Journal of Reliability
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To cite this article: Yiliu Liu and Xiao-Lin Wang 2025 *J. Reliab. Sci. Eng.* **1** 032003

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IOP Publishing | ISECAEP
Journal of Reliability Science and Engineering
J. Reliab. Sci. Eng. **1** (2025) 032003 (14pp)
https://doi.org/10.1088/3050-2454/ae033b

Topical Review

Warranties of batteries: requirements, state-of-the-art, relevant analysis methods, and research perspectives

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Received 21 May 2025, revised 12 August 2025
Accepted for publication 4 September 2025
Published 15 September 2025

Abstract

As an essential energy storage solution, batteries are playing a vital role in the broader transition toward decarbonized transportation and renewable energy utilization. Warranty, a key element of after-sales services, guarantees that a product would perform its functions as intended. While warranties are standard for most mechatronic products, battery warranties exhibit distinct characteristics such as capacity retention guarantee and usage-based warranty limit. In this paper, we provide a whole picture of battery warranties by summarizing the particular requirements and current practices. We then discuss how research advancements in general product warranties and battery maintenance can be leveraged to advance battery warranty research. Finally, some promising research topics on battery warranties are presented and discussed. Overall, this positioning paper summarizes state-of-the-art information on battery warranties, which can be useful for researchers and practitioners interested in warranties and the battery sector.

Keywords: batteries, electric vehicles, reliability, warranties, maintenance

Notations

2D	Two-dimensional
BaaS	Batter-as-a-service
BESS	Battery energy storage system
DoD	Depth of discharge
EOL	End of life
EV	Electric vehicle
FRW	Free repair/replacement warranty
IEC	International Electrotechnical Commission
MCDM	Multi-criteria decision making
PRW	Pro-rata warranty
RUL	Remaining useful life
SOC	State of charge
SOH	State of health
SOW	State of warranty

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1. Introduction

As an essential solution to decarbonizing transportation, EVs are rapidly penetrating the global market, thanks to decreasing battery and vehicle costs, growing sustainability awareness of consumers, and ongoing policy supports. According to the annual Global EV Outlook report published by International Energy Agency (IEA 2025), global EV sales grew by more than 25% and exceeded 17 million in 2024, accounting for over 20% of all vehicles sold; the market was led by China, where over 11 million EVs were sold and the sales share was almost 50%. With the rapid adoption of EVs, onboard battery systems have emerged as a crucial component of modern transportation. In addition, batteries also play a vital role in the broader transition toward sustainable energy systems: BESSs are being increasingly deployed across power grids to mitigate the inherent variability and intermittency of renewable energy sources such as wind and solar (Divya and Østergaard 2009, Hannan *et al* 2021). As a result, the application of battery technologies and products has evolved significantly, from compact cells used in consumer electronics to large-scale storage systems used for, for example, transportation electrification.

When evaluating whether to adopt EVs, battery quality and performance (e.g. battery capacity, driving range, durability, safety) are important factors for customers to consider (Arco 2024). On the other hand, batteries inevitably degrade over time due to chemical instability, repeated charge-discharge, and environmental stresses such as extreme temperatures, resulting in diminished storage capacity and reduced efficiency. To relieve customers' concerns about battery quality and performance and comply with the regulations, it is a common practice for vendors to provide warranties for the whole EVs as well as the battery packs. Warranty is essentially a contractual agreement between the warrantor and the customer, to specify product performance, buyer responsibilities, and what the warrantor (generally the manufacturer) needs to do if the product fails to meet the stated performance (Blischke and Murthy 1992, Murthy and Djamaludin 2002).

Currently, warranties of various forms are provided for almost all durable products, and EVs and batteries are not exceptions (Cai and Zhao 2022). In practice, performance gaps exist between the claims of battery manufacturers and the reality, where warranty services are needed. For manufacturers, warranties also play an important role in marketing, given that more generous warranty signals higher product quality/reliability and provides greater assurance to customers (Murthy and Djamaludin 2002). Indeed, through a choice experimental survey in China, Li *et al* (2020) have found that battery warranties have a significant positive effect on attracting customers to adopt EVs.

Battery covers 30%–50% of the total cost of an EV (Xie *et al* 2025b), and thus it is natural that warranty services on battery expense a large proportion of the total after-sales cost. Moreover, warranty design and servicing are increasingly critical and complex when batteries are becoming larger and more complicated. When batteries are only small cells, simple FRW can be the most suitable policy. However, considering complex impacts of vehicle battery failures and potential catastrophic consequences of large BESSs, deliberate warranty contract design and well-planned warranty servicing strategies are highly necessary.

Warranty management (including warranty policy design, warranty cost analysis, warranty data analysis, and warranty regulation issues) has been well studied in the last decades (Murthy and Blischke 2006, Blischke *et al* 2011, Murthy *et al* 2016), with the intensive case studies in the automotive industry. However, studies focusing on batteries, including those used for powering vehicles and for other energy storage purposes, are surprisingly few and scattered. It is reasonable to suspect that the warranty policies and analysis methods for general mechatronic products cannot be simply copied/-pasted to the battery sector, considering some particular characteristics of battery systems and the associate management approaches. Inappropriate warranty management may lead to undesired additional costs for battery manufacturers (Arrinda *et al* 2022). On the other hand, research and regulations for batteries pay much more attention to their safety performance, such as IEC 62933-1 (IEC 2024) as the guidelines for safety of BESSs, but studies on warranty management of batteries are still lacking. Therefore, an overview of the unique requirements of warranty management for batteries and the potential challenges in satisfying them can be helpful.

This paper is expected to bridge such a gap and provide a whole picture on state-of-the-art studies to the researchers and practitioners interested in warranties and the battery sector. The existing warranty analysis methods that can be applied for batteries are identified, and some suggestions on future research directions are presented. It should be emphasized that this work is not a systematic review on battery warranties, since the existing studies in this field are very few. Xie *et al* (2025a) have published a review paper on service management of EVs very recently, which provides some information on battery warranties, but its focus is more on general operations modes and management of EVs, neither on warranty analysis nor batteries. The aim of this positioning paper is to collect useful information for warranty studies of batteries. For example, studies on battery degradation and maintenance are intensive; although not all of them are directly related to warranty, it is still meaningful to identify some of guidance on warranty studies.

The remainder of this paper is organized as follows: section 2 lists the specific requirements for warranty policy design and analysis of batteries, which motivate this review. Section 3 summarizes state-of-the-art warranty studies and practices. Section 4 reviews the existing studies on general warranty analysis and battery degradation analysis and maintenance while identifying their potential for battery warranty management. Finally, section 6 proposes potential research topics within battery warranty management.

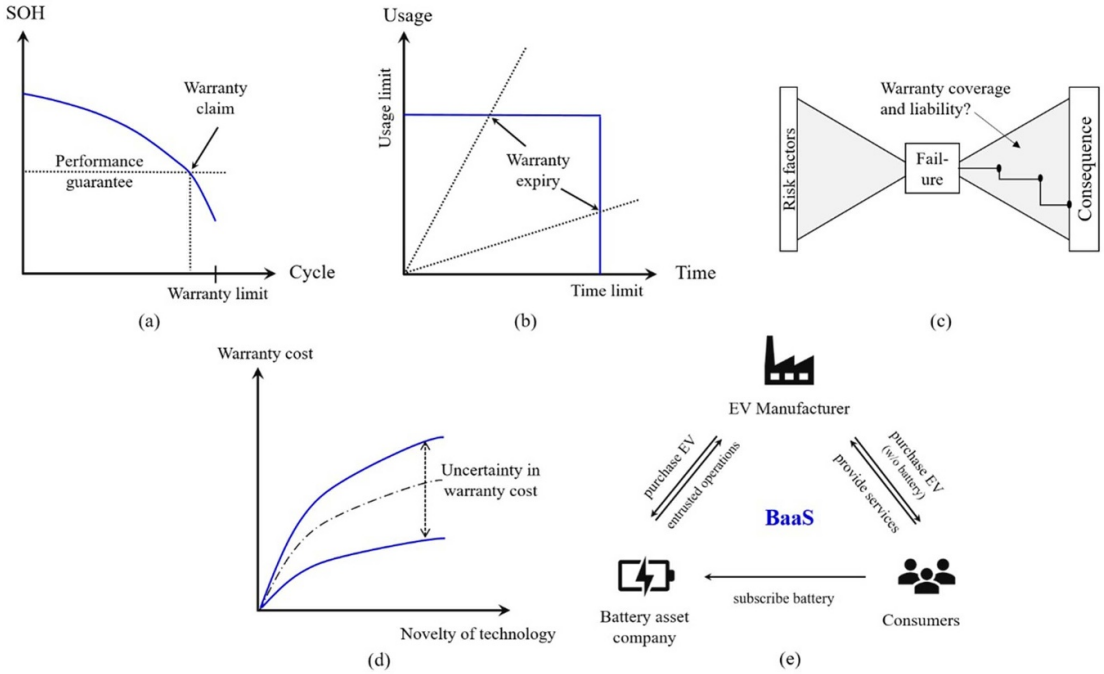


Figure 1. Key characteristics related to battery warranties.

2. Particular requirements for battery warranty design and servicing

Compared with most mechatronic products, batteries have some particular characteristics that are related to warranty design and servicing. Figure 1 illustrates five key characteristics that will be discussed one by one in what follows.

2.1. Performance-based claims

In many cases, when a noticeable failure occurs on a product, such as an onboard air conditioner failure, a warranty claim is raised from the user to the manufacturer. Reliability or failure probability of items is the foundation of estimating the number of warranty claims (in turn, warranty cost) and designing the associated warranty policy. However, warranty claims related to batteries are not only from functional failures, but also from lower performance than expected (Wang *et al* 2021). In addition, when battery performance degrades more rapidly than expected, a claim may also be raised. Warranty based on such claims can be regarded as performance-based or capacity-based warranty (Warshay 2021).

The performance of batteries is often indicated as *state of health* (SOH). In a simple way, the SOH of a battery system can be estimated by the relative dischargeable capacity at the present divided by the nominal or rated capacity of a new battery (Xu 2022). In daily use or short-term performance evaluation, SOH can be estimated with SOC, as the ratio of battery storage capacity to the maximum level (Murnane and Ghazel 2017, Pierpaolo *et al* 2024) and DoD, as the percentage of battery capacity that has been discharged from the fully charged state (Khojasteh *et al* 2021). When SOH decreases to a certain level, due to increased impedance and reduced thermal stability, the battery can be regarded coming to its end of life. This can be regarded as a battery failure (often called soft failure in reliability engineering), meaning that it can no longer serve its application purposes. In the EV sector, the threshold value of SOH to the end of life is often set as 70% currently (Arrinda *et al* 2021).

It should be noted that SOH is not the only performance indicator for batteries. For example, a common performance indicator for BESSs is energy throughput, which is defined as the total amount of energy throughput a battery in charging and discharging within its lifetime (Khojasteh *et al* 2021). Similarly, if the energy throughput is lower than expected, a warranty claim may be raised.

2.2. Two-dimensional requirements

The life of batteries is always evaluated with their charge-discharge cycles, and thus 2D warranty (Wang *et al* 2015, Wang and Xie 2018, Wang *et al* 2019b) is needed for batteries to involve both calendar time and actual usages. As mentioned in Searles and Schiemann (2014), battery manufacturers often stop their warranty based services when the number of cycles exceeds a finite threshold, and also limit their warranty within a specific period of time. Under the 2D warranty, it is required that the actual SOH of a battery is not lower than the expected SOH in the warranted charge-discharge cycles or in the specified time period.

It is worth noting that SOH also presents 2D characteristics when it is used for batteries installed on EVs, because it can be calculated as a percentage of original capacity (e.g. 75% of 100kWH) or reflected by a reduced maximum driving range of the EV (e.g. 325 km after one year of use compared with 400 km at the beginning). Although the previous one is

assumed to reflect the health status of the battery itself more accurately, the latter one is easier realized by users. The actual driving range can be affected by different parts of the car and road situations, but given the marketing role of warranty, it should be considered in warranty analysis.

2.3. Safety and liability

A critical technical challenge for batteries is the potential safety and environmental risks. Lithium-ion batteries face thermal runaway and fire hazards. In warranty design, it is necessary to clarify what kind of consequences of battery failures should be handled by the manufacturer and covered by warranty services. From the risk management perspective, if a battery failure is regarded as the pivotal event in a Bow-Tie analysis (e.g. see Liu (2025)), the accidental scenario around this event can stop at an end event of repair, stop with the occurrence of a fire, or stop at a very serious consequence where the fire results in several fatalities. If the failure is due to a design or manufacturing defect, the manufacturer should be responsible for compensation. However, even though it is not hard to clarify the liability, the varying consequences of battery failures bring challenges in warranty analysis and warranty cost estimation.

Meanwhile, although some defects that may result in safety issues should be considered in warranty management, it is essential to highlight that warranties are always specified for those quality problems in design and manufacturing, instead of unexpected accidents where the loss should be compensated by insurance. Warranties of batteries should distinguish themselves from liability contracts or insurance contracts.

Since BESSs are often integrated with renewable energy generation, their failures can lead to significant consequences (Bakeer *et al* 2022), including interruptions in power distribution or even localized blackouts. As BESSs become increasingly critical to grid stability, the issue of liability in the event of system failure gains importance. Specifically, the responsibilities of battery manufacturers in cases of power loss need to be clearly defined and addressed within warranty agreements, ensuring transparency and accountability in both technical and legal frameworks.

Warranty service vendors of batteries, especially those of BESSs, are diverse dependent on the business models, who can be the manufacturers of batteries, BESS integrators, third-party service providers, or insurance-backed service providers. Such a situation is not fully particular for batteries, but it should be noted that when different warranty service vendors are selected, they may have different warranty coverages and different liabilities.

2.4. Rapid technical development

Battery technologies are being developed in a very fast way. In general, batteries on EVs are becoming smaller with larger energy density, faster charging speed, and easiness in maintenance and replacement (Xu *et al* 2022). On the other hand, BESS can employ different types of battery materials and technologies, such as nickel–metal hydride (NiMH), sodium–sulfur (NaS) and vanadium redox-flow batteries (Zhao *et al* 2018). With the changes in technologies adopted, warranty costs can be expected varied even when the warranty policies and clauses remain relatively stable. Adaptive and scalable analysis methods are thus required for warranty cost estimation.

Moreover, rapid technical development leads to faster obsolescence. In some extreme cases, the EVs might be obsolescent even before the expiry of battery warranty. This necessitates more innovative warranty design and servicing strategies. Designing novel warranty policies in this scenario might be coupled with business model innovation for EVs, which will be discussed later.

In addition, with more concerns on environmental protection and sustainability issues, battery recycling and disposal are also considered in warranty management since batteries have potential environmental impacts. Some batteries that are originally used in EVs can be recycled and reused in BESSs for stationary energy storage (Kotak *et al* 2021), which proposes a new topic for warranty policy design and analysis.

2.5. New business models

Some EV companies, like NIO, are practicing BaaS business model under which users rent batteries for their EVs with a swappable-battery design, rather than buy batteries together with cars (Shi and Hu 2024, Zhou *et al* 2025). Such a business model reduces the initial expenses of customers but allows reallocation of batteries between users. It is regarded as a win-win mechanism of customers and the EV manufacturer but raises new requirements for warranty design and analysis.

The positive side of BaaS is that batteries are managed in a centralized fashion (Mæland 2024), so advanced battery health management systems can be leveraged to maintain them more effectively and cost-efficiently. For example, the charging processes of all batteries can be monitored, so the voltages of all battery cells are balanced and kept at an optimal level. As a result, the reliability and capacity of batteries would be improved, and so would their service life. The negative side is that since batteries are shared among users, it is very difficult to clarify the user responsibilities for failures or degradations due to inappropriate usage. More importantly, when users face battery failures, it is assumed that they have the right to claim free replacement and even compensation. Such new scenarios need to be considered in warranty policy design and contracts related to BaaS.

Servitization is another new business model in the EV sector that may influence battery warranty policies (Xie *et al* 2025a). Under this model, customers pay a fixed fee per unit of service consumed, while the battery's ownership remains with the fleet operator who is responsible for battery operations and maintenance. For example, Miles Mobility operates 3000+ vehicles (VW ID.3 EVs, vans, etc.) in large cities in Germany, charging users by the driven kilometers[3].

[3] https://invers.com/en/.

This 'pay-per-mile' structure removes time pressure on trips and makes costs predictable. However, shared EVs undergo significantly more charge-discharge cycles than private cars, leading to faster battery degradation. Fleet operators are also important stakeholders in such a business model, and so EV manufacturers may need to negotiate with the fleet operators for battery health monitoring and fleet battery swapping and replacement clauses.

A common challenge induced by BaaS and servitization to warranty design is that batteries are circulated among many EV owners who have distinct driving habits, usage rates, and dynamic operating conditions. These aspects can have a significant impact on battery reliability and lifetime and pose difficulty for warranty cost analysis.

In addition, consistent with the spirit of circular economy, second-hand batteries that were used to power EVs can be reused for energy storage in power grids (Rajaeifar *et al* 2022). Although the batteries are used ones, the BESSs with these batteries still need to be regarded as new products with some fully new parts. Such combined products propose new requirements for warranty design and analysis.

3. State-of-the-art warranty management practices in the battery sector

This section reviews the current warranty policies for batteries provided by EV and BESS vendors and their practices in warranty management.

3.1. Warranty policies for batteries

EV vendors always provide a separate warranty policy specific to batteries, meaning that it is different from the warranty policies to the other parts of a vehicle. In the automotive industry, including EVs, 2D FRW is always provided to customers. In a 2D FRW, manufacturing defects occurring usually warrant full replacements or free repairs, but the services are limited within a certain time period (calendar time) and a certain amount of usage (mileage for EVs and their onboard batteries) in a 'whichever-comes-first' manner. Most EV vendors are providing warranty services for batteries in 8 years or 100 000 miles/160 000 km (whichever comes first) in all markets with some slight differences. For example, Tesla extends the warranty to 120 000 miles for some long-range models while setting minimum 70% retention of battery capacity over the warranty period. U.S. federal mandates a minimum 8-year/100 000-mile warranty, while California will extend this to 10-years/150 000-miles in 2030[4]. Some representative warranty policies for EVs and batteries are summarized in table A1 (see appendix).

In addition, EV manufacturers often provide customized warranty (Liu *et al* 2013), with a longer warranty period for the battery than other parts and distinct warranty policies. For example, Volkswagen provides 8 years or 100 000 miles/160 000 km battery warranty of BEV, and battery energy content degradation warranty lasts for 5 years or up to 100 000 miles for PHEV, while 3-year/60 000 mile warranty for whole cars of both types[5]. NIO provides a 5-year/150 000 km warranty for cars in Norway, a 10 year rust warranty and a 5 year paint warranty, while 8-year/160 000 km warranty on the high-voltage battery[6]. Tesla provides more detailed distinct warranties for different parts[7]. For example, the company provides warranty to batteries on the new Model X cars within 8 years or 150 000 miles, whichever comes first, with minimum 70% retention of battery capacity, while offering differentiated warranty periods for the parts directly purchased from the company, such as 4 years or 50 000 miles to drive units, 2 years or 25 000 miles to touchscreens and media control units, 4 years to wall connectors, and 1 year or 12 500 miles to vinyl wraps.

It should be noted that while EV battery warranties vary across manufacturers, EV modes, countries sold, they typically cover the following main aspects: warranty duration and mileage limits, coverage for manufacturing defects, capacity retention guarantees, transferability, and exclusion terms, among others.

Compared with EV manufacturers, BESS vendors offer more flexible warranty terms based on negotiations with users or owners whose numbers are limited. These flexible terms typically include formulas instead of a fixed table of values and use operational metrics as inputs to provide adjusted warranty services for a given timeframe (Warshay 2021).

When a pre-owned EV is sold during the warranty period, whether the warranty can be transferred to the new buyer would affect its resale value. Currently, many vendors allow warranty transfer, so that the new owner can benefit from the remaining warranty (RW) period. This will increase the residual value of the whole EV and thus boost the sales of new EVs.

3.2. Coverage of battery warranties

Warranties of batteries always cover the manufacturing faults, and those problems due to users' factors and accidents are excluded. Table 1 presents some defects of batteries that are not covered by normal warranty (according to Clarke (2024) and BatteryWorld (2025)).

In practice, it is sometimes very difficult to reveal the real causes of many failures. For example, users do not realize their negligence in use, and thus they will not report wrong behaviors in their warranty claims, which may mislead subsequent failure cause analysis and warranty cost estimation.

Battery warranties generally include capacity retention guarantees over the warranty period. Currently, many EV vendors guarantee 70%–75% retention of battery capacity at the end of the warranty period. This means that if the battery capacity falls below the guaranteed percentage, then

[4] https://www.cnanational.com/learn/agent.

[5] https://www.vw.com/en/owners-and-services/about-my-vehicle/maintenance-and-warranty.html.

[6] https://www.nio.com/no_NO/nio-service.

[7] https://www.tesla.com/support/vehicle-warranty.

Table 1. Some battery defects that are not covered by warranty.

Defects	Explanations and examples
Normal wear and tears of batteries	Metal corrodes and active materials lose naturally overtime.
Accident damage	Battery damage resulted from a collision.
Physical damage	Battery failure due to external damage such as external shocks and flood, and exposure to unexpected conditions such as high temperature in storage.
Incorrect applications	Batteries are used in applications that are not within the purposes. For example, batteries for normal EVs are used for racing activities or stationary sources of power.
Negligence in use	Users do not notice the guidance or conduct regular checks and maintenance as required. No charging in long-term, undercharging or overcharging may accelerate battery failure.
Unauthorized services	Some parts or auxiliary components of the battery pack have been changed in unauthorized workshops.
Invalid modifications	Failures from software that are installed without approval from the manufacturer.

the manufacturer would provide compensation. It is interesting to learn from the warranty practice in the solar panel industry, where the performance decline rate is guaranteed. For example, SunPower guarantees that the modules' minimum peak power rating at the end of the first year should be no less than 98% of the original rating and the maximum annual decline in peak power rating is 0.25%[8].

It is noteworthy that the recent 'right to repair' movement might require manufacturers to remove some exclusion terms in their warranty contracts. For example, according to the directive of European Commission (2024), manufacturers will be prohibited from using contractual clauses, hardware or software techniques that impede the repair of goods, unless justified by legitimate and objective factors. As a result, repairs and maintenance performed by third parties would no longer invalidate the warranty.

4. Existing studies with potential for tailor-made warranties of batteries

The objective of this section is to review the existing studies on general warranty analysis as well as battery reliability and performance analysis, with the focus on those that have potential in battery warranty management. The relationship of the topics of the subsections is illustrated in figure 2, and it can be found that the warranty studies are conducted at the different levels with integrating the research results from lower levels.

Research on battery maintenance, degradation modeling, and failure prediction/detection is intensive. Using the search engine of Web of Science, more than 6000 articles can be found with the keywords of 'battery' and 'maintenance'. However, very few of them have been connected to warranty analysis. In this section, we select and present those as important inputs for warranty analysis and warranty policy and strategy design.

[8] https://assets.ctfassets.net.

4.1. From general warranty policies to specific battery-oriented policies

The results of fundamental warranty theory studies can facilitate warranty policy design for batteries. Warranty providers should rely on a certain warranty policy to specify the warranty length and usage limit, capacity retention guarantee, type of compensation, and the inclusion/exclusion terms, among others.

As discussed previously, 2D warranties have been well studied by considering calendar time and mileage (for automobiles) or the number of printed pages (for printers). Such policies have been and will be used in the battery sector. For batteries, however, the usage dimension can be quantified through metrics such as mileage driven (as currently adopted by most EV manufacturers for battery warranty specification), the cumulative number of charge-discharge cycles, and total energy throughput. In the relevant studies, Otieno *et al* (2019) have analyzed the suitability of an age-based warranty model and a mileage-based warranty model for absorbent glass mat batteries. Based on the 2D warranty philosophy, Arrinda *et al* (2022) have proposed a warranty policy specific for batteries, where the warranty services should be provided based on the observed/estimated SOH of batteries. In such a policy, three variables are considered:

- RW, indicating how much of warranty period is still available when the manufacturer needs to provide repairs.
- Remaining health, indicating the deviation in terms of performance of battery from original and the closeness to the EOL threshold.
- RUW. It considers the RUL of a battery, which is the calendar time from the present to the moment when the EOL threshold is reached. Then, RUW quantifies the deviations between predicted RUL based on the current status and expected RUL.

All the three variables are set with the value range of [0,1]. Theoretically, if RUW is less than 1, meaning the performance of the battery is lower than expected, then a warranty

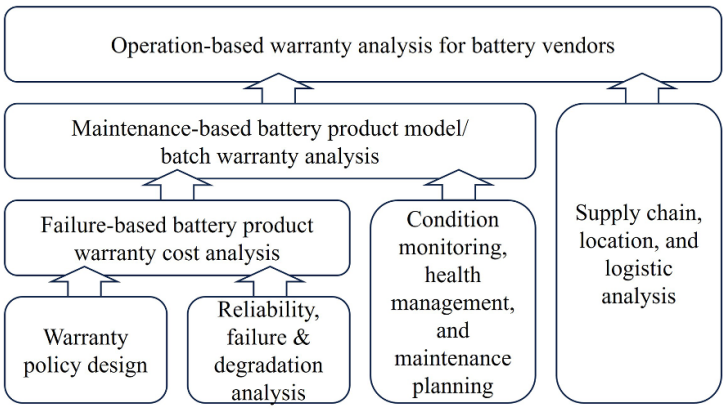


Figure 2. Relationship of the topics of reviewed studies.

claim can be triggered. From the warranty policy perspective, this approach belongs to FRW category, and in practice, such a threshold can be set to avoid too many warranty services. Although we have found no publicly documented case in which an EV vendor has adopted this mechanism, it is conceptually feasible for balancing customer reassurance against finance caution.

Batteries inevitably degrade with use due to chemical instability, repeated charge-discharge cycles, and environmental stress, resulting in diminished storage capacity and reduced efficiency. An essential characteristic of battery warranties is the guarantee on battery performance degradation during the warranty period. Considering warranty claims stem from degradation, DNV's report (Warshay 2021) has listed typical metrics used in battery warranty, including:

- Calendar-based performance degradation—Ratio of the original capacity for each year without considering usages.
- Cycling-based performance degradation—Ratio of the original capacity for each year based on usages. For example, 95% capacity in Year 2 with one full discharge per day.

The aforementioned studies predominately treated standard warranty and performance guarantee separately. Wang *et al* (2021) studied a performance-based warranty policy for products like batteries, which combines standard warranty and performance guarantee at the end of the warranty period. When the battery's performance fails to meet the guaranteed level, three compensation policies, free replacement, penalty, and full refund, are proposed and the associated warranty policies are designed and compared using numerical studies. PRW also can be introduced for batteries based on this performance-based method, to provide compensation in the situation of faster degradation than expected and to reduce warranty costs while keeping satisfaction of customers.

In general, FRW is simple and attractive for customers and encourages higher perceived value of a product, but it often implies higher cost risk for the manufacturer if failure rates are high and encourages careless use. On the other hand, PRW can reduce cost burden on the manufacturer, and it is fairer in cases where the product has been partially used or worn, such as batteries. However, PRW is more complicated for customers to understand and thus is less appealing from a marketing perspective. For more discussions on the advantages and limitations of FRW, PRW and other standard warranty policies, readers can refer to the review papers and books by Murthy and his co-authors (Murthy and Djamaludin 2002, Murthy and Blischke 2005). For battery products, FRW and PRW can be integrated as combined warranty (Wang and Xie 2018). Under the combined warranty, the warranty period can be divided into sub-intervals with varying renewal terms. For instance, failures in the first sub-period trigger full warranty resets, while later failures result in partial coverage.

4.2. Battery reliability and degradation analysis for warranty cost estimation

The key to warranty cost analysis lies in estimating the number of warranty claims raised during the warranty period, which might result from battery failures and/or violation of the performance guarantee. This necessitates an appropriate battery reliability model that is based on the understanding on the reliability and failure/degradation mechanism of batteries that are influenced by battery material properties, electrochemical reaction processes and usage conditions.

Reliability issues of EVs and batteries have been well studied (e.g. see the review papers by Gandoman *et al* (2019)). In general, there are two types of reliability models suitable for battery warranty analysis, which can be regarded as failure models and degradation models.

The first type employs appropriate probability distributions to describe the failure time as a function of battery age, or the duration that SOH is from 100% to the threshold of EOL. Higher reliability in such a model is reflected as lower rates of battery failures, which can decrease warranty claims and in turn reduce warranty costs (Lin and Silfvenius 2025).

In current literature, Otieno *et al* (2019) have utilized battery warranty claim data, with the information on calendar time and total miles driven for each claim, to calculate optimal warranty limits for minimizing warranty costs. In doing so, they compared the suitability of age- or mile-based warranty

models. Based on the historical warranty data of a lead-acid battery pack model manufactured by a Chinese battery company, Wang *et al* (2019b), in their case study, adopt the maximum likelihood estimation method to fit the Weibull distribution and estimate its parameters. The result is then used to demonstrate the piece-wise renewing FRW policy proposed in their work. Lin and Silfvenius (2025) has proposed a three-level model for analyzing the impacts of battery reliability. At the micro-level, user behavior (e.g. charging patterns) and real-time battery health data can be used to estimate warranty claims. The meso-level involves industry stakeholders using dynamic degradation models to design warranty terms with battery lifespan. At the macro-level, it integrates with regulatory frameworks like the EU Battery Passport mandate traceability, ensuring compliance during warranty servicing.

The second type of reliability model characterizes performance deterioration of batteries, generally via stochastic processes. Since the degradation of batteries is often non-monotonic, the Wiener process is more suitable for modeling battery degradation than gamma and inverse Gaussian processes (Zhang *et al* 2018). Zhao *et al* (2023) propose to optimize accelerated degradation tests to predict warranty return rate before product release and demonstrate their method using a real case study on acid rechargeable batteries. In their work, the Wiener process is adopted to characterize the degradation process of batteries, and the link function is employed to capture the effect of elevated stress on the battery degradation process. Heterogeneities in the customers' usage mode and return pattern are also incorporated. The factors weakening reliability of batteries include chemical factors, such as impurities and concentrations, corrosion, joining procedures, materials processing and cell closures (Gandoman *et al* 2019). For warranty analysts, it is always difficult to understand all the electrochemistry knowledge, but these actuarial approaches can rely on statistical models and machine learning methods for estimating the degradation with time.

Regardless of the reliability analysis model adopted, capturing the effect of operational and environmental conditions (often called *covariates*) on battery failure or degradation process is essential for warranty cost analysis. Such covariates include usage intensity (e.g. the number of charge-discharge cycles per year, mileage driven per year) and environment temperature, among others. In failure models, covariates can be modeled by using the accelerated failure time model or the proportional hazard model, while the effect of covariates can be captured by the link function in degradation models. In their study of performance-based warranties, Wang *et al* (2021) considered competing hard and soft failures, which are described by failure and degradation models, respectively. The impact of usage rate on both failure and degradation processes was captured by a time-scale adjustment method.

Understanding how battery failure or degradation occurs across real operating conditions is critical yet challenging. The majority of laboratory battery tests are conducted under constant charge-discharge profiles, which are incapable of reflecting dynamic profiles during real operating conditions. Nevertheless, the aging mechanism of batteries under real and dynamic operating conditions is still unclear. For example, Geslin *et al* (2025) found that dynamic discharge enhances battery lifetime substantially compared with constant current discharge. As a result, more in-depth research is needed in this respect.

4.3. Considering condition-based maintenance in warranty analysis

Maintenance policy is an important element of any warranty contract. Regular maintenance and care are vital to keep batteries operating reliably and efficiently. Considering a certain battery product model or at least a batch of sold battery products, EV manufacturers need to provide maintenance guide for their batteries, and then design and implement warranty services based on the guide. For example, BYD recommends customers to prevent repeated deep discharges, create consistent charging routines, and avoid prolonged exposure to extreme temperatures[9] .

To conduct maintenance more efficiently in relatively lower cost, advanced battery management systems have been adopted by many EV manufacturers to manage their battery's health. For instance, Tesla's battery management system maintains precise voltage and temperature control with real-time monitoring, coupled with Tesla's mobile app that keeps owners informed about their battery's health[10]. The deployment of battery management systems makes prognostics and health management (PHM) possible for batteries. The PHM tasks for batteries include, but not limited to, SOH estimation, RUL prediction, and predictive maintenance. Kong *et al* (2024) systematically review recent advances in battery PHM from the perspective of key PHM steps.

In the case of battery repair, the failed battery cell is replaced by a new one, so the cells inside the battery would have different degradation levels. This causes an imbalance issue, which in turn accelerates the degradation of the whole battery and brings uncertainties to the second-life of the battery for BESS. Almuhtady *et al* (2014) introduced a degradation-informed battery swapping policy by combining optimal swapping and substitution actions over a finite time horizon. Swapping refers to the interchange in the placement of two batteries within a fleet, while substitution means the replacement of degraded batteries with new ones. The policy takes advantage of differentiated degradation rates inside the battery fleet and optimally adjust the battery placements at different time intervals. Sun *et al* (2020) extended the work of Almuhtady *et al* (2014) by relaxing the assumption of deterministic battery degradation, and incorporated battery reallocation into the condition-based maintenance framework for battery degradation management. While the aforementioned studies focus on the fleet level of EVs, their ideas are inspiring for batteries.

In addition, motivated by the uncertain usage patterns and return timings that are inherent in the shared service-oriented business model (such as BaaS), Ruan *et al* (2024) proposed a

[9] https://www.byduae.ae/en/news/electric-car-maintenance-guide/.
[10] https://xray.greyb.com/ev-battery/tesla-innovations-in-battery-management-systems.

personalized condition-based maintenance policy accounting for these uncertain and heterogeneous factors. A decision rule was developed to guide the decision on when to inspect the equipment state and when to take maintenance actions.

With the recent advances in PHM for industrial systems in general and batteries in particular, battery warranties can be designed with consideration of condition-based maintenance philosophy and prognosis results. Unfortunately, this topic has not received any attention in the current literature. Condition-based warranty policies based on battery degradation analysis deserve in-depth investigation.

4.4. Warranty logistics and management for batteries

The objective of warranty logistics is to ensure the availability of spare parts in a warranty service network and minimize downtime of products distributed in different nodes while balancing stock-out risks against inventory costs (Murthy 2004). Its tasks include strategically managing inventory for replacements and recalls, as well as supply chain and reverse logistics network optimization (Calmon and Graves 2017). Warranty logistics is often challenged by intermittent and lumpy demands of spare parts driven by random part failures (Zhang *et al* 2021). For battery warranties, these challenges are amplified due to the high cost, technical complexity, and safety-critical nature of battery components.

Researchers have applied a variety of methods to analyze warranty logistics. Existing studies have highlighted that predictive analytics are highly useful for demand forecasting and inventory planning to ensure that spare parts are available in warranty services with reasonable costs (see the review paper by Zhang *et al* (2021)). By integrating historical failure rates of certain products, real-time performance data, and environmental factors (such as usage patterns), it is possible to estimate the amount of warranty claims and in turn the demands of spare parts (Calmon 2015). Advanced prognostic methods should be tailor-made for battery warranty logistics to anticipate failures and optimize spare parts distribution (Chung *et al* 2020) while accounting for the varying impacts of electrochemical reactions on battery degradation and addressing unique challenges such as estimation of non-linear SOH degradation.

Spare part supply chain network modeling, design and optimization are also important for controlling the total warranty cost of a battery manufacturer. Existing topological facility and inventory location studies regard the number of geographically dispersed service centers and their locations as variables and aim to minimize transportation costs and lead times while ensuring spare parts availability across a supply network (Melo *et al* 2009, Farahani *et al* 2014, Puerto *et al* 2018). The warranty distribution network resembles a closed-loop supply chain network with particular challenges in managing reverse flows from refurbished products. Ashayeri *et al* (2015) developed a mixed integer programming model for designing the warranty distribution network with recovery processes. Rezapour *et al* (2016) studied an integrated flow planning framework in forward and after-sales supply chains for providing product-warranty packages. These are also expected to be the basic logics of spare part supply network optimization in the battery sector. Recent advancements have combined stochastic processes for modeling demand uncertainty (Jin and Liao 2009, Xie *et al* 2024), and machine learning for real-time rerouting. These can be helpful for warranty logistic network design of batteries. However, it is still essential to account for unique constraints of battery products and relevant services, such as their high weight-to-value ratio and safety regulations for transporting hazardous materials.

It should be noted that there are also studies that link the vulnerabilities and risks of warranty logistics with geopolitical issues (Cheng *et al* 2024, Ren *et al* 2024). However, such topics are out of scope of this paper.

5. Discussions and research perspectives

This paper has so far presented state-of-the-art warranty policies and implementations in the battery sector, which are expected to be helpful for further research in warranty design and analysis of batteries. In this section, we would like to highlight some potential topics. Figure 3 illustrates a road map for the potential research endeavors on battery warranties.

5.1. Combined warranty policy considering battery performance indicators

Since EVs are relatively new entrants in many markets, they heavily rely on manufacturer warranties to reassure potential customers of their reliability and long-term value. These warranty policies not only serve marketing functions but also carry significant economic implications. Therefore, it is essential to assess whether current warranty offerings are cost-optimal from both manufacturer's and consumers' perspectives.

Battery performance is multi-dimensional, such as capacity retention, internal resistance, and charge-discharge cycles, which necessitates the development of warranty policies that account for multiple performance indicators. In this context, multi-criteria optimization becomes a powerful tool for defining warranty terms that balance cost, risk, and customer satisfaction. Zhao *et al* (2018) have developed a MCDM framework with a Delphi-based expert evaluation approach for BESSs. This methodology could be adapted and extended to other battery products to better capture the trade-offs among different degradation indicators.

Furthermore, as discussed in section 4.1, a combined warranty model of FRW and PRW can be more flexible. Future research should explore how such hybrid policies can be customized based on a set of performance indicators, potentially using reliability models or machine learning to forecast battery aging and usage patterns.

5.2. Warranty design for new business models

In the BaaS business model, the batteries are managed by a battery asset company in a centralized model. In this manner, when the battery manufacturer sells batteries to the asset company, it can offer cumulative warranties (Murthy and Blischke

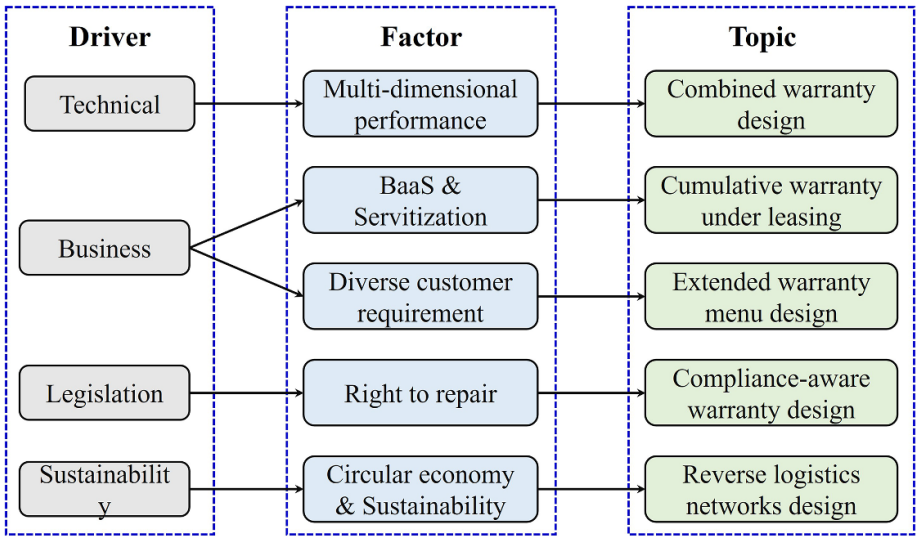


Figure 3. Potential research topics for battery warranties and their drivers.

2006) for the whole fleet of batteries. Without specific guarantee for individual batteries, cumulative warranties are expected to reduce administrative costs to buyers as well as vendors. An additional benefit to the vendor is that cumulative warranties can reduce the number of replacements provided, in an expected fashion, because unusually early battery failures could be compensated by batteries with long lifetimes. The idea of cumulative warranties can be implemented in various ways; more detail can be referred to Blischke (1990), Murthy and Blischke (2006) and Rao (2021).

Peng (2023) has studied warranty services in the BaaS mode, traditional battery purchasing mode, and the combining mode of the above two. She considered market demand of batteries as a linear function of battery price and warranty length and compared the three modes by calculating their profits respectively. She found that when the warranty period is much longer or shorter than average leasing duration, the BaaS mode is more profitable. It should be noted that this study is based on basic FRW policy without renewals, and thus future research should expand this analysis by incorporating more nuanced warranty types. Xie *et al* (2025b) investigated the manufacturer's optimal pricing strategies for battery-leasing services under performance-guaranteed warranties and examined the impact of various collaboration models between the manufacturer and a battery asset company. Considering different stakeholders in the new business modes of batteries, new models for warranty cost decomposition and warranty cost allocation are expected. For example, for batteries in BaaS or shared EVs and BESSs, warranty costs can be broken into replacement/repair expenses and fixed maintenance costs. Quantitative frameworks for warranty allocation and liability distribution among manufacturers, asset owners, and service providers would be highly valuable.

5.3. Warranty studies for complying with new legislation

The recent right to repair movement in the USA and European Union challenges the current warranty practices for a wide range of consumer products, including household appliances, consumer electronics, and vehicles. Although the current right to repair laws or directives do not extend to EVs and batteries, this regulatory shift opens up new research avenues, including compliance-aware warranty design, long-term cost forecasting, and reverse logistics planning under extended support obligations.

Take the European Union's right to repair directive as an example. It prohibits manufacturers from using, for example, contractual clauses to obstruct the repair of the product unless justified by legitimate and objective factors. Also, it requires manufacturers to provide consumers with an extra year of warranty if they choose to repair the product instead of replacing it. In addition, the directive requires manufacturers to provide spare parts for consumers and third-party repairers for up to 10 years after a product's launch. It is clear that this movement will create both challenges and opportunities for battery manufacturers to adapt and innovate their warranty practices, from warranty policy design to warranty cost analysis to warranty logistics.

5.4. Extended warranty design and pricing

Up to now, the battery warranties we discussed are base warranties, which are generally provided by the manufacturers at no additional cost. In recent years, offering extended warranties has become a prevalent practice for EV manufacturers, retailers, and third-party insurers to extract more profits from customers. For example, Tesla offers an Extended Service

Agreement to selected models, allowing customers to extend warranty coverage by up to 2 years or 25 000 miles, whichever occurs first. However, it seems that most EV extended warranties do not cover powering batteries. The only exception is MotorEasy, who claims that their extended warranty is the first of its kind in the UK to include the powering batteries.

Although extended warranties have been studied extensively (Murthy and Jack 2014), the particular requirements for battery warranties are not considered. A promising research direction lies in studying consumer willingness-to-pay for extended battery warranties. In addition, a prevalent phenomenon in after-sales markets is the offering of extended warranty menus (Wang *et al* 2020, Wang 2023). Investigating the optimal design and pricing strategy for extended warranty menus, possibly with differentiated performance guarantees, dedicated to batteries is of interest.

5.5. Warranty management for circular economy and sustainability

Since EV batteries can be reused for BESSs, circularly economic issues need to be considered in battery warranty management. From the warranty policy design and analysis perspectives, recycling clauses and cost sharing regulations should be included not only for societal duties but for economic responsibilities. For example, if an EV manufacturer can reuse or resale the replaced EV batteries, then its expenses in warranty services can be compensated. Then, a larger margin to the break-even point can promote a more generous warranty policy to play better in marketing. To support circular economy principles, integrated warranty and recycling strategies should be developed. These would include mechanisms for value from repurposed batteries and material reclamation, and their implications on warranty servicing cost offsets.

For warranty logistics management, reverse logistics networks for EOL batteries and reuse planning are critical, which can be regarded as a closed-loop supply chain design. Research potential lies in streamlining the recycling processes under warranty programs and the subsequent repair/remanufacturing and repurposing works. Such topics have been studied in the consumer electronics (Ashayeri *et al* 2015, Rezapour *et al* 2016, Calmon and Graves 2017) and EV industries as a whole (Yildizbaşi *et al* 2018), which can be referred in the battery warranty logistics and associated warranty policy designs.

Furthermore, sustainability issues should be considered in warranty design and management of batteries because such products designed for sustainability-friendliness may cause environmental pollution if they are not manufactured with high quality or used in an appropriate way. Multicriteria decision-making methods have been developed for resolving safety and sustainability issues in battery supply chain (Kumar *et al* 2021), but there is still a need for quantitative models that incorporate environmental impact and carbon footprint into warranty cost analysis, using methods such as life-cycle assessment integrated with multi-objective optimization.

Acknowledgment

This work was supported in part by the National Natural Science Foundation of China (Grant Nos. 72201180, W2511076). The work conducted by Yiliu Liu is supported by EU Marie Curie Staff Exchange program (No. 101181231) and Norwegian Research Council (No. 352375).

Appendix. Summary of current warranty policies for EVs.

In table A1, we summarize some representative warranty policies for EVs and batteries (as of December 2024). We can see that the standard battery warranty adopted by most manufacturers is 3 years/36 000 miles, with 70% retention of battery capacity.

Table A1. Summary of current warranty policies for EVs (as of December 2024).

Brand	Vehicle warranty	Battery warranty	Capacity guarantee	Additional notes
Tesla	4 years/50 000 miles	8 years/100 000–150 000 miles	70%	Higher mileage coverage for premium models
Hyundai, Kia	5 years/60 000 miles	10 years/100 000 miles	70%	
BYD	6 years/150 000 km	8 years/160 000–200 000 km	70%	Mileage coverage for batteries differs across countries
Ford, Chevrolet, Honda, Jeep, Mazda, Nissan, Toyota	3 years/36 000 miles	8 years/100 000 miles	70%	
Li Auto	5 years/100 000 km	8 years/120 000 km	—	Warranty policy in China

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