// BATTERY AGING IN PRACTCE

Battery aging in practice: Analysis of over 7,000 vehicles provide deep insights into battery life and vehicle residual value

The results of the analysis show significantly less aging than anticipated and provide a positive outlook for the continued use of batteries.

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Table of contents

Introduction and motivation

Basics and definitions of terms

Results and interpretation

Summary and contact

1. Press articles and social media shape the perception of a high residual value loss of electric cars due to battery aging.

In recent months, numerous newspaper articles and social media posts have raised concerns about the accelerated aging of batteries in electric vehicles (EVs). Used EVs have been described as "lying on the shelves like lead", claiming that the rapid aging of the battery significantly reduces its range. This reduced range substantially limits the practicability of the vehicle, leading many consumers to view used electric vehicles as unusable.

The critical reporting and the general decline in demand for EVs have led potential buyers to increasingly question the risk of a total economic loss of electric vehicles. Since the battery accounts for a significant 20% to 30%[1] of an EV's cost, its aging has a major impact on the residual value of the vehicle. Consumers want to know if batteries in EVs often need premature replacement and the potential financial consequences this would entail.

This study examines the question of how stable the capacities of batteries in electric vehicles are, and if concerns regarding premature aging are justified.

"EVs at a mega loss - these electric cars are now bargains"

„E-Autos mit mega Verlust - diese Stromer sind jetzt Schnäppchen"

-Focus Online-

"Residual value of EVs: The current generation of e-cars follows the logic of an economic total loss"

„Restwert von E-Autos: Die aktuelle E-Auto-Generation folgt der Logik eines wirtschaftlichem Totalschadens"

-MSN-

"Demand is zero: used EVs are not selling"

„Nachfrage gleich Null: Gebrauchte E-Autos verkaufen sich nicht"

-Tagesschau.de-

"Why the battery status of electric cars is often a mystery"

„Warum der Akkuzustand beim E-Auto oft für Rätsel sorgt"

-Tagesschau.de-

1) The exact share of battery costs in the total price of an electric vehicle can vary greatly, depending on factors such as vehicle type, vehicle class, cell chemistry and battery capacity.

2. Fact-based education is the key to electromobility success.

Electromobility plays a vital role in combating climate change by significantly reducing greenhouse gas emissions. However, this transition also presents several challenges. Aside from high production costs, understanding the specific benefits and drawbacks of this emerging technology compared to traditional drive systems remains a key hurdle. Thoroughly educating consumers is essential to address misconceptions, particularly about electromobility and battery life. Misinformation can hinder the adoption of electric vehicles by amplifying unfounded fears, which reduces social acceptance and market growth. Providing accurate and transparent data is critical to create a realistic understanding of battery performance and building consumer trust in electric vehicles. This study aims to clear up misunderstandings and empowering consumers to make informed purchasing decisions based on reliable information.

Summary of the results: Electric vehicle batteries have a long service life - even with intensive use.

The analysis indicates that electric vehicle batteries used for high mileages exceeding 200,000 kilometers have a remarkable service life. Most batteries retain over 80% of their original capacity in the long term, remaining reliable well beyond the standard warranty periods. Advances in cell chemistry and optimized battery management systems also enhance performance, leading to longer service lives.

While factors such as vehicle type and usage patterns can influence battery aging, its economic value is retained even in heavily used vehicles. Once removed from the vehicle, the batteries can be used as stationary energy storage solutions. Additionally, critical raw materials such as lithium and nickel can be removed through recycling, ensuring long-term value and sustainability.

3. The longevity of batteries is determined by their residual capacity.

Batteries naturally lose capacity and efficiency over time and with use, a process referred to as calendar aging (time-related) and cyclical aging (usage-related). Calendar aging occurs as chemical structures within the battery cells change over time, even without active use. Cyclical aging results from the stress of repeated charging and discharging cycles. Together, these processes degrade the battery's state-of-health, negatively affecting both its energy storage capacity and overall performance.

Explanation of the "State-of-Health" (SoH)

The state of health (SoH) is a key figure that reflects the degree of battery aging. In its new state, a battery’s SoH is 100%. There is currently no universally accepted or standardized definition for the state of health in industry and science. Manufacturers and sectors pursue different goals and use varying calculation methods, which can explain this variation. For example, some vehicle manufacturers prioritize maximizing the initial range of their electric vehicles, accepting a later reduction due to battery aging (small buffer, see next page). Others rely on a large buffer, which limits the initial range but compensates for aging, ensuring a more constant range over the vehicle’s lifespan. These strategies can even vary within a manufacturer's model range. Therefore, there are currently no uniform standards or norms for defining SoH.

This study uses a simple definition of SoH, which refers exclusively to battery capacity. Other factors such as the internal resistance or the charging and discharging history are not taken into account.

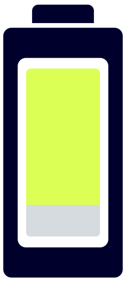
This results in the following formula for calculating the SoH:

$$\text{SoH} = \frac{\text{Capacity}_{\text{Current}}}{\text{Capacity}_{\text{New}}}$$

4. Understanding residual capacity – the meaning of gross and net capacity.

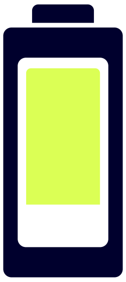
When determining the SoH, it is important to clearly distinguish between gross and net capacity. A uniform understanding prevents misunderstandings and ensures the comparability of information across different manufacturers and testing providers. This enables a clear assessment of the battery condition and provides reliable insights into the energy available for everyday use.

Gross capacity



- Gross capacity describes the amount of energy installed in a battery.
- Part of this capacity is designed as a "buffer" to protect the battery from overloading and deep discharges.
- Some vehicle manufacturers use this buffer to compensate for the effects of aging.
- The buffer is inaccessible to the user and cannot be factored into range calculations.
- The gross capacity is less relevant for determining the SoH, as it represents the total capacity rather than the usable capacity available to the consumer.

Net capacity



- Net capacity refers to the usable portion of the battery. This describes the amount of energy that is available to the consumer under ideal conditions.
- The buffer is excluded in the net capacity.
- The net capacity of a new battery corresponds to a SoH of 100%.

Net capacity

Buffer

5. Capacity deviations in practice.

In everyday use, differences in available capacity and range of the vehicle can occur independently of the aged battery. External factors such as temperature, driving habits, and charging behavior influence the amount of energy the battery can use. The battery achieves greater electrochemical efficiency at optimal temperatures between 20 and 25°C. However, this thermodynamic effect is imperceptible to the driver without specific measurement methods. It is important to emphasize that this does not refer to the effect of reduced range due to increased energy consumption for heating in winter. While the energy is still considered available, it is used to heat the vehicle, leading to a noticeable decrease in range.

Capacity deviations can also be influenced by the emergency reserve. This represents the difference between the displayed remaining capacity and the actual net capacity available. Even if the vehicle displays 0% charge, a small part of the net capacity is still available to cover a short distance, such as to the next charging station. The size of this emergency reserve varies by manufacturer's strategy, leading to significantly different ranges at low charge levels.

6. Independent residual capacity tests for SoH evaluation.

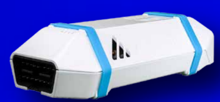
The aim of this study is to answer the question: “How severe is the battery aging in real world conditions?” To achieve this, two steps were taken in the study. The first step involved 50 vehicles from the P3 electric vehicle fleet to investigate battery aging. The study considered the driving and charging behaviors of the vehicle owners to capture the variations between usage and manufactures.

In the second phase of this study, Aviloo, a leader in battery diagnostics with more than 60,000 capacity tests conducted, contributed data from over 7,000 vehicles with up to 300,000 kilometers of mileage. Using their highly accurate premium test (Fig. 1), Aviloo enabled a detailed quantitative analysis of battery aging in relation to mileage, further enriching P3’s database.

Previous estimates of battery aging, such as the P3 SoH model, relied on academic and laboratory data[2)]. These also typically reviewed individual cells rather than complete battery packs or vehicles. However, in this study the data is based on real vehicle data accounting for all external influences. The data also depicts various battery management systems and the associated aging strategies of the vehicle manufacturers. The study provides a robust baseline for understanding the actual aging process of EV batteries.

This is how a SoH test with Aviloo works:

1. The user connects the AVILOO Box to the vehicle's OBD interface and drives the vehicle until the battery is discharged from 100% to 10%.
2. While driving, the AVILOO Box continuously collects battery-relevant data and transmits it to the AVILOO servers in real time.
3. The AVILOO servers validate and analyze the collected data, including adjustments for compensation factors for temperature and discharge rates.
4. The state of health (SoH) of a battery is expressed as a percentage and is calculated by comparing the current extractable energy to the energy available when the battery was new.
5. The user is provided with a battery certificate that includes the currently available capacity in kilowatt-hours (kWh) and the state of health (SoH) value expressed as a percentage.



AVILOO-Box, which is connected to the OBD interface of vehicles.

2) The P3 SoH model for estimating aging is based on literature values and models two-stage linear aging. Studies that have been used to assess battery aging include: Impact of Dynamic Driving Loads and Regenerative Braking on the Aging of Lithium-Ion Batteries in Electric Vehicles, Journal of The Electrochemical Society, 164(A3081); Ali, H., Beltran, H., Lindsey, N. J., & Pecht, M. (2020). Assessment of the Calendar Aging of Lithium-Ion Batteries for Long-Term Space Missions. Timilsina, L. et al. (2022). Battery Degradation in Electric and Hybrid Electric Vehicles: A Survey Study. Clemson University; Keil, P., & Jossen, A. (2017).

7. Field data shows significantly slower aging than previously assumed.

The study reveals that the capacity degradation of the battery accelerates in the first 30,000 kilometers, but then stabilizes and progresses almost linearly. The observed aging process confirms that the degradation in the later usage phases is significantly lower than in the initial phase.

A key factor behind the initial capacity loss is the formation of the SEI layer (solid electrolyte interphase) on the anode during the first charging and discharging cycles. During the formation of this layer, lithium is "consumed" or converted into degradation products, reducing the amount available for energy storage. After the SEI layer has stabilized, this capacity loss slows down significantly.

While the data shows a considerable variation, a clear trend emerges: the majority of the measured batteries are above 80% SoH, even after more than 200,000 km. Regression analysis confirms that the SoH remains stable even at high mileages of 200,000 to 300,000 kilometers showcasing the impressing longevity of modern batteries.

The P3 fleet data is based on intensively used 3–5-year-old vehicles, providing additional insights into real-world usage conditions and capacity losses. These data points show the SoH of P3 vehicles and Aviloo's data matching, illustrating a significantly better service life compared to theoretical models.

Nearly all tested P3 vehicles show a SoH above 90%, indicating that the batteries in the P3 fleet maintain excellent performance despite coming from different manufacturers, being used in varying ways, and undergoing heavy usage.

Previous aging models, such as the P3 SoH model, are primarily based on measurements of battery cell aging conducted in laboratory settings. It has been observed that these models tend to provide a much more pessimistic estimate of degradation. However, field data indicate that, under real-world conditions, vehicles (especially those with high mileage) retain their actual capacity for a longer period.

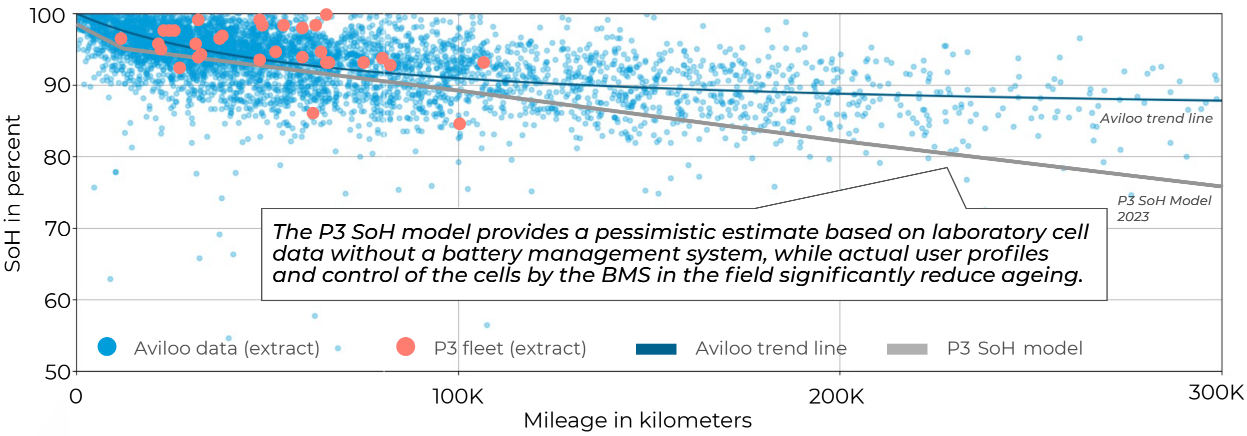


Fig. 1: SoH vs mileage for EVs with batteries >30 kWh.

8. Different usage patterns lead to variability in the field data.

The data analysis highlights considerable variability in SoH values for similar ranges. This variation arises from multiple influencing factors, including charging habits and usage patterns (see next page). In addition, car manufacturers place varying degrees of importance on minimizing battery degradation, which leads to equally different strategies for dealing with battery aging. The buffer provided by manufacturers can be used to significantly reduce the perceived aging experienced by drivers during the warranty period. Some vehicle manufacturers also use software updates to adjust charging performance, thereby influencing battery aging.

When interpreting the results, it is also important to note that the data availability for vehicles with over 200,000 kilometers of mileage is significantly more limited compared to vehicles with lower mileage. Currently, only a small number of vehicles with such high ranges driven exist on the market. This limits the reliability of conclusions for higher mileage ranges and contributes to greater variability in the data.

In addition, the "survivorship bias" must be taken into account. This describes the bias that arises when only successful or "surviving" vehicles are considered in an observation. In the present study, this means that only vehicles that were still roadworthy at the mileage tested were considered. Vehicles that are no longer in use due to battery failure are not included. This can make the reliability of the vehicles appear somewhat overly positive. However, failures in electric vehicles are generally rare. When failures do occur, they are only occasionally attributable to the traction battery.[3)] Individual cases, such as failures caused by specific usage behaviors or production defects, can still occur. These typically happen within the warranty period and therefore rarely pose a financial risk to consumers.

A comprehensive understanding requires the use of large datasets to make reliable statements. The data collection in this study meets this requirement and provides consistently positive results regarding the long-term reliability of electric vehicle batteries. The observed variability in the results can be partly attributed to individual usage patterns. While long-term capacity retention is evident even in intensively used batteries, certain behaviors can further help preserve battery health. The following table provides an overview of the most important factors influencing battery aging.

3) ADAC breakdown statistics 2023

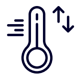
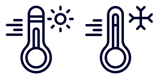
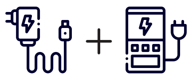
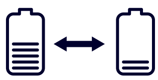
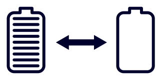
9. Moderate charging and driving behavior can increase battery life.

I. Influencing factors calendar aging (time, "non-use"[4])

	Positive impact[5]	Negative impact[5]
Temperature Excessive temperatures drive chemical reactions that accelerate capacity degradation. **It is recommended to park the vehicle in moderate to low-temperature environments.**	Low to medium temperatures (< 25 °C)	High temperatures (>60 °C)
State-of-charge (SoC) The state of charge also affects the chemical processes in the battery—high voltages[6] accelerate battery aging, especially during extended periods of inactivity. **For prolonged idle times, it is recommended to park the vehicle with a low[7] (~10%) to moderate (~50%) state of charge.**	Low to medium SoC (10 - 50%)	High SoC (> 80%)

4) "Non-use" refers to the state of a parked vehicle without being charged; 5) Basically, the indicated behavior can be considered positive or negative. Different cell chemistries and also the SoC must not be disregarded for detailed analyses; 6) The quantification of "high" depends on the cell chemistry; 7) The car should not be parked at 0% SoC to prevent deep discharge;

II. Influencing factors cyclic aging (usage[8])

	Positive impact	Negative impact
Temperature Both excessively high and low temperatures can accelerate aging mechanisms during use, such as increased SEI formation, lithium plating, and the breakdown of the chemical structure. **The ideal scenario for cycling (charging and discharging) is to maintain the temperature within a moderate range of 20–50°C.**	 Medium temperatures	 High and low temperatures
Charging speed Frequent fast charging (at high C rates, >3-4 C), stresses the chemical structures due to high temperatures, currents and voltages. Frequent fast charging ages the battery, while **occasional fast charging has no significant effect on aging.**	 Rare fast charging	 Frequent fast charging
Charging behavior Regularly driving the vehicle completely empty and recharging it to 100% (high depth of discharge / DoD[9]) leads to higher loads within the batteries and thus increased aging. **Regular cycling at a low DoD, e.g. between 20% and 80%, is advantageous.** Occasional high DoD for long distances have no significant effect on aging.	 Small DoD and ØSoC	 High DoD and ØSoC
Driving behavior Strong acceleration and long journeys at high speeds cause high currents to flow, which increases the temperature and puts more strain on the battery. **Moderate driving behavior slows down battery aging.**	 Constant, low speeds	 High speeds and acceleration

8) "Usage" refers to either driving or charging the vehicle; 9) "Depth of Discharge," which indicates the range of discharge, can, for example, represent 0% to 100% or just 40% to 60% of the State of Charge between which cycling occurs.

10. Long warranties for battery systems confirm confidence in their durability.

In recent years, vehicle manufacturers have strengthened their expertise and confidence in battery systems through growing experience and continuous technological advancements. As a result, they now offer increasingly robust warranties. The warranty assures a residual capacity of at least 70% up to a certain age or mileage, whichever is reached first. If this capacity falls below the guaranteed threshold, the warranty covers repair measures such as replacing the entire battery pack or individual modules (including the use of refurbished components) to restore the guaranteed capacity.

The standard warranty for EV battery systems is currently eight years or 160,000 kilometers. In comparison, consumers only receive a warranty of around four years and 80,000 kilometers for the entire vehicle and the other components. In recent years, battery systems have been significantly improved through optimized cell designs, improved chemical compositions and advances in thermal management and software. Among other things, these developments aim to protect the batteries from unfavorable conditions such as extreme temperatures or excessive current flows.

Manufacturers are offering increasingly extensive warranty conditions.

The data presented in this study shows that in practice the SoH rarely falls below 70% within the warranty period. In addition, the first manufacturers have extended their warranties to ten years or well beyond 200,000 kilometers. For example, Lexus, a pioneer in battery warranties, offers a ten-year or one-million-kilometer warranty extension for its UX 300e model. These improved warranty terms reflect manufacturers' growing confidence in the longevity of their battery systems.

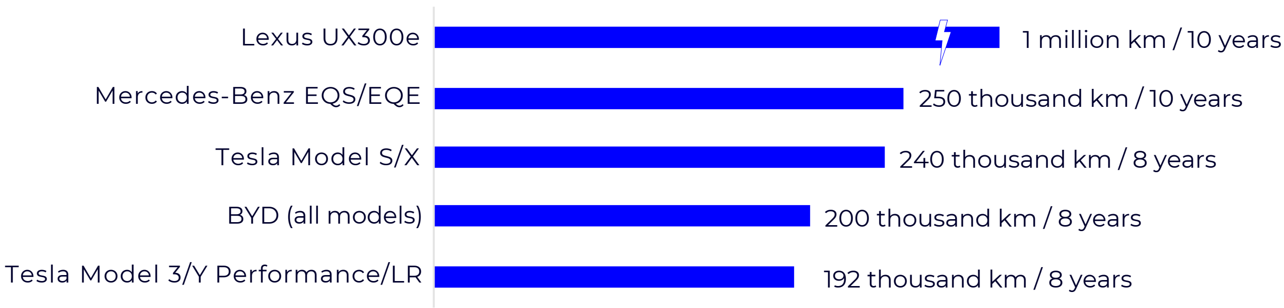


Fig. 2: Warranty periods for EV battery systems.

Sources: ADAC, manufacturer information on new car warranty

11. The long service life allows for a second life of the battery.

The lifecycle of a battery can be divided into several phases: End-of-Warranty (EoW), End-of-First-Life (EoFL) and End-of-Second-Life (EoSL). The EoW marks the point at which the manufacturer's warranty ends due to the mileage, or the time elapsed since purchase. After this point, the manufacturer no longer guarantees a minimum SoH. Analyses have shown that batteries can continue to be used in vehicles with sufficient capacity even beyond the warranty period. In fact, the EoFL typically occurs well before the battery reaches 70% SoH. The EoFL can be defined based on the following criteria:

- The vehicle is no longer roadworthy, although the issue is not caused by the battery.
- The battery, despite its capacity, is affected by defects (e.g., in the busbars or control units) but can still be repurposed through refurbishment or by extracting individual modules.
- The remaining capacity, and consequently the range, is no longer sufficient to meet the expectations of drivers for an electric vehicle.

At the EoFL, the battery is removed from the vehicle and analyzed. Depending on its condition, it can continue to be used in a second-life application[10)]. If deemed suitable, the battery is repurposed by replacing and renewing components, allowing it to have a second life, for example, in stationary storage systems. The EoSL is reached when the battery is no longer suitable for further use due to excessive capacity reduction or safety risks and must be recycled.

An exemplary progression of the State of Health (SoH) throughout the lifecycle phases of a battery.

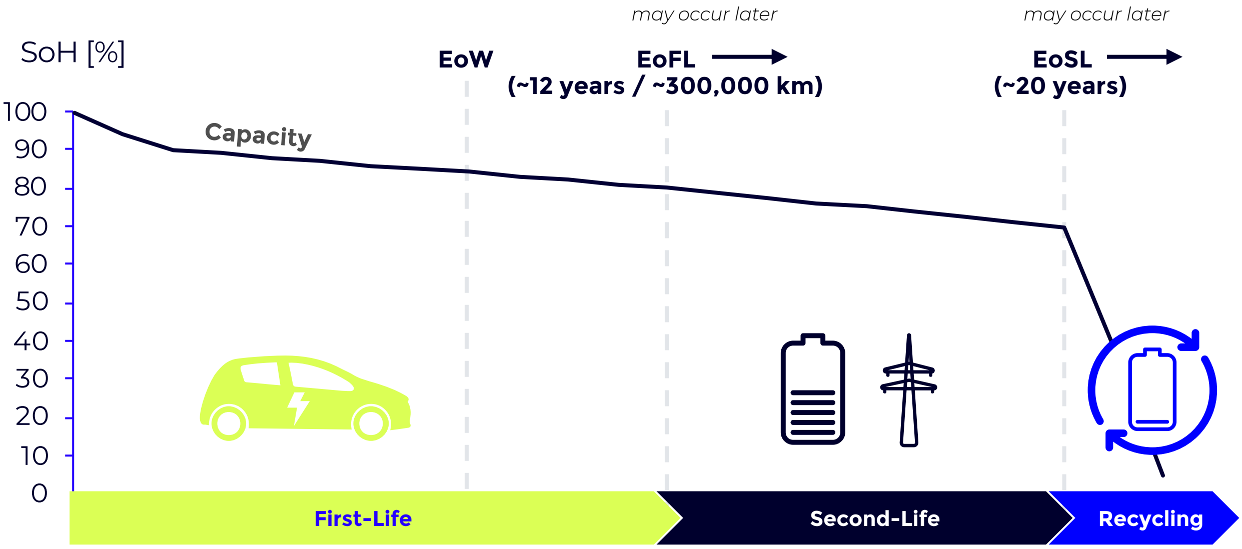


Fig. 3: SoH vs mileage for EVs with batteries >30 kWh.

10) The conditions that a battery must fulfill in order to be suitable for a second-life application can be found in the publication "Wertstoffkreislauf von Traktionsbatterien aus Europa: Potenziale von Second Life Anwendungen" by the Elektromobilität Süd-West c/o e-mobil BW GmbH.

12. The battery has a high residual value even after its usage in an electric vehicle.

The residual value of electric vehicles refers to the estimated value of a vehicle after a certain period of use. While the residual battery value is largely determined by current market prices for electric vehicles and the prices of new batteries, the condition of the used battery also plays a key role. A loss of residual value is to be expected in each life cycle phase. This also depends on various factors. In practice, once the EoFL has been reached, the battery is tested to determine whether it is still suitable for a second-life application. Even a severely aged battery does not mean a total economic loss after the first or second life, as valuable raw materials such as lithium, nickel, and copper are still preserved. By recycling batteries, these metals and other materials can be recovered and used for the production of new batteries and thus continue to have an economic benefit. An exemplary analysis of the residual value of a lithium-ion battery shows that it accounts for 20-30% of the value of a new electric vehicle. Within the warranty period, the loss in value is heavily dependent on aging and the remaining capacity[11]. After the warranty expires, a greater loss in value is to be expected. At the end of the first life, the battery may still have a significant residual value through a second use, depending on the cost of new batteries. The decision on further use is made by the company that owns the battery at the EoFL and tests it for suitability. The value of the used battery can be increased through reprocessing until it finally reaches a minimum value that a recycling company will pay for it, regardless of its state of health. This willingness to pay depends on the number of metals contained, current market prices, recovery rates, and process costs.

An exemplary progression of the residual value throughout the lifecycle phases of a battery[12]

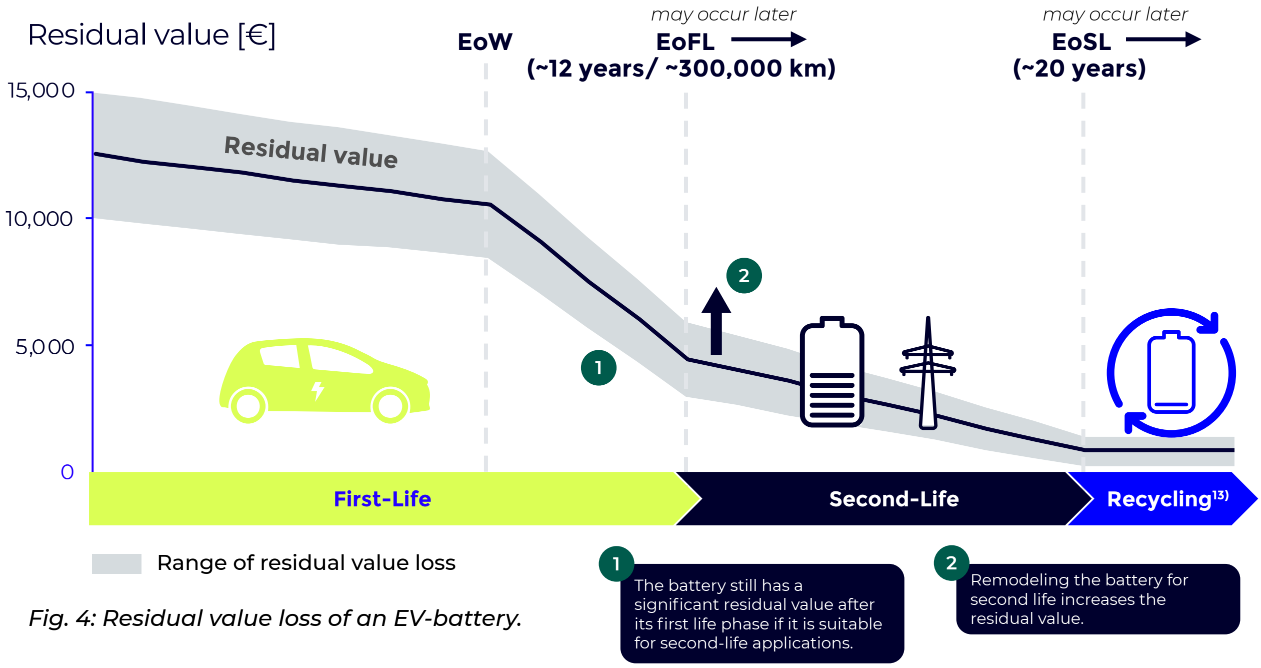


Fig. 4: Residual value loss of an EV-battery.

11) Pure consideration of the decline in capacity. A market-based valuation taking into account low current prices for new batteries causes the value to fall more sharply depending on the market situation. 12) Simplified illustration with an example of the residual value of an EV battery with 75 - 100 kWh from a German premium vehicle manufacturer. 13) The value of the battery after the second service life is based on so-called metal payables and the metals contained at market prices that a recycler is typically willing to pay for the battery.

13. Summary

The study demonstrates that electric vehicle batteries maintain a long service life even when used intensively. With mileages of over 200,000 kilometers, most batteries retain more than 80% of their original capacity and are therefore usable far beyond the usual warranty period. Technological advances in cell chemistry and battery management systems further increase the performance and durability of the batteries.

Electric vehicle batteries have a long service life.

Field data shows that batteries in electric vehicles only lose a small amount of capacity in the long term and continue to perform well even with mileages of over 200,000 kilometers.

Independent SoH measurements create greater confidence.

Standardized and reliable SoH measurement methods are important tools for assessing the health of used electric vehicle batteries and evaluating them for second-life applications.

Battery life can be further optimized by the user.

The longevity of the battery can be further improved through battery-friendly usage behavior (e.g. by parking at medium SoC, charging with low currents and moderate driving behavior).

Technological advancements as the key to improved longevity.

Technological advancements have significantly enhanced both the performance and longevity of electric vehicle batteries. Improved cell chemistries, thermal management, and battery software provide better protection against premature aging, enabling manufacturers to offer warranties of up to ten years or over 200,000 kilometers.

A battery can have several lives.

Even at the end of their service life in the vehicle, the batteries remain usable. If a battery system or components are removed from an electric vehicle, there are numerous options for reuse, which means that a significant residual value is retained.

List of abbreviations

DoD = Depth-of-discharge
EoFL = End-of-first-life
EoSL = End-of-second-life
EoW = End-of-warranty
EV = Electric Vehicle
OBD = Onboard diagnosis
SoC = State-of-Charge
SoH = State-of-Health

List of figures

LET'S EXPLORE WHAT WE CAN ACHIEVE TOGETHER!

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