batteries

Article

Understanding the Economics of Aged Traction Batteries: Market Value and Dynamics

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Abstract: The growing demand and market penetration of electric vehicles (EVs) have led to an expansion in the size of the market for used EVs, accompanied by a continuous increase in the return rate of aging battery systems. Consequently, a second-hand market for aged battery systems, known as second-life batteries, is slowly emerging. Understanding this market is crucial for enabling a functioning circular economy for batteries. This paper analyzes the market mechanisms influencing price formation for used goods, drawing parallels to the largest second-hand market, the used car market, and applies them to the second-life battery market. By examining these mechanisms, insights are provided into the dynamics of the second-life battery market, facilitating the development of strategies to optimize resource utilization and sustainability in the EV industry. Finally, the second-life battery price index is introduced, increasing the transparency of prices for lithium-ion batteries and the circular economy.

1. Introduction

The use of lithium-ion batteries (LIBs) in automotives and other applications such as stationary energy storage is steadily increasing [1,2]. An annual return volume of about 63 GWh of LIBs is expected to be available for recycling, reuse, and remanufacturing in 2030 [3]. With the increasing relevance of sustainability and rising return volumes in the future, a functioning circular economy for batteries is required. When an electric vehicle reaches the end of its life (its EOL), the traction battery can still have a high value and be suitable for other applications. A possible application for these batteries having reached the end of their first life is in stationary energy storage systems [4].

One of the several factors that determine the future of a battery system after it reaches its EOL is its remaining value and its corresponding market price compared to the cost of recycling and new batteries. Unfortunately, there is barely any information about second-life battery (SLB) prices available, as is evident by the many assumptions needed by Fischhaber et al. [5] to calculate the economic viability of second-life battery systems in different use cases. This lack of available information is emphasized by Frank et al. [6], who showed that different price expectations exist and that there is explicitly no common price understanding in the European market for SLBs. Another study by Wu et al. [7] suggests a leasing model to compensate for the asymmetry of information available to customers about SLBs and also outlines the recycling value as the lowest value possible for a battery system to have. Wu et al. [7] also discuss the specific price points at which SLBs are and are not viable and discuss their competition with new batteries, but are not able to give

concrete pricing data. This lack of information, the lack of transparency, and the lack of pricing data must be addressed in order to enable a functioning SLB market.

Since LIBs are publicly traded, their value and associated cost are influenced by several market factors. One of these factors is the value correlation between the used car market, with its electric vehicles (EVs) and the pricing of used batteries. The used EV market is an enormous market and contains a large volume of used LIBs as part of used EVs [3]. This paper uses the US used car market as an example due to its size of nearly 40 million vehicles traded in 2022 and the good availability of data on price developments [8]. By understanding the underlying mechanisms that influence the price of used LIBs, investors may be able to predict whether second-life applications are an economically viable business case in the future compared to new batteries.

We have divided this paper into four main sections: "Methodology" (Section 2), "Markets for used goods: electric vehicles and second-life batteries" (Section 3), "The second-life battery price index and future scenarios" (Section 4), and, finally, the "Conclusions" section (Section 5). The results provide an overview of the development of battery pricing for new batteries and used batteries, the cost of recycling, and the cost of the raw materials necessary for LIB production. The methodology is explained in the following section. The structure of this paper is shown in Figure 1.
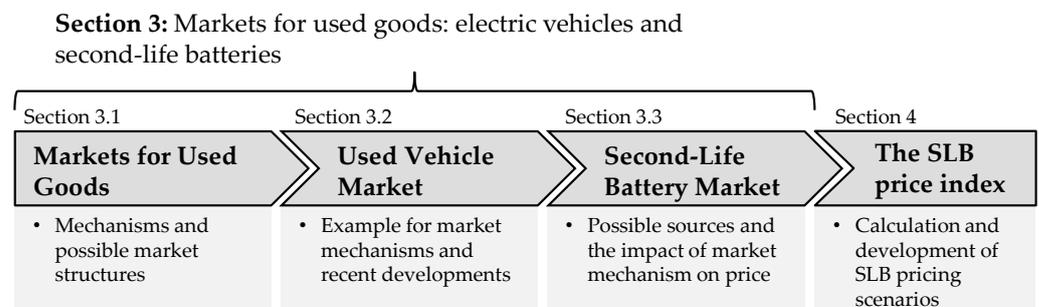
Section 3: Markets for used goods: electric vehicles and second-life batteries

Section 3.1	Section 3.2	Section 3.3	Section 4
Markets for Used Goods	**Used Vehicle Market**	**Second-Life Battery Market**	**The SLB price index**
• Mechanisms and possible market structures	• Example for market mechanisms and recent developments	• Possible sources and the impact of market mechanism on price	• Calculation and development of SLB pricing scenarios

Figure 1. The structure of this paper.

2. Methodology

The objective of this research was to track the price development of second-life batteries (SLBs). Therefore, this paper introduces the SLB price index. To provide a better understanding of the price development of SLBs, markets for used goods and their mechanisms, specifically the market for used EVs, were analyzed. As a result, the most important and common market mechanisms that influence a market for used goods and its price development were identified, explained, and interpreted. The example of the used car market was then used to validate these mechanisms and derive effects and influences on the market for SLBs. These results ultimately allowed us to make a comparison between the mechanisms impacting the pricing development of the used EV market and the SLB market.

After the main pricing mechanisms and their impacts had been identified, the SLB price index was introduced as an independent price indicator, which will be published quarterly by our research team in the future. The data for the SLB price index was collected by consulting the scientific literature and industry references, and through our cost calculations. The assumptions and sources used are presented and discussed in this paper. Finally, the findings of the SLB price index were used to derive and discuss four scenarios of future second-life and new battery price developments. These scenarios were used to contemplate the future potential of SLBs in comparison to new batteries.

3. Markets for Used Goods: Electric Vehicles and Second-Life Batteries

3.1. Markets for Used Goods

A market for used goods is subject to different effects and forces acting on it and impacting the price and quantity of the good traded during a certain period. As described by David Ricardo in 1817, a market price is formed by demand and supply and is impacted

by different mechanisms [9]. A few of these mechanisms and their impacts on demand, supply, and price will be covered in the following discussion.

One of the most significant market mechanisms is called "adverse selection", as outlined by Nobel laureate George A. Akerlof in his paper "The Market for Lemons" in 1970. Akerlof suggests that asymmetries of information between buyers and sellers regarding the quality of a traded good can lead to a reduced trading volume of the good and even trigger a complete market collapse. If a market equally consists of both good- and bad-quality goods that are non-distinguishable to the buyer, the average price paid for said goods by the buyer is fair and the market is in equilibrium. However, if the market is not evenly balanced (e.g., bad products are sold, good products are held), the buyer is not willing to pay the previously fair price. Consequently, sellers of good-quality goods must sell their goods underpriced and tend to retract their offers. By retracting their good-quality offers, they consequently further increase the percentage of bad-quality goods in the market even more [10].

Another influence on the pricing of goods in second-hand markets can be the psychological or emotional value of said goods. According to Ariely et al. [11] and Salem et al. [12], the price that a seller is willing to accept may be higher than that acceptable to the buyer due to the emotional value of the good. The emotional value attached to an object is based on personal experiences and can somewhat compensate the product's depreciation in price. The problem with a rising emotional value lies in its inequality between the seller and buyer. If the object has emotional value to the seller, and therefore the threshold price for which they are willing to sell it is increased, the object might not hold the same value to the buyer. In conclusion, potentially no agreement on a price can be found [11,12].

A relevant concept in a market for used goods is the distinction between the residual value and the resale value of an object. The residual value is the value an object is expected to have after a fixed term: for example, a car after a leasing period. This residual value is calculated before a contract is signed and does not change during the duration of the contract. On the market, this value can be used to calculate monthly lease payments, and typically, a car can be bought for its residual value plus additional fees by the driver at the end of a lease. The resale value of an object, however, is the original value of the object subtracted by the amount the price has depreciated since the object was bought. This value is determined by the market for the specific good and is therefore volatile and can be subject to periodic and aperiodic changes [13].

Next, the economic situation of the market participants and the market environment in general can impact a market for used goods. After a period of low and stable yearly inflation rates of less than 3% in the US between 2008 and 2020, the inflation rate rose to more than 6% in the years 2021 and 2022 [14]. According to Harvard Business Review, the main causes for this increase lie within the war in Ukraine and the resulting risen energy and food prices, shipping problems on the side of the supplier, and an increased demand for physical goods instead of services during and after the COVID-19 pandemic on the demand side [15]. As a reaction to the risen inflation, many central banks raised their interest rates [15,16]. Consumers seem to react to increased inflation and interest rates by postponing purchases or opting for cheaper versions of a desired product as an alternative [17]. One method of guiding a market in a desired direction can be through incentives or subsidies provided by a government. Such incentives can vary heavily by region and therefore create markets with different prices for the same good. While the impacts of incentives for new goods on the secondary market for the same good have not been fully discovered, some research concludes that incentives can increase the demand for a good, such as new electric vehicles, but are only one of many factors impacting a buyer's decision [18].

While the price of a good on a market is influenced mainly by the demand and supply, different participants can lead to a market behaving in different ways and having different market structures. While a Business-to-Consumer (B2C) market typically consists of many different buyers, contributing a small portion of the total market revenue, a Business-to-

Business (B2B) market typically consists of fewer buyers with therefore higher proportions of the total market revenue. B2B pricing is typically more individual and privately agreed upon between the buyer and seller due to the fewer but larger-volume transactions and the subsequently increased importance of each transaction [19]. The third possibility is a Customer-to-Customer (C2C) market, which can often be characterized by the traded good being second-hand and offered through E-commerce platforms. A C2C market is highly individualized, has low transaction costs, and can have problems with quality control or payment guarantees [20,21].

Beside the differences between private or commercial sellers and buyers, a market is also characterized by the market structure, which defines how a market is comprised. The four main market structures are initially defined by von Stackelberg as follows:

1. Perfect competition: The market consists of many different buyers and sellers and is open to new entries and exits. Both buyers and sellers have plenty of information on the good sold, and the price is purely determined by the supply and demand.
2. Monopolistic competition: A market with monopolistic competition consists of many buyers and sellers as well, but the products sold differ slightly from each other. These differences enable the seller to partly control the pricing of their goods, and therefore the price is not purely determined by the supply and demand but can be influenced by it.
3. Monopoly: A monopolistic market exists if there is only one seller in the market for a good and a potential buyer has no alternative sellers. In a monopolistic market, the pricing and supply can be controlled by the seller.
4. Oligopoly: This market is characterized by the supply being met by multiple but few sellers. These sellers can somewhat influence the pricing of their products but are still in competition with each other [22].

As indicated in the different market structures, substitutes can play a crucial role in market dynamics. A substitute (product B) for a specific product (product A) is considered as such if the demand for product B rises in correlation with an increase in price for product A. If this correlation is true, customers can switch from one option to the other and thereby impact the market. The typical characteristics for substitute products include them having the same or a similar use, providing the same or a similar performance, and having a comparable availability [23].

An important aspect of a buying decision for a customer is the comparison of a desired object to different alternatives. Depending on the desired good, various properties can be compared between options. A simple example is the rated output power of a vehicle, which tends to increase with the amount of money spent on the vehicle. How much money a desired amount of output power is worth to a customer is highly individual and dependent on factors such as the amount of money available to be spent, the desired use case for the vehicle, and more. Depending on the traded good, new and used goods can be compared regarding an identical property on the same scale of attractiveness and therefore compete with each other. While a customer who is willing to spend more money might go for the new product, a more price-conscious customer might go for the used alternative at lower costs [24].

The market mechanisms discussed above are illustrated below using the market for used vehicles as an example. These results are then utilized to explain the price developments of used internal combustion engine vehicles (ICEVs), EVs, and used batteries.

3.2. The Used Vehicle Market

The market for used vehicles consists of several sellers, like private sellers, franchised dealerships, and non-franchised dealerships, and is heavily dependent on the market for new vehicles [25]. The number of vehicles sold on the second-hand market in recent years in the US was nearly three times larger compared to the number of new vehicles sold (13.6 m new and 38.6 m used light vehicles sold in the US in 2022) [8]. One aspect that follows from the size of the used vehicle market is how well it can be documented and

how much information is available. To the consumer, several independent sources provide information on the variation in quality between different cars and revisions (new and used) and disclose adequate pricing and price development data. While the pricing of used vehicles can be influenced, especially in a C2C market, by the emotional value of the vehicles and other subjective factors, sufficient data can enable potential buyers to spot these pricing effects. This aspect makes the used car market close to a perfect competition according to the definition given earlier. In comparison, the EV market and the used EV market are much smaller, and are much more dominated by distinct players. This can be illustrated quantitatively, since the dominant EV manufacturer in 2023 in the US was Tesla with a market share of 55% [26]. The market for used electric vehicles thereby does not exhibit perfect competition and is currently closer to an oligopoly.

While the price for the average new vehicle in Q3 2023 plateaued at an all-time high of around USD 45,000, new electric vehicles were sold for a higher average price of around USD 55,000 [18]. The average duration a new vehicle took to sell was less than 40 days, while electric vehicles took more than 60 days to sell [27]. The development of this difference in the time taken to sell the vehicles is shown in Figure 2 and might be an indicator for a weakened demand for EVs. Factors that might be hampering the demand for EVs are uncertainty about the price development of EVs; increased interest rates, which lead to less capital spending [17]; and consumers preferring conventional vehicles due to lower prices and uncertainty with the development of the EV market. These reasons and their mechanisms will be covered in the following discussion.
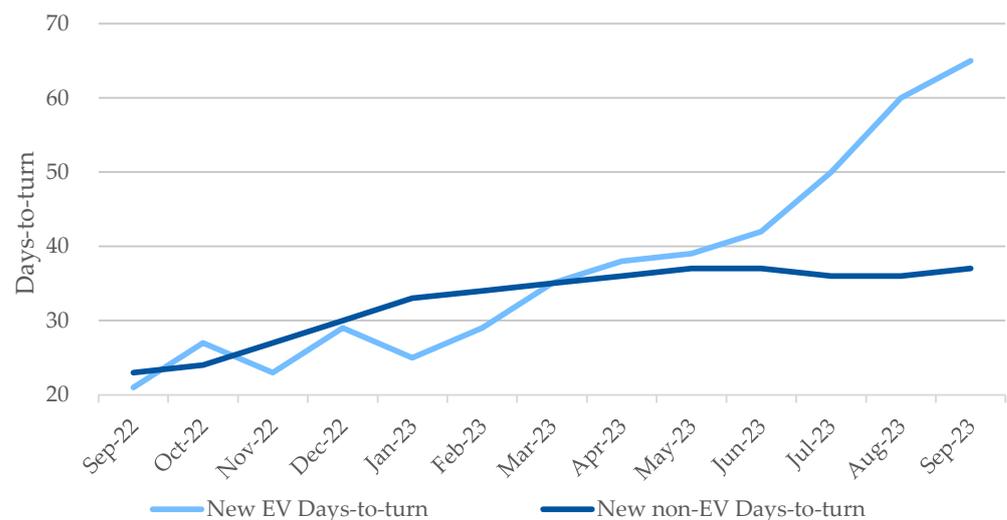

Figure 2. Days to turn for EVs and industry vehicles (based on Edmunds' analysis [27]).

3.2.1. Uncertainty Surrounding the Price Development of EVs

Figure 3 shows falling prices for three-year-old or newer EVs from September 2022 to September 2023, which might be another indicator for a weakened demand leading to reductions in price being necessary to stabilize the units being sold.

The demand for new EVs might be even more hampered by an increased loss in value, which is especially present in EVs. While a 2021 Tesla Model Y had an average trading price (ATP) of USD 66,637 in September 2022, its ATP fell to USD 40,522 in September 2023, which is the worst depreciation of all vehicles investigated [27]. One reason for the increased depreciation of EVs might be the incentives and tax exemptions in different markets and the dropping prices for new EVs. In the same period of September 2022 to September 2023, Tesla dropped the base price of its Model Y Performance vehicle by USD 15,500 to USD 54,490. Looking at a longer 3-year value development of used Teslas, Recurrent finds that they do not depreciate significantly more than comparable ICE vehicles [28].
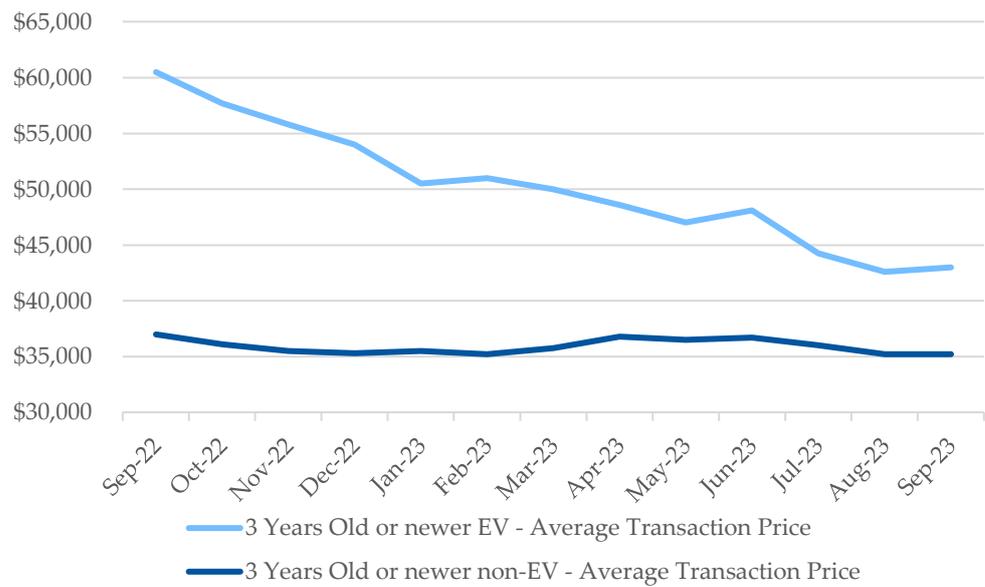
Figure 3. Price development of EVs and non-EVs (based on Edmunds' analysis [27]).

We attribute the reductions in pricing of the Tesla Model Y between 2022 and the end of 2023 to two factors: falling prices of the raw materials and increasing competition for EVs. The prices of raw materials needed for LIB production dropped significantly between January 2023 and September 2023. In order to put the price developments into perspective, we have plotted the depreciation of the 2021 "Model Y" as tracked by Edmunds [27], the development of the pricing of the newer "Model Y Performance", and the cost per kWh of the raw materials needed for a comparable NMC and LFP battery pack (Figure 4).
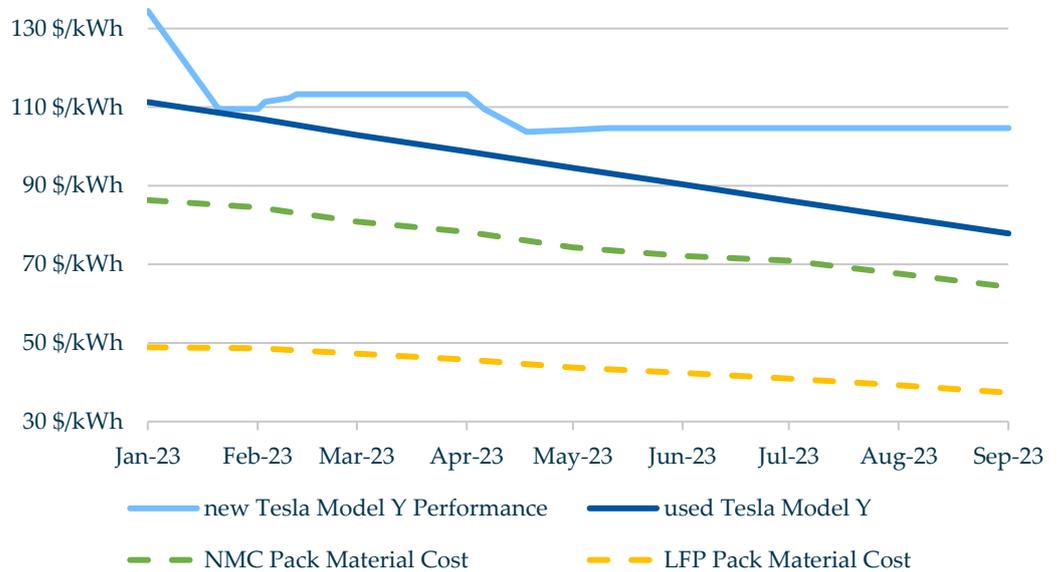

Figure 4. Price development of new and used Tesla Model Y vehicles (specific to the U.S.) and battery materials.

The development of the cost per kWh of the LFP and NMC battery pack is based on data about battery compositions in kg/kWh from Accardo et al. [29], Olivetti et al. [30], and Sun et al. [31], and the raw material prices in USD/kg were obtained from the price monitor of the German Mineral Resources Agency [32]. The pricing of the new and the used Tesla Model Y vehicle is divided by 78.1 kWh as its battery capacity, and it is assumed that the battery amounts to 15% of the vehicle's total cost [33]. The average cost per kWh

of the used Tesla Model Y followed the price development of the raw materials for LIB packs to some extent, as Figure 4 illustrates, and the price development of the new Model Y Performance shows a similar trend.

Another relevant factor besides the falling material prices might be the increased competition on the electric vehicle market introduced by manufacturers such as BYD. BYD sold over three million vehicles in 2023 (an increase of 61.9% YoY) compared to Tesla, who sold about 1.8 million vehicles (an increase of 38% YoY) in the same year [34,35]. The majority of both companies' new vehicles are sold in China. While Tesla remained the leader in terms of pure EV sales within 2023, 1.6 million of the 3 million vehicles sold by BYD were battery electric vehicles (BEVs). The last quarter of 2023 was the first time BYD sold more electric vehicles than any other manufacturer worldwide [36]. These facts highlight the increasing competition for new EVs in different markets.

3.2.2. Increased Interest Rates and Alternatives to EVs

Possible explanations for the weakened demand for used EVs and their recent increased depreciation described earlier might be that customers are opting for new EVs instead of used ones or going for cheaper ICEVs instead. A reason for customers to choose new instead of used EVs might be their similarity in price. The demand for electric vehicles correlates positively with fuel pricing according to Whitehead et al. [37], and ICEVs and EVs are therefore substitute products for each other, as described earlier. We consider the increased inflation and interest rates combined with the cheaper average pricing of ICEVs compared to EVs to be the main factors pushing consumers towards purchasing a conventional ICEV. Furthermore, the uncertainty of the resale value of a used EV compared to its residual value might be impairing the demand further.

3.2.3. Uncertainty about EVs and Their Future

The buying decision for an EV is positively impacted by environmental concerns and economic considerations, besides other factors like performance, government subsidies, and more [38]. Negative impacts on the purchasing decision include technological concerns associated with viewing EVs as an infant and dangerous technology [39]. One can therefore speculate that sales of EVs might still be held back by uncertainty about the technology, as well as about the longevity of EVs and their readiness level. What might be pushing consumers towards buying a new EV instead of a used one besides the economic factors are information asymmetries and uncertainty about the quality and longevity of used EVs [40]. Due to these concerns, it is necessary for policymakers and governments to uphold and create a legal framework to ensure a minimum quality for new and used EVs.

3.3. The Market for Second-Life Batteries

The pricing of SLBs from the used vehicle market is heavily dependent on the development of the second-hand vehicle market itself. Our analysis of this market suggests that the price development of used EVs is impacted by factors such as adverse selection and uncertainty about the development of raw material pricing, high interest rates, and an oversupply of new and increasingly cheaper EVs. Other main sources and impacts of the different market mechanisms for SLBs will be discussed as follows.

3.3.1. Second-Life Batteries and Their Potential Sources

Traction batteries are referred to as SLBs after being designated for repurposing. There is a multitude of origins for SLBs. The most common scenario discussed in the literature entails a traction battery from an EV reaching its EOL.

The EOL of a battery is mainly caused by two factors and is partially dependent on the property relations regarding the battery. An owner who is interested in maximizing the value of their traction battery along its whole life cycle is determined to retrieve the battery in the best state possible. This entails its state of health (SOH) and calendric age.

Besides the optimization of the life cycle value, warranty issues are also considered by vehicle manufacturers [41,42].

This reasoning does not apply to owners who are interested in maximizing the value of the battery in its vehicle application. In this case, the deteriorated performance of the battery mainly causes its EOL [43,44]. This behavior is amplified because the end user can barely check the proper SOH while the battery is being used in the vehicle [45]. The battery in this state might be suboptimal for a second-life application [41,42]. A huge variation in the SOH and therefore quality of the returning vehicles and their batteries has to be expected [45]. This aspect is further detailed in Section 4.5.

A battery reaching its EOL should be evaluated regarding its suitability for a second-life application. Additionally, EOL EV batteries might not be the most suitable category of SLBs for second-life applications. Even though a remaining capacity of 80 percent is often used as a criterion, there are doubts surrounding whether this might even be worth pursuing. In terms of battery aging, there are three possible reasons why this criterion must be re-evaluated and other EOL criteria should be proposed. Firstly, there is a high probability that a battery contains a remaining maximum capacity (SOH) higher than 80 percent after the vehicle has reached its common life span [46]. Secondly, scenario analyses suggest that a remaining capacity below 80 percent is sufficient for EV users to fulfill their typical distance requirements [47]. Lastly, some data suggest that the repurposing of the battery must be conducted far earlier than this criterion suggests in order to significantly decelerate cell aging [46].

This discussion illustrates that the vehicle's EOL is controversial despite being commonly considered as the major source of SLBs. Other sources for potential SLBs have not yet been sufficiently examined in the literature. Four other possible sources for SLBs are discussed in this paper, including Research and Development (R&D), recalls, production scraps, and accidents.

Traction batteries from R&D might be a suitable source for SLBs. In automotive R&D, vehicles and battery systems undergo several cycles to prove their compliance with common standards. Even if these batteries exhibit complete functionality, they will ultimately not be placed in an EV designated to be sold to a customer. A second-life application, however, might incorporate these batteries. In the best-case scenario, only cyclic aging effects have influences on these batteries. Calendric aging would not deteriorate the state of their health due to the short period of time between the R&D phase and the sale on the SLB market. R&D batteries can also stem from vehicles in the homologation process. These vehicles are either sold as used vehicles or discarded. In the second case, the batteries can be removed by vehicle recyclers and constitute a potential source of SLBs. Nevertheless, it is hard to predict the volumes of available R&D batteries. This stream highly depends on the OEMs' specific procedures and the variety of battery models in their portfolios.

There is another source of SLBs even before they enter a series vehicle. It is projected that in 2030, approximately 1750 to 1850 GWh of batteries will be manufactured in Europe [48,49]. A common assumption for the production scrap rate at the cell level in the literature is between 5 and 10 percent [50,51]. Therefore, 1575 to 1758 GWh of manufactured cells are assembled to make battery modules and packs. For this assembly process, a lower scrap rate can be expected since these steps are composed of fewer error-prone process steps. Therefore, we assume a production scrap rate of 0.5 to 1.5 percent, allocating a subset of 7.9 to 26.4 GWh of deficient modules and packs in the production line. Some of these units simply do not pass the quality assurance process and are therefore not authorized for installation in EVs. However, based on industry statements, many of these units are still suitable for second-life (SL) applications, but there is currently no evidence on the percentage of production scrap ultimately eligible for repurposing.

Another source of batteries for the SLB market could be recalls. While there were around 900,000 recalls in 2023 affecting BEVs or PHEVs according to our calculations, the majority of the recall cases identified could have been fixed through repairs, simple workshop adjustments, or software updates. However, for a portion of the total recalls,

a replacement of the traction battery is expected. The reasons for battery replacements are heterogeneous, ranging from monitoring issues, impurities, and leakages to thermal risks [52]. Whereas recalls appear as a potential source of SLBs, an evaluation of the recall cases suggests that this category must be treated diligently. In the majority of recall cases, in which the battery has caused the recall incident, the battery might not be in a justifiable state for repurposing. Standards like the DIN IEC 63330 define the types of adverse impacts on traction batteries that can occur during their use in a vehicle, prohibiting their second use [53]. The circumstances of the recall and the battery must be evaluated individually to determine whether any possible defects could influence the suitability of the battery for a second use-case.

Theoretically, even EV accidents might be another origin from which battery systems could become available for the SL market. This would be the case if vehicles were declared a total loss in the expert report, even though the battery system can still be used without risk. However, this scenario requires a clear evaluation of the battery's safety, for which more research is needed. Sourcing traction batteries that originate from vehicles that have been involved in accidents in order to repurpose them is an objectionable approach. Again, the DIN IEC 63330 currently excludes batteries from EVs that have been involved in an accident from being repurposed [53].

3.3.2. Implications of Market Mechanism for Second-Life Batteries

The first market mechanism discussed here is adverse selection and applies to both the market for used cars and the market for used batteries similarly. While on the used vehicle market, the seller can already have more information than the buyer, this effect is equal or even stronger for the used battery market since the testing of the battery remains reserved to the seller. Sharing the detailed results of the testing provides no significant advantage to the seller. However, the variation in SOH may require sellers to provide their respective customers with at least this value as a market differentiator.

For other effects, assessing the type of buyer and seller is crucial. The used vehicle market is commonly seen as a B2C and C2C market. The SLB market will prospectively be of a different kind. The handling of EOL batteries requires competencies and compliance with regulations, which an individual person cannot provide. This particularly applies to the disassembly of the battery system from the vehicle and the transportation of the battery system [54,55]. Therefore, the buyers of SLBs will mostly be integrators and it is unlikely that a private household would directly purchase EOL batteries. Hence, the SLB market is mostly a B2B market. This conveys implications for the effects of the emotional value. While there can be an emotional value attached to a vehicle, the same rationale does not apply to used SLBs. This stems from the different actors on the C2C used vehicle market in comparison to the SLB market and the different emotional attachments that can be formed by a user. There is also an analogy that strengthens this hypothesis. Battery swapping is a present concept in research. Therefore, car owners are willing to exchange their battery for another on a frequent basis if this represents an economical strategy. Apparently, there is therefore no emotional value attached to a traction battery that hinders this procedure from a user acceptance perspective.

The effects of the residual value in comparison to the resale value regarding SLBs is partly inherited from the used vehicle market. An SLB has a resale value that is determined by the respective sum that the battery is traded for. The residual value of the SLB requires more differentiation. The EV battery is a part of the vehicle, which is assigned a residual value at the beginning of a lease term. Therefore, the EV battery constitutes a significant part of the residual value. However, there is no particular residual value for a traction battery unless it is leased as a single component. In conclusion, the clear differentiation between residual and resale values cannot be evenly transferred to the SLB market.

Inflation and interest rates as well as government incentives can have a similar impact on SLB pricing as they have on used vehicle pricing. The characteristic of the used battery market consisting of mostly B2B transactions leads to a typically slower adaption

to changes, with buying and investing decisions usually being planned over a longer timespan compared to an individual customer. However, these effects are not specific to used batteries and inflation and interest rates do have an impact on the used battery market. While incentives for purchasing an electric vehicle have been far more prevalent in the past, to our knowledge there is no case in which purchasing SLBs instead of new batteries has been incentivized by a government authority. This can raise the question of whether such a measure might be necessary to expedite the commercialization of second-life applications.

While the used vehicle market is close to a market with perfect competition due to its diverse market structure, the SLB market is limited in the number of its actors. As laid out previously, there are only a small number of buyers and sellers on this market. Therefore, we anticipate that this market will be dominated by oligopolistic characteristics, which can influence the pricing dynamics differently.

As discussed earlier, the used vehicle market offers substitute products to customers. There is a potential choice between different types of vehicles, e.g., regarding their propulsion system (ICE, BEV, or PHEV). The interdependences between SLB pricing and the demand for new batteries are negligible according to our analysis. We do not expect SLBs to significantly substitute and have an impact on the pricing of new batteries. We do, however, consider new batteries as possible substitute products to SLBs, as explained in Section 4.

Popularity by choice is a dominant phenomenon on the used vehicle market and means that a buyer can prefer some good over another due to specific reasons. This effect is also present on the SLB market. The main reason to prefer one battery model over another is the level of its suitability to be repurposed and ultimately integrated into an SL application. This can be influenced by factors such as the battery geometry, expected battery longevity, cell chemistry, and more. Nevertheless, SLBs are still traded in small numbers [56], which severely restricts consumer choice and weakens this effect.

The preceding discussion contrasted the used vehicle market with the used battery market regarding the different market mechanisms and their impacts. Table 1 gives an overview of the different market mechanisms in these markets and to what extent these mechanisms apply. A full circle (●) indicates a high relevance of the mechanism, partially full circles indicate a partial relevance (◑ ◑ ◔), and an empty circle (○) indicates that the market is not impacted by the market mechanism. This assessment is based on our analysis of the markets and could change with future developments.

Table 1. Overview and relevance of market mechanisms for the pricing of used vehicles and used batteries in comparison.

Market Mechanism	Used Vehicle Market	Used Battery Market
Adverse selection	●	●
Emotional value	●	○
Residual vs. resale value	●	◑
Inflation and interest rates	●	◕
Government incentives	●	○
Market relationship	B2C, C2C	Mainly B2B
Market structure	Perfect competition	Oligopoly
Substitute products	●	◔
Popularity by choice	●	◑
Price transparency	●	◔

In conclusion, several of these mechanisms can lead to a low pricing transparency on the SLB market. A low supply and oligopolistic structures combined with limited infor-

mation on the product amplify information asymmetries. This may cause SLB prices to be significantly inflated. The level of standardization for the evaluation of SLBs, and especially the battery EOL after its use in a vehicle, to ensure a good and homogenous quality also currently poses challenges. Introducing common and fair standards for evaluating SLBs might be a solution to reduce informational deficits [57]. To mitigate this deficit, we are introducing the SLB price index to create price transparency for SLBs and enable their wider use and adoption (Section 4).

4. The Second-Life Battery Price Index and Future Scenarios

Considering the example of the adverse selection of Akerlof, it becomes clear that product transparency contributes to continuous and sustainable market growth, as the requirements and expectations of all business partners are stimulated. For this reason, the second-life battery price index (SLB price index) was developed as part of this research work. The SLB price index is intended to serve as a uniform and independent price indicator for the repurposing of traction batteries and will be published quarterly in the future under this term by our research team. The SLB price index includes market prices for different products and services such as new batteries (black), battery repurposing costs (red), current SLB prices (gold), and the recycling price (green) and raw material value (gray). The repurposing and SLB prices are calculated specifically for the European market, while the other values are applicable worldwide. As these indicators differ depending on product-specific criteria such as the system architecture or cell chemistry, the SLB price index is only valid for specific types of batteries. In this context, the SLB price index is presented in Figure 5 for NMC622/graphite SLBs and in Figure 6 for LFP/graphite SLBs, both on the battery pack level. The terms NMC622 and LFP describe the chemical composition of the cathode material of the respective battery cells ($LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$ and $LiFePO_4$) [58]. The sources of the data points shown in Figures 5 and 6 are discussed in the following sub-chapters.
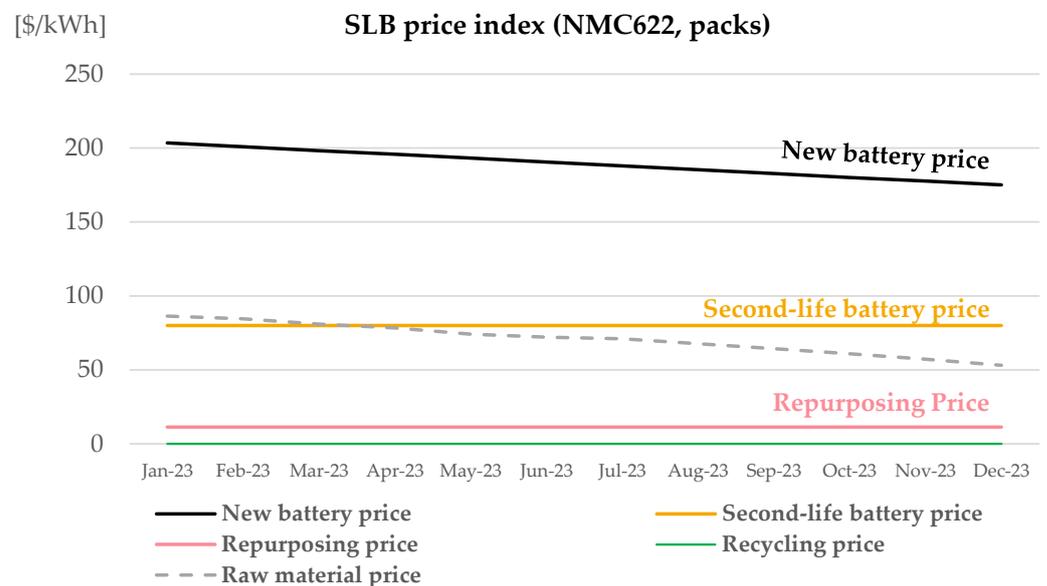

Figure 5. Second-life battery price index for lithium-ion battery packs (NMC622/graphite).
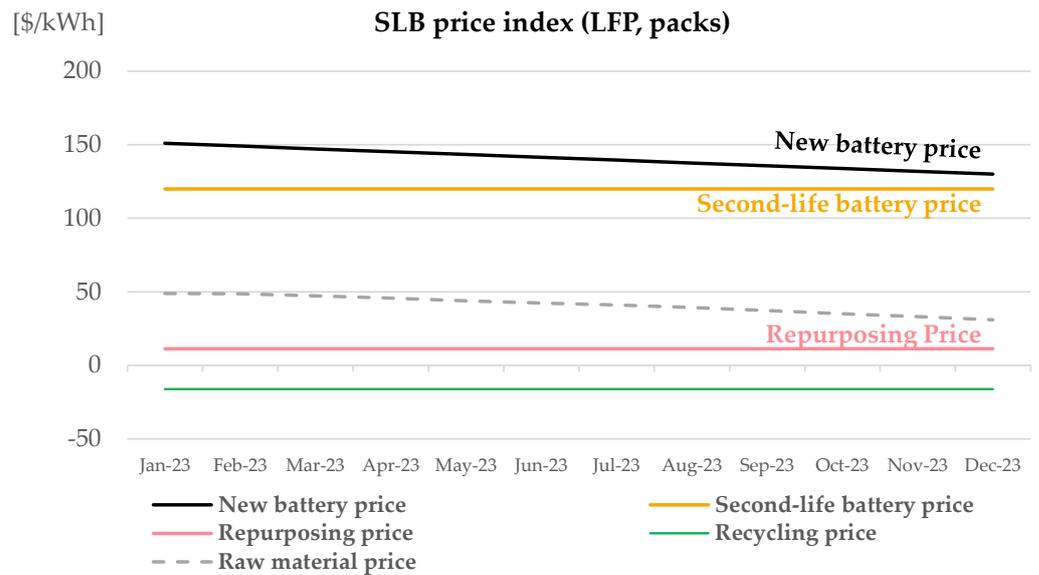
Figure 6. Second-life battery price index for lithium-ion battery packs (LFP/graphite).

4.1. Calculation of the Market Price for New Batteries

There is very limited information about market prices for new battery packs. The only well-known reference in this regard is the annual battery price survey from Bloomberg New Energy Finance (BNEF). This BNEF survey summarizes battery prices for various application areas and cell chemistries and calculates a volume-weighted average. According to this survey, battery prices decreased by over 82 percent between 2013 and 2023. However, major price decreases were realized between 2013 and 2020 (Figure 7).

Figure 7. Volume-weighted average lithium-ion battery pack prices from 2013 to 2023 in real 2023 US dollars (USD) (based on BNEF analysis) [59].

In detail, BNEF estimates a market price of about 130 USD/kWh for LFP battery packs and 95 USD/kWh for LFP cells in 2023. Also, BNEF finds LFP cells to be about 32 percent cheaper compared to their NMC counterpart, resulting in 140 USD/kWh for NMC cells. For the calculation of NMC pack prices, we assume that the costs of modules, peripherals, BMSs, and housing are the same for NMC and LFP battery packs, resulting in a cost difference of about USD 35/kWh between the cell and pack levels. Under this assumption, the price for NMC packs can be estimated to be about USD 175/kWh. For 2022, BNEF estimated battery pack prices to be about 14 percent higher compared to 2023, which

is mainly due to the high price level for the battery's raw materials falling significantly between 2022 and 2023 [59,60].

Generally, it must be noted that prices for NMC cells need to be calculated specifically based on individual NMC variants, e.g., NMC111, NMC622, or NMC811. Also, the BNEF estimation corresponds to a weighted average value from passenger cars, buses, commercial vehicles, and stationary storages. Due to lack of more accurate information for new battery pack prices, the SLB price index is currently based on the presented approximations for 2023.

4.2. Calculation of the Market Price for Second-Life Batteries

For the goal of approximating the average SLB market price for NMC622 SLBs, Circunomics GmbH provided accurate data points of their battery trading platform. In 2023, this platform actively traded over 280 MWh of SLBs in the European market. This corresponds to about 5600 battery systems when considering an average SLB capacity of about 50 kWh [3] (p. 12). For the representative SLB volume offered on the platform, an average SLB price of about 90 USD/kWh for NMC622 battery packs was calculated. For LFP, significantly higher prices are currently being charged on the European market, averaging at 120 USD/kWh. For both chemistries, there are also multiple offers on the module level, which can be summarized at an average of 107 USD/kWh.

One correlation that can be observed is that the prices for SLBs are significantly higher at the module level than at the pack level. This is very counterintuitive, since new batteries increase in market value based on their degree of assembly. However, it must be considered that aged traction batteries enter the second-life market as the result of a repurposing process. As battery repurposing on the module level includes additional processing steps such as battery disassembly and multiple transportation efforts, there are additional repurposing costs, which are finally reflected in the SLB module pricing. This is only one of the reasons why the repurposing price is also included in the SLB price index.

4.3. Calculation of the Repurposing Price

The repurposing price reflects the expected repurposing costs and profits for transferring aged traction batteries into second-life applications. Thus, the repurposing price represents marginal costs and therefore has a lower price limit for SLBs in the market. For estimating the price of repurposing traction batteries, the cost of transporting the batteries has been determined based on three independent industry offers in Germany. These offers included an average transport distance of 1000 km as well as costs for ADR-compliant transportation and packaging material with a total payload of 90 percent. Based on these data, transportation costs were calculated to be 200 USD/battery pack for every single transportation process. As we assume that battery packs must be transported at least twice (from the collection point to the repurposing entity and finally to the end customer), the transportation price was considered twice.

Next, the testing costs for SLBs were estimated to be about 200 USD/pack based on an EOL pack testing set-up using battery pack testing equipment made by Digatron Power Electronics GmbH and a dedicated 40-foot testing container from DENIOS SE. For the testing procedure, we considered mechanical, optical, electrical, BMS, performance, and safety tests, which are comparable to end-of-line tests in battery pack production. This is only an approximation and can differ significantly based on the testing set-up and equipment, especially since there is no standardized testing procedure for SLBs. In summary, the battery repurposing costs for SLBs were calculated to about 12 USD/kWh for SLB testing and transportation. A comparison of battery repurposing costs is shown in Figure 8.
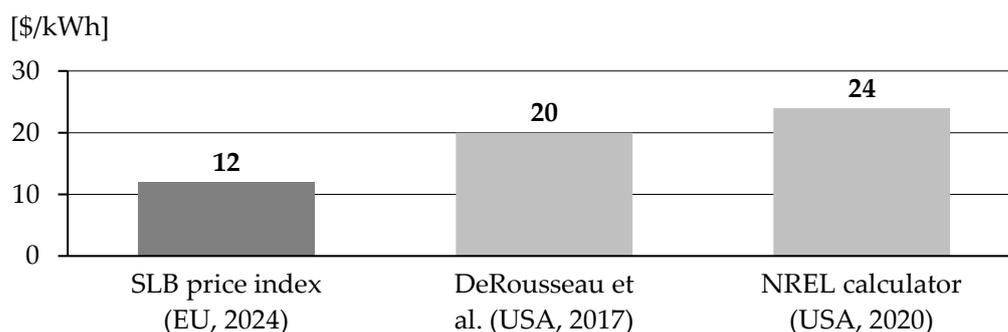
Figure 8. Comparison of battery repurposing costs estimated for different sources for SLB packs (sources: Derousseau et al. [61] (p. 1577) and NREL Battery Second-Use Repurposing Cost Calculator (b2u-calculator)).

The NREL calculator also refers to the repurposing of SLB modules. In terms of SLB module prices, the battery disassembly process is another relevant cost factor. Currently, the SLB price index mainly focuses on the SLB pack level, which means that no disassembly costs were considered at this point. Nevertheless, accurate data for battery disassembly are provided by Lander et al. [62] (p. 4).

4.4. Calculation of the Raw Material Value

The raw material value represents an indicator for battery material price fluctuations. This indicator is calculated based on representative battery material shares multiplied with material prices. Since material shares in battery packs can differ according to the active materials and system architecture, the SLB price index uses an average composition (Table 2) proposed by Accardo et al. [29] (p. 8), Sun et al. [31] (p. 1741), and Olivetti et al. [30] (p. 231).

Table 2. Material shares for LFP and NMC622 battery packs.

	Al	Cu	C	Ni	Mn	Co	Li
Share of material for LFP, [kg/kWh]	1.647 kg	0.878 kg	1.090 kg	-	-	-	0.500 kg
Share of material for NMC, [kg/kWh]	1.647 kg	0.878 kg	0.980 kg	0.641 kg	0.200 kg	0.214 kg	0.630 kg

For the material prices, the monthly price monitor from the German Mineral Resources Agency was used, which collects and uniforms data from different exchanges such as the Shanghai Metals Market (SMM), the London Metal Exchange (LME), and Fastmarkets. In conclusion, the SLB price index uses market summaries of exchange prices for individual battery materials such as lithium, manganese, cobalt, nickel, aluminum, graphite, and copper (Figure 9) [32].
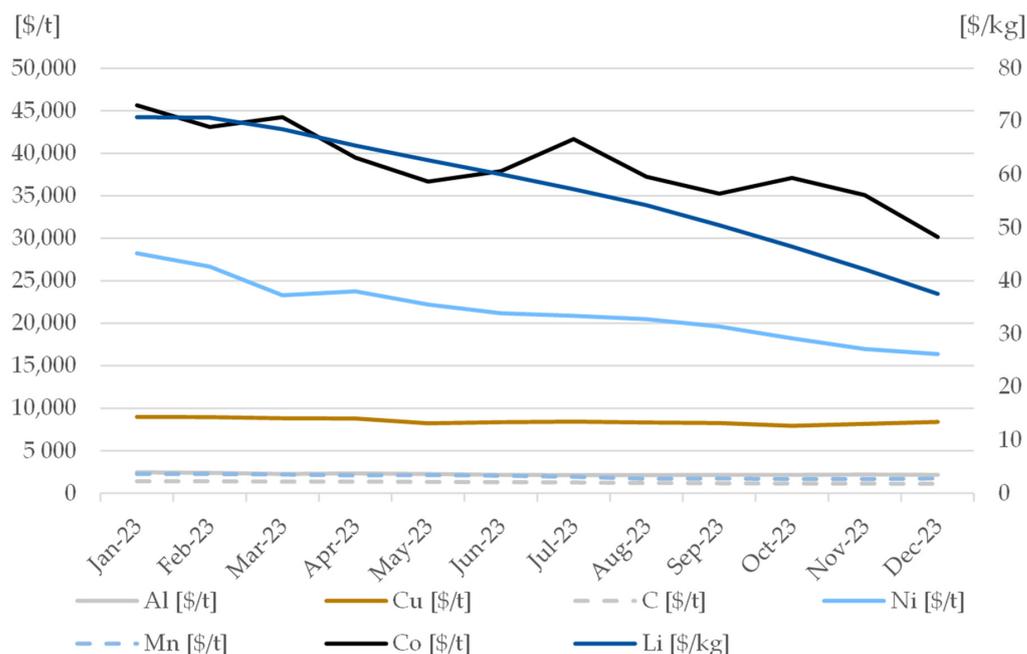
Figure 9. Prices for battery materials (based on price monitor data from the German Raw Materials Agency [32]; price monitor data are published monthly; lithium prices are based on the processed battery-grade lithium carbonate).

4.5. Calculation of the Recycling Price

In the case of battery repurposing, the recycling price is also a relevant factor since recycling costs could be transferred to the SLB operator, regardless of whether the effects of this are positive or negative. For example, when battery recycling reaches a techno-economically viable state, battery owners will be paid for their EOL batteries. In the case of battery repurposing with an associated change of ownership, the recycling fee will be factored into the price for the SLBs.

Unfortunately, there is no uniform recycling price in Europe. From our discussions with the European battery recycling industry, we can summarize that, on the one hand, the active materials naturally have the greatest influence on the recycling price and must therefore also be considered specifically in the SLB price index (especially for NMC and LFP). On the other hand, further aspects such as hydrometallurgical processing, recycling efficiencies, and the resale of the materials are key price factors for recyclers. The latter is in turn dependent on the dynamic material pricing. As a result, in some cases recyclers must charge for their services, while in other cases they can offer battery recycling free of charge, i.e., without an additional fee but also without remuneration for EOL batteries.

The presented correlation is also confirmed by other research. The recycling cost model presented by the Argonne National Laboratory [63] (p. 29) shows that NMC622 and NMC811 as well as NCA batteries are recycled without additional fees. Thus, it can be concluded that no major effect on SLB pricing is present. In contrast, the recycling of LMO and LFP batteries carries additional charges of 1 USD/kg (LMO) and 2 USD/kg (LFP), respectively, which could have a negative effect on SLB pricing. In future, the SLB price index will track the development of recycling prices for this discussed purpose.

4.6. Scenario Analysis for the SLB Price Index

This research paper constitutes the first publication of the SLB price index. It is noticeable that retrospective collection of reliable data points is very challenging, especially for costs and prices within the highly dynamic battery industry. For this reason, only a snapshot of the price indicators can be taken at this time for the time interval studied in this research (2023). With the upcoming quarterly publications, we will depict a historical

market trend and ideally create more transparency in this market. However, it is still possible to provide an outlook and discuss potential scenarios for the SLB market.

Considering the price development for new and second-life batteries, there are nine theoretical scenarios, each representing a price increase, stagnation, and decline. However, only certain scenarios are likely, which we will discuss. The scenarios for the price development of new batteries can be limited to a price drop or stagnation. This is because continuous price reductions for LIBs have been observed over the past 30 years. At the same time, new battery technologies are entering the market for traction applications, which can at least be expected to lead to further price reductions. Overall, a price increase is considered to be highly unlikely. For SLB pricing, a continuous price increase can also be excluded. Therefore, it can be assumed that the current SLB market price is a local peak in Europe, as the market is still very young, resulting in various price-increasing effects. These effects are explained in the following sub-chapters. In this context, potential price scenarios can be summarized as presented in Figure 10.
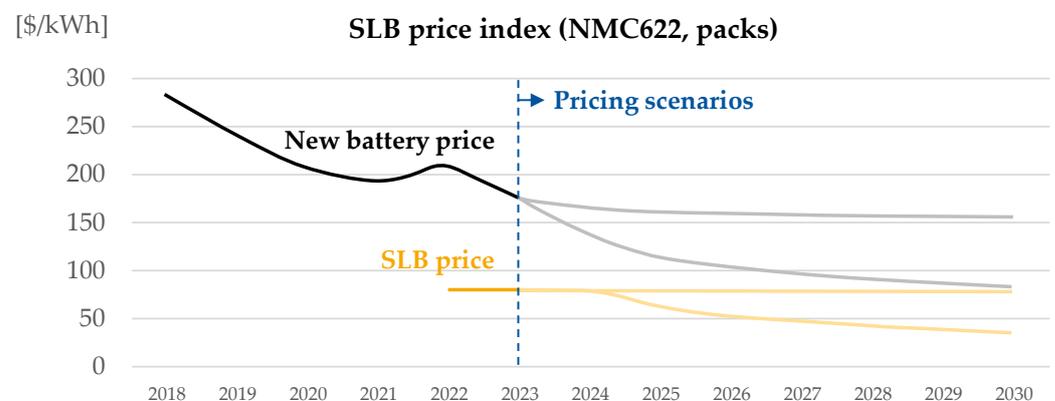

Figure 10. Overview of potential price development scenarios for new and second-life batteries.

4.6.1. Appropriate Market Share of SLBs (Scenario 1: The Most Likely Scenario)

Decreasing prices for both new and aged battery systems could result in an appropriate market share for SLBs. In recent years, product and process innovations have already led to significant cost reductions for new batteries. Thus, the market integration of alternative battery technologies that are not based on lithium (e.g., sodium-ion batteries) or require less cost-intensive materials such as nickel or cobalt (e.g., sulfur) could lead to further price reductions for new batteries due to the reduced dependence on material-specific market dynamics and supply bottlenecks. Furthermore, it can be assumed that the innovation of battery technology still has huge potential, considering expected innovations in LIB cell chemistries and system architectures [64]. Hereby, it must be considered that SLBs benefit from product and process innovations just as new batteries do, but with a corresponding time delay. In a larger time frame, this aspect increases the likelihood of this scenario. In a shorter period (up to 5 years), a significant price reduction for SLBs can be assumed due to increasing standardization in the areas of testing and liability. As a result, companies are encouraged to focus on battery repurposing and SLB prices will decrease as soon as a functioning repurposing supply chain is established. As a result, this concept could be adopted and further improved by other market participants in a blueprint-like manner, leading to reduced repurposing costs and again to lower SLB market prices in near future.

Nevertheless, the most important aspect of SLB cost reduction remains to increase market transparency, according to the results discussed in Section 3.3. The inhomogeneous availability of information on the SLB market regarding battery quality and pricing is currently leading to a significantly inflated market price. Based on these correlations, we believe that prices for new batteries and SLBs will fall in upcoming years, as presented in Figure 11.
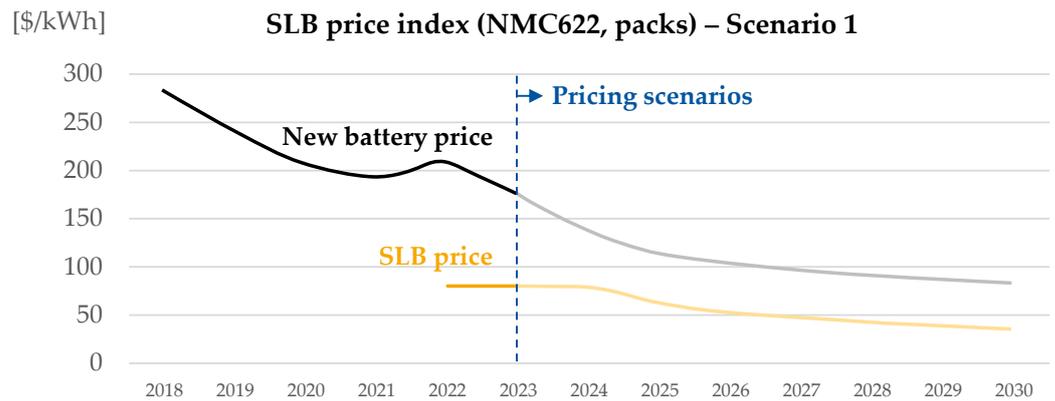
Figure 11. Decreasing market prices for new and second-life batteries (Scenario 1: appropriate market share of second-life batteries).

4.6.2. Best-Case Scenario for SLBs (Scenario 2: The Likely Scenario)

In 2022, prices for new battery packs were about 16 percent higher compared to those in 2023, which was mainly caused by exponentially rising material prices for lithium and nickel. Today, battery material prices have reached a healthy market price again. However, due to political constraints and civil disturbances, price fluctuations may occur again at any time, especially considering the persistently high dependency on the material supply chain in Asia. As a result, stagnation in prices for new batteries could be a possible scenario in the short to medium term. In contrast, prices for SLBs are mostly independent of the price dynamics for materials and could therefore profit from the expected potential price reductions, like in the first scenario. This scenario is represented in Figure 12.
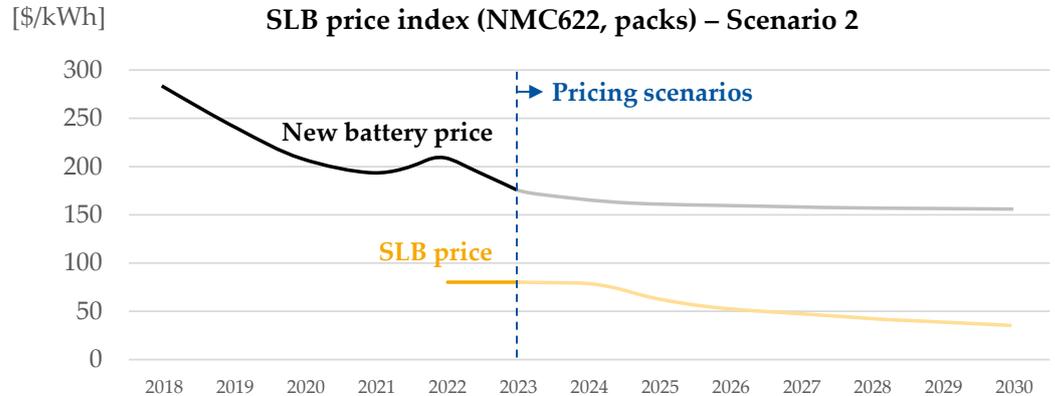

Figure 12. Stagnating market prices for new batteries and decreasing prices for second-life batteries (Scenario 2—best-case scenario for second-life batteries).

4.6.3. Limited Market Penetration of SLBs (Scenario 3: The Less Likely Scenario)

This scenario is characterized by stagnating prices both for new batteries and for SLBs. We believe this scenario to be very unlikely since the market for LIBs still offers a lot of potential for innovation that would lead to overall price reductions for both new batteries and SLBs. Stagnating prices could potentially occur in the short term if the time to market for such innovation is longer than experts assume. Overall, this scenario would lead to a lower market penetration of SLBs compared to Scenario 2, as the profitability of a second-life business case becomes less likely. Nevertheless, the relevance of this scenario (Figure 13) over a larger timeframe is questionable due to the aspects explained above.
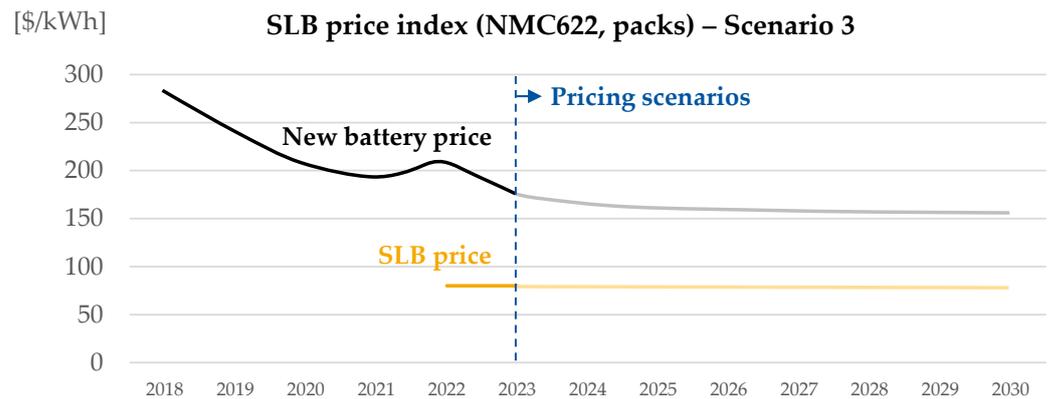
SLB price index (NMC622, packs) – Scenario 3

[$/kWh]

New battery price

Pricing scenarios

SLB price

Figure 13. Stagnating market prices for new and second-life batteries (Scenario 3—limited market penetration of second-life batteries).

4.6.4. Worst-Case Scenario for SLBs (Scenario 4: The Unlikely Scenario)

The combination of decreasing market prices for new batteries and stagnating SLB prices represents one of the most feared challenges for battery repurposing in the long term. This is due to the resulting cost pressure of new batteries as they represent a substitution product for SLBs. As a consequence of the time lag between the production of a new battery system and the return of an SLB, the former benefit from process and product innovations and thus realize cost potentials much earlier. However, it must be considered that SLB prices also have significant reduction potential, as explained in the first scenarios. We also believe that EU market prices are currently very high due to a lack of transparency and because SLBs could be offered at significantly lower prices. The question remains as to how quickly such price reductions can be realized, because the smaller the price difference between new batteries and SLBs, the more challenging it will be for the SLB market to remain competitive. However, compared to the price development scenarios shown, we consider this scenario to be the least likely, especially because SLB prices will be aligned with those of new battery systems in the future as market transparency increases. The discussed scenario is shown in Figure 14.
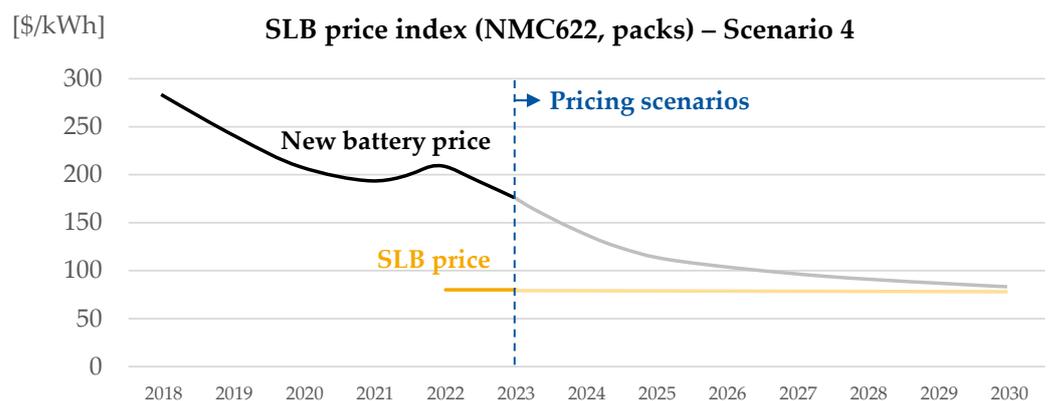
SLB price index (NMC622, packs) – Scenario 4

[$/kWh]

New battery price

Pricing scenarios

SLB price

Figure 14. Decreasing market prices for new batteries and price stagnation for second-life batteries (Scenario 4—the worst-case scenario for second-life batteries).

5. Influencing Factors for Second-Life Battery Pricing

In previous chapters, the SLB price index and associated price indicators were introduced. At this point, it must be considered that the SLB price index indicates the average market price for battery systems with defined characteristics. In contrast to new products, where manufacturing tolerances and regular quality control checks ensure a minimum specified product quality, it is common in the used goods market for product quality to vary significantly. For SLBs, this context is even more important as the ways in which they

are used in EVs co-determine their functionality in subsequent second-life applications. Thus, SLB prices are subject to wide fluctuations in product quality. The remaining battery functionality can partly be expressed by the SOH, which is why this parameter also represents an SLB price factor.

There are also numerous battery system architectures and cell chemistries, which make it difficult to provide a standardized price for SLBs. In consequence, certain SLBs are better suited for conversion to a second-life application than others. The reasons for this could be the dimensions of the pack, the operational limitations in EV applications, or explicit second-life operating modes in the BMS. Although batteries do not have an emotional value like some vehicles do, these aspects still lead to a popularity factor. SLBs with higher popularity can be offered on the market for prices above the average value, as there is a higher demand. At the same time, the availability of SLBs remains a huge pricing factor as stationary energy storage systems are generally designed with batteries of homogeneous quality.

6. Conclusions

Based on studies of the market for used goods, our subsequent analyses of used vehicles and used batteries, and our introduction of the price index, we would like to summarize and conclude the following aspects of this work:

- Our comparison of the used car market and the market for used batteries shows that the market mechanisms that apply to the used car market only partially apply to the pricing of SLBs. The main differences are (1) the business model (B2C and B2C models for used vehicles; a B2B model for used batteries); (2) the market structure (perfect competition for used vehicles; oligopoly for used batteries); and (3) the current lack of price transparency for used batteries. For SLB pricing, it should be noted that the aspects of "government incentives" and "emotional value" do not apply.
- To counteract the lack of price transparency for SLBs, the second-life battery price index was introduced in this study. This index acts as a price indicator for different SLBs and compares them with the price of new batteries as well as considering the repurposing price and recycling price. In future, this index will illustrate historical pricing and thereby act as a tool for market predictions and strategic decisions. Therefore, it will be published by our research team at regular intervals.
- Given the relatively low costs for repurposing and recycling SLBs, the current market offers significant profit potential for stakeholders. Conversely, failing to make functional SLBs available on the market will result in high opportunity costs for battery owners.
- Based on the scenarios presented in Section 4.5, competition between new batteries and SLBs cannot be excluded in general. However, it should be noted that SLBs benefit from the same cost reduction potential as new batteries, but with a delay in time. Ultimately, this means that price competition is only a temporary market effect that will balance itself out over a longer period.
- Despite the price indication derived from the SLB price index, product-specific price volatility due to deviating product qualities cannot be avoided. The SOH is an important parameter for correcting the average price of SLBs in the market towards more realistic prices.

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