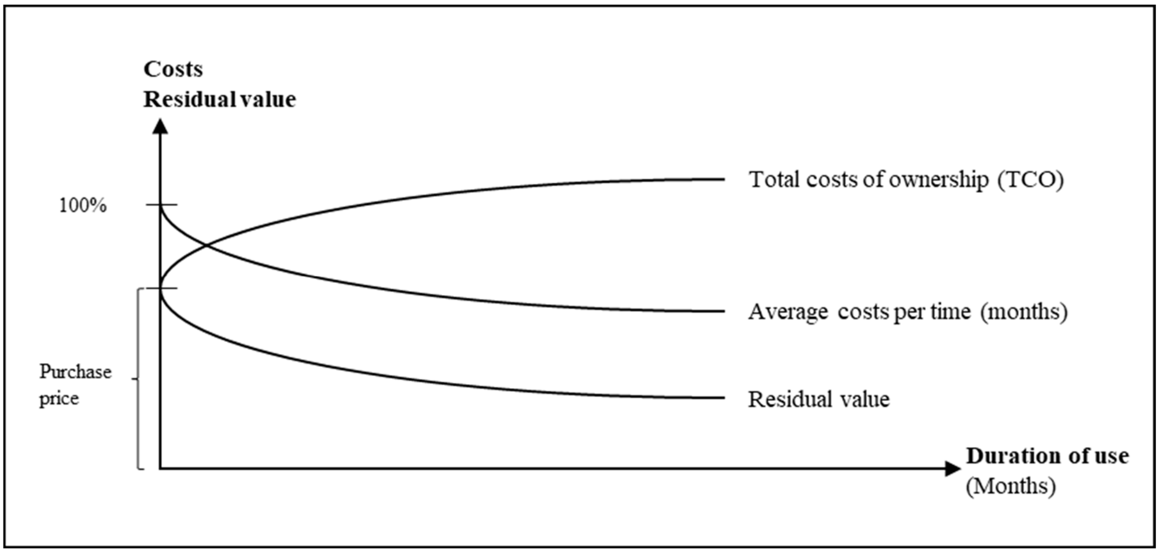

Figure 3. TCO over the life cycle–basic model (own design).

3.2. Extending the TCO Model by Considering Multi-Life Applications

If, instead of one, three life cycles are now represented in the model over the duration of use, this leads to additional refurbishment costs ($r_{1/2}$) with a positive effect on the residual value of the product (see Figure 4). In addition, every other application of the product in a different life cycle will affect the TCO due to other maintenance or running costs (cf. Figure 4).

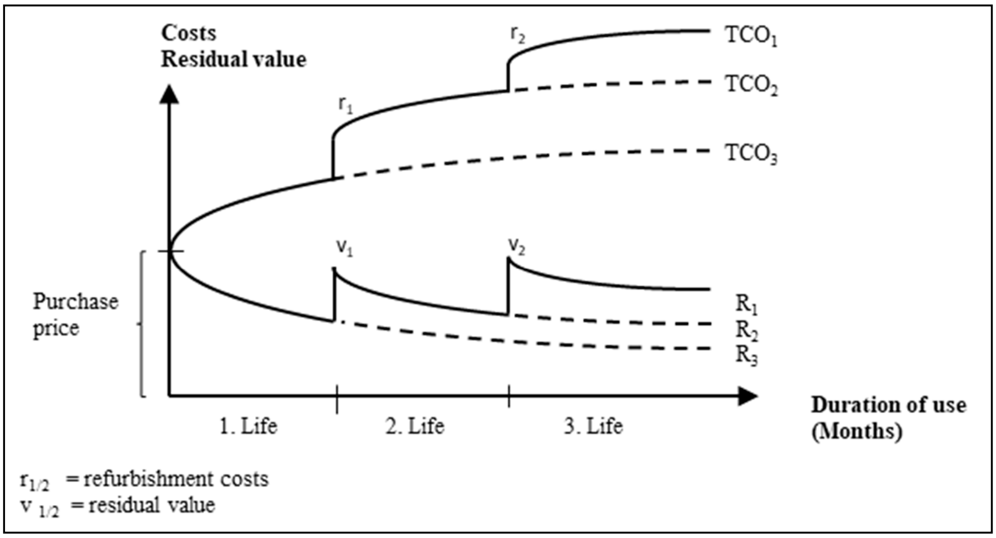

Figure 4. TCO for multi-life products (own design).

Figure 4 is based on the assumption that the purchase price decreases slightly as a result of the multi-life approach, because it will be possible to develop modular products via digital platforms and to link the various applications or life cycles over the duration of use using "multiple business models" [37]. Digitalization is therefore needed for the circular economy [65] and "the emergence of enabling technologies, more supportive consumer preferences, or new business risks will drive increased adoption of circular business models" [16]. However, it requires several companies to collaborate on digital platforms, because such platforms can improve the cost-efficiency of the first life by the second and third life (ibid.). Therefore, it is important to examine whether collaboration in the development and sale of ecologically attractive multi-life products via digital multi-life platforms can be economically attractive, because these products also increase sustainability [48]. This should be examined in a little more depth.

Cooperation on platforms aims at joint value creation by the partners [33]. This can be conducted through joint innovation [66] via a modular technological architecture "to create new complementary products and services" through partners (innovation platforms, [17], p. 18) and/or through an exchange on "a multi-sided market-place that enables re-use of shared resources", i.e., activities and assets (transaction ecosystems, [67]). Both types of platforms are relevant for multi-life products, because partners can collaborate on innovation platforms to develop products that may have several applications, and transaction platforms that can be helpful to an offering via various life cycles (Figure 5).

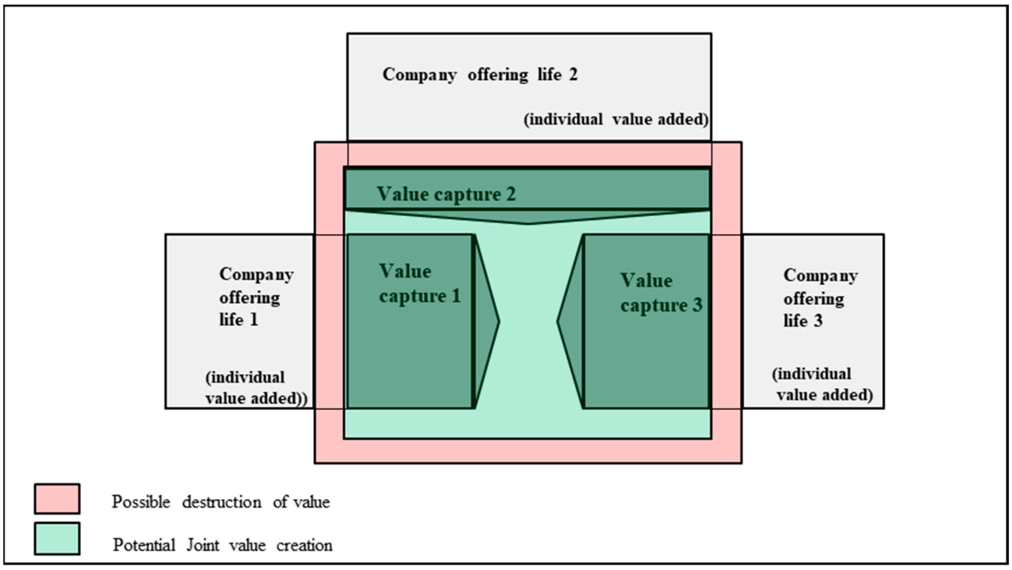

Figure 5. Joint value creation with multi-life products (own design).

The challenge is, however, that ecosystems not always create value, but can also destroy it (see Figure 5) and are then not sustainable [17]. At least, if several partners are involved in offering the multi-life solution, the dependencies, and interdependencies are no longer controllable by an individual company, but depend on the interactions of all partners (multilateral relationships, [61]). There is thus a risk of an outflow of resources and capabilities when cooperating with competitors (coopetition, e.g., [68]). Moreover, there are the risks of mistakes in building digital platforms such as mispricing, mistrust, hybris, and mistiming [17], as well as in "digital interdependence, information [cyber] security, and regulatory complexity" [69].

Nevertheless, explanations of cooperation on platforms are a prerequisite for the joint development and offering of (multi-life) products. Essential explanations for joint value creation are according to Jacobides et al. (2018) [70]:

1. modularization [71] taken from the transaction cost theory [72–74] and
2. complementarity [35,75] via (supply-side) economies of scope [58] by the transfer of human capital or knowledge as quasi-public goods [76] which generate transaction costs in every reutilization [17,77] for the two types of platforms).

Further explanations of joint value creation on platforms, such as value co-creation with the customers through demand-side economies of scope, scaling (mainly customers) without additional costs through economies of scale according to the network theory [78], pricing on two-sided markets (subsidizing a group of partners, often the consumers, e.g., [17,79]) and data-based learning with AI [80] are not so relevant for an initial assessment of the economic potential, because they relate more to the demand side than to the supply of multi-life products.

3.3. Modelling Economic Potentials of Ecologically Attractive Multi-Life Products

This model focuses on the simplicity reasons on the traction battery in a car. It is assumed that the batteries are used with flexible duration (according to the charging and driving behavior) and that the property rights are clarified. After the first battery life, the car normally has still a longer life period before it will be scrapped or recycled. The propulsion of the car for further use as well as scrapping and recycling, will generate further costs and revenues that are neglected here simplistically. It is also clear that at the beginning of a multi-life battery use, additional batteries are first needed in order to be able to get by with 12 percent fewer batteries later in the running system as mentioned [47]. In times of scarce resources, this is of course a challenge.

Furthermore, it is assumed that if complementary partners collaborate via a digital platform, the value (residual value) may increase with every life cycle as costs decrease (TCO). As a measure of the economic attractiveness of a multi-life product we developed the indicator M. It is the result of dividing

- the total cost of ownership (TCO) over several life cycles (multi-life) minus the residual value at the end of these life cycles divided by the duration of use in months (average cost per time, cf. Figure 3) by
- the average cost per time of the sum of the single-life products,

$$\text{i.e., } \mathrm{M} = \frac{\frac{\sum(TCO)(m) - R(m)}{\sum(D)(m)}}{\frac{TCO(s) - R(s)}{D(s)}}$$

where TCO = Total cost of ownership, R = residual value, D = Duration of use, m = multi-life and s = sum of single lives. We selected this indicator M to be able to run scenarios on multiple life regulations more easily. A comprehensive economic impact assessment with a calculation of the net present values, however, still requires a more detailed assessment of revenues, which cannot be undertaken reasonably until an initial economic potential of these multiple-use concepts can be determined [81].

The indicator M is mathematically also the difference of the integrals between the average aggregate single-life cost function and the average multi-life cost function over time (cf. Figure 6) and expresses the economic potential of a multi-life product. For reasons of simplicity, it is assumed that the prices of the products in the market place remain the same in both single and multi-life application, so that a cost advantage turns into an economic advantage. This relationship is not formulated with unsteady functions, because they are complicated to solve but do not provide additional insights. However, indicator M is likely to fall significantly in the event of a second and third life.

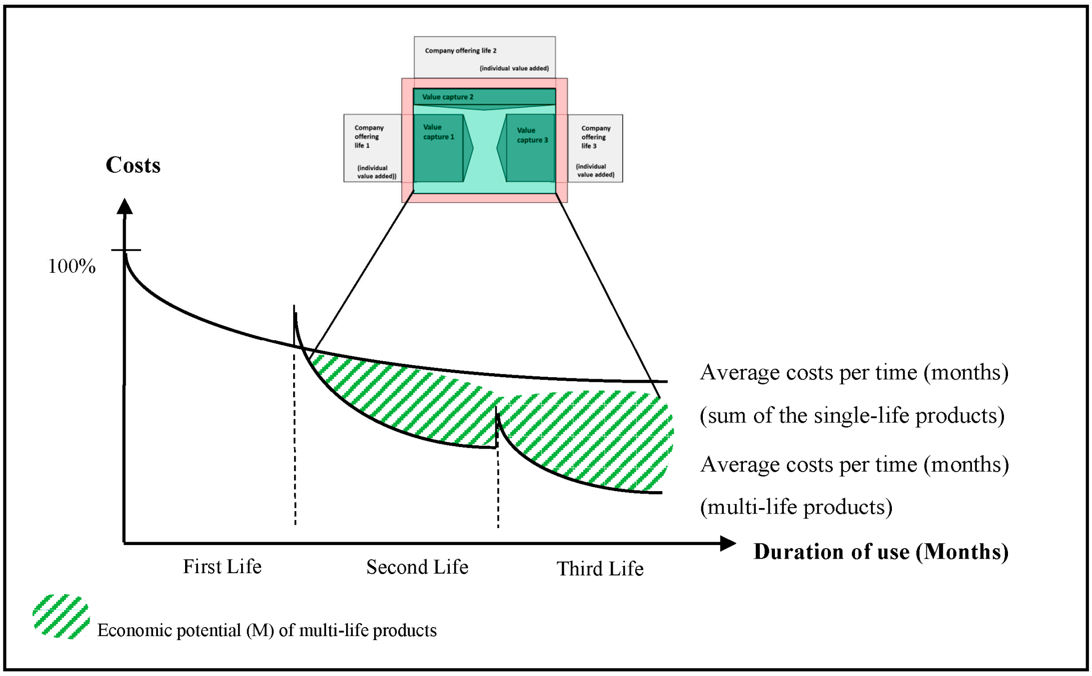

Figure 6. Average cost per time over the life cycle (simplified illustration-own design).

Using the indicator M, economic potentials for the lithium-ion battery as a multi-life product can now be estimated. This estimation is an expansion of the method of potential analysis in controlling [82], which is an ex ante assessment of the economic potential of a given strategy [83,84].

4. Empirical Examination: Potential Assessment

The economic potential of increasing sustainability by means of multi-life products will now be estimated for the example of lithium-ion batteries [1,85,86]. For this purpose, the examination method is first briefly presented (Section 4.1), then the results are summarized (Section 4.2) and discussed (Section 5).

4.1. Methodology

In order to determine the economic potential of the multi-life approach (Figure 5) more precisely, the influencing parameter shown in Figures 3–5 must be determined and calculated for the specific example. Here, the single lives of a large lithium-ion battery for cars, a lithium-ion battery for home storage systems for solar power and a lithium-ion battery for fork lifters, will be compared to a lithium-ion battery with multi life cycles: installed in a car in the first life cycle, re-used in a home storage system for solar power in the second life cycle and re-used again in a forklift truck in the third life cycle.

It is assumed that the entire duration of use is the same in both cases. In addition, a modular structure is assumed for the multi-life battery which fits all three use cases and can be replaced at the optimum point of time. At the same time, this requires a digital platform that monitors the battery at all times and provides an information base to optimize the duration of use in the various life cycles with the help of AI-based empirical values [87].

We carried out the economic potential analysis of the multi-life battery in four steps: in the first step, relevant data on the state of the art of lithium-ion batteries and their application in EVs were collected by means of desk research. More precisely, battery capacities, initial investments, running times, running costs, and residual values were determined on the one hand as input for an assessment of the three single-life batteries (each with a single use) and on the other hand as input for an assessment of a multi-life battery with adaptations for multiple uses over the duration of use (see Table 1). For this purpose, industry reports as well as scientific publications and articles in academic journals were reviewed.

Table 1. Battery capacities, initial investments, running times, running costs, and residual values for a single-use lithium-ion battery and a multi-life battery [1,2,85,86,88–92] and various expert interviews e.g., at The Battery Show Europe 2022 at Stuttgart.

Evaluation of a single life battery (in case of isolated use)		Evaluation of a multi-life battery (with adaptations for multiple use over the duration of use)	
First use in electric cars			
Capacity	60 kWh	Capacity	60 kWh
Initial investment	EUR 6000	Initial investment	EUR 7800
Lifecycle	8 years	Lifecycle 1	8 years
Operating costs p.a.	EUR 600	Operating costs p.a.	EUR 780
Residual value	EUR 2480	Refurbishment costs	EUR 1920
Second use as power storage for photovoltaic			
Capacity	48 kWh	Capacity	48 kWh
Initial investment	EUR 9600	Initial investment	-
Lifecycle	10 years	Lifecycle 2	10 years
Operating costs p.a.	EUR 960	Operating costs p.a.	EUR 780
Residual value	EUR 3970	Refurbishment costs	EUR 1920
Third use in forklifts			
Capacity	30 kWh	Capacity	30 kWh
Initial investment	EUR 3600	Initial investment	-
Lifecycle	2 years	Lifecycle 3	2 years
Operating costs p.a.	EUR 360	Operating costs p.a.	EUR 780
Residual value	EUR 1488	Resale/Recycling value	EUR 390

In the second step, a cost model was developed by using the information collected as input factors and deriving statements on the economic attractiveness of multi-life batteries. The main assumptions which had to be made for this (see Figure 7) have been validated by experts (in industrial companies and management consultancies and discussed at The Battery Show Europe 2022 at Stuttgart, Germany in June 2022 with many participating companies).

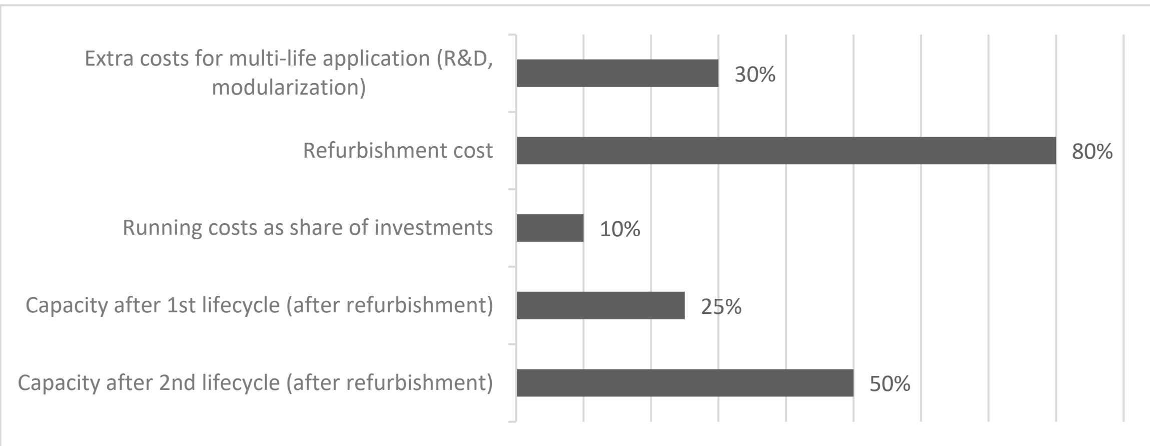

Figure 7. Main assumptions for multi-life batteries [1,2,85,86,88–90].

The aim of step 3 was to develop and record the multi-life indicator M (see Figure 5 in Section 3.3). Subsequently, the data from the basic model (Figures 3–5) were incorporated into an Excel-based TCO model. To calibrate the model, in addition to the expected cost savings based on plausibility considerations and expert interviews, the indicator M for the best possible and worst possible assumptions was developed.

Based on the expected value, various regulatory scenarios were then developed in step 4, since the development of sustainable business models with regard to the EU green deal will lead to massive regulatory changes [4]. A de-attractivisation of single-life batteries compared to multi-life batteries is to be expected and is already being debated in the political discussion.

A de-attractivization of a single-use product can be justified by arising external effects [3], because unlimited emissions, for example, are free of charge. In order to internalize these external effects with those which cause the emissions, CO_2-limits are needed which will force the transition to battery-powered electric vehicles. Because batteries are still expensive, vehicle prices will increase with the forced transition to electric mobility [3]. The price increase is even higher when the emissions are considered along the entire value chain (including that of battery production, which is highly energy-intensive). Therefore, pricing which reflects actual costs needs to internalize externalities [93]. It can be achieved through European mandates for CO_2 limits which will accelerate the more efficient electric power plants.

4.2. Results

Modeling shows that without state regulations in a realistic, but still somewhat economically conservative estimation of the economic core of multi-life batteries, its costs over the duration of use are 5% lower than that of the three single-life batteries without additional state regulations (M = 0.95). In the best-case scenario, M improves to 0.81, in the worst case it deteriorates to 1.98. All cases still have some buffers for unknown risk factors. One buffer is that a ratio of 1:1 is assumed here, i.e., refurbishment costs of 1000 euros also increase the residual value ($v_{1/2}$) by 1000 euros, which is a very conservative assumption [94]. An additional buffer is the duration of use of the battery in the individual applications/life cycles (given the construction of indicator M, a reduction in the overall duration of use has a negative effect, and an increase has a positive effect). However, if, for example, the first life cycle (use in the electric vehicle) is shortened and the second (use in the photovoltaic system) is extended, this can have an overall positive effect. This shows that there are possibilities to optimize the individual length of the life cycles if, for example, the property rights are clarified and the battery data can be monitored.

In addition, we have taken into account that the product engineering costs of the multi-life battery increase through frontloading (design-to-multi-life, see e.g., [95]) compared to design-to-purpose in the single lives. However, optimization potentials through modularisation have not yet been taken into account.

Therefore, the calculated cost savings are likely to be deemed by potential investors or established companies considering solid multi-life models to be too low for the risk involved. In addition, a multi-life approach also poses some challenges and additional work for companies which may make it difficult or impossible to move away from single-life batteries. Accordingly, we investigated whether the regulatory scenarios show a significant impact on the potential cost savings (see Figure 8).

Scenario 1 (a multi-life battery without state regulations) was chosen as the starting point. It is based on the above assumptions and is considered the actual scenario at the present time. That translates into a savings of 1000 euros over the total life cycle. Compared to the single-life applications, Scenario 2 assumes subsidies of multi-life technologies, regulatory frames for battery testing and refurbishment, modular design, and construction with standard power electronics as possible influencing factors, resulting in a savings potential for multi-life batteries of 3100 euros compared to single-life batteries. The effect is even greater in scenario 3 (additional material tax on critical elements, tax advantages for the purchase of second-life batteries), where a cost reduction of 4000 euros can be achieved. Scenario 4 shows a strong additional regulatory measure favoring the de-attractivisation of single-life products via additional taxes, leading to a saving potential of 4800 euros. If we assume-supplementary to scenario 4-no increase in costs for multi-life products due to regulatory measures, scenario 5 shows an impact of 30% resulting in a cost reduction of 10,100 euros.

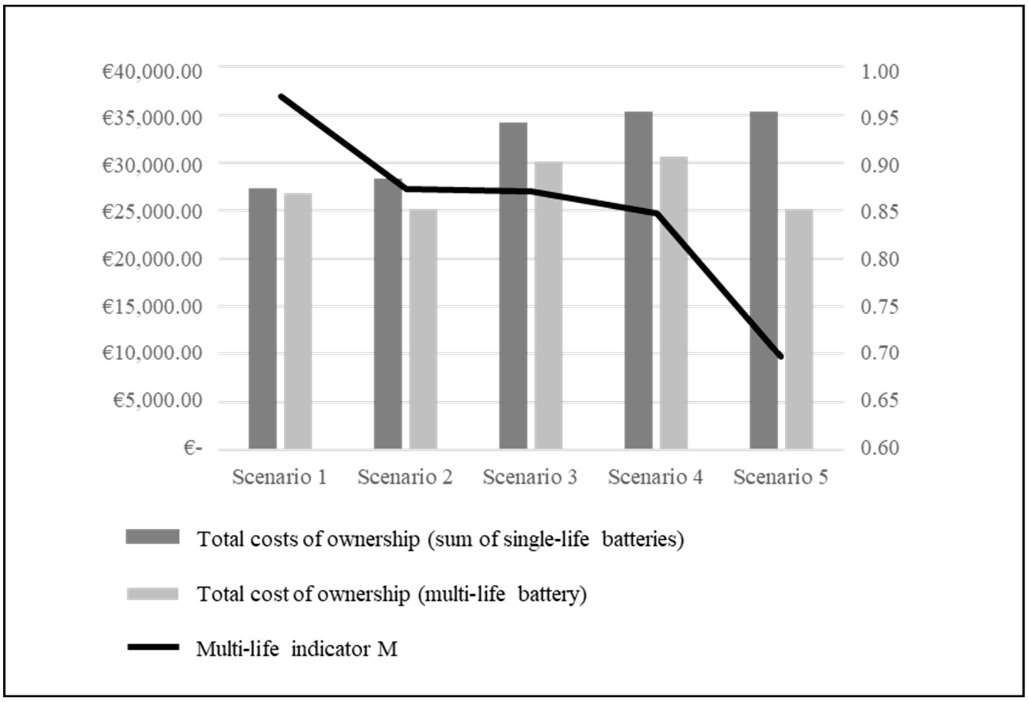

Figure 8. TCO development and multi-life indicator by regulatory scenario (own calculation).

The results show that, with the help of regulatory intervention, multi-life batteries can achieve an indicator M between 0.95 and 0.70 compared to single-life batteries, which is quite attractive from an economic point of view. In the example analyzed here, this means a maximum cost-saving potential over the duration of use of 10,100 euros. In the next section, we will discuss the management implications which follow from this.

5. Management Implications

The calculation of the minimum viable core of multi-life batteries already offers small economic potentials that justify regulations and will increase as a result of such regulations. If this minimum viable core is now improved and expanded, further potentials arise.

First of all, however, the question arises as to whether the additional profits generated (10,100 euros per vehicle) should be shared between the partners involved in the various life cycles or invested in R&D for new solutions, or used as a buffer to compensate for any price adjustments which have not been taken into account here.

An alternative use would be to reduce the purchase price at the beginning of the first life cycle (and then in all subsequent life cycles). If the prices of battery electric vehicles were reduced by, for example, 3500 euros per vehicle, this would result e.g., in the German market in an additional sales effect of more than 1 mil. vehicles between 2023 and 2030 alone based on a market model [39]. This additional effect leads to further economies of scale and thus makes the advantages of the multi-life models stronger. Multi-life products then generate self-enforcing mechanisms.

In addition, modularization potentials from frontloading in the product development process, i.e., from design-to-multi-life [95] are likely to be added.

6. Conclusions

In view of the economic potentials identified, the next step is to develop multiple business models [37] for multi-life applications via digital platforms and then examine the repercussions on the supply chain. Multiple business models are necessary, because the profitability of the first application will be influenced by the second and third applications [16]. This is not a simple matter, because companies often do not have certain capabilities or change their existing ones. In multiple business models, "different business models (with different business model cores) are interconnected and mutually reinforcing via an overarching business logic" [37], which enables a new form of synergy utilization. They are based on competitive strategies as decisions about the allocation of scarce resources to achieve competitive advantage and differ significantly from each other in terms of the value architecture, value proposition to customers, and profit model [96].

Thus, our study contributes to answering the research questions. First, we succeeded in finding a model for calculating the potentials of multi-life products and extending it accordingly. With our model, we are able to calculate the potential of multi-life products in general. We calculated these potentials using lithium-ion batteries as an example. This allowed us to answer our first research question and show that multi-life lithium-ion batteries have an economic potential [21–27]. We were also able to show that these potentials are particularly dependent on political conditions [28–31]. This also allowed us to answer our second research question. With the potential analysis, we can provide important information for the development of business models, showing precisely the external factors and policies and their influences on the pricing model of multi-life lithium-ion batteries [19,20,97,98].

Further economic potential is possible if the set of partners who develop multiple business models via digital platforms join together to form "structural ecosystems" as a particularly close form of value creation networks [61]. Such an ecosystem is defined as an "alignment structure of the multilateral set of partners that need to interact in order for a focal value chain to materialize" [61].

The analysis of economic potentials is thus the starting point for designing a blueprint of such an ecosystem with an overarching value proposition, operating model, and joint value creation through governance [36] based on the interplay of digitalization, modularization, and collaboration which forms the basis of multi-life platforms [65,99]. Two types of such ecosystems can be distinguished [100]:

1. Innovation ecosystems to create new complementary products and services on innovation platforms [17], e.g., through value-added use of exchanged data and/or
2. Transaction ecosystems with an exchange on "a multi-sided market-place" to re-use shared resources" (activities and assets) via transaction platforms, e.g., through in joint maintenance contracts for the various applications of the battery [17,100].

7. Limitation and Outlook

The model and the case study presented here show that there is a minimal viable core of a multi-life product which can be a starting point for new business models leading to both greater sustainability and higher economic value (see also [48]).

Limitations lie in the mechanisms of the model, which still needs to be modeled more in detail. For example, the product engineering process could be considered in more detail, and the advantages of modularisation could be taken into account [101]. The (positive) economic impact of the value stream from further vehicle use (e.g., as a used car) must be modeled as well. After that, a full, NVP-based impact, assessment is possible [81].

Moreover, some questions remain unanswered, e.g., How should suppliers in sustainable ecosystems be involved in the development of multi-life products? Is it better to reduce battery costs through multi-life applications or by scaling battery production? And therefore, can the EV value chain be extended through multi-life applications? Further, the questions arise: What is the best option to fill the battery pipeline before a 12 percent reduction in battery demand is achieved, if the critical battery materials are scarce [47]?

Who offers multiple life products-presumably not just one company, but several, but who then takes on the role of orchestrator in such an ecosystem [70]? How are the property rights over the multiple-life product distributed, i.e., are e.g., the batteries in the car leased [102]?

There is up to now also no systematic view on how business models in the circular economy must be structured [65], i.e., what the multiple business models already mentioned [37] must look like that. Furthermore, there is a need for further consideration of the multi-life ecosystems, which bind the partners together even more multilaterally and create additional economic potential through joint innovations or an intensive potential through joint innovations or an intensive exchange of resources and activities via platforms.

Therefore, future research should

1. Refine the present TCO model, including through a design -to-multi-life in product development,
2. Support the offering of multi-life products through multiple business models and
3. Drive the further development of the interaction of partners via platforms to an interaction in ecosystems, in order to be able to develop further economic potential.

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