Fair Market Valuation of Electric Vehicle Batteries in Second Life Applications*

Amadeus Bach
ambach@uni-mannheim.de
MISES
University of Mannheim

Simona Onori
sonori@stanford.edu
Energy Science and Engineering Dept.
Stanford University

Stefan J. Reichelstein
reichelstein@stanford.edu
MISES, University of Mannheim
GSB, Stanford University

Jihan Zhuang
jihan123@stanford.edu
Energy Science and Engineering Dept.
Stanford University

August 2024

*We thank Marie-Louise Arlt (discussant), Stephen Comello, Bruis van Vlijmen, seminar participants at the Stanford StorageX Group meeting, TRR 266 Annual Conference 2023, University of Mannheim, VfS AURÖ Workshop 2024, and 12^{th} Mannheim Conference on Energy and the Environment for helpful comments and suggestions. Authors are listed in alphabetical order. Correspondence and requests for materials should be addressed to Amadeus Bach (email: ambach@uni-mannheim.de).

Abstract

The rapidly growing number of lithium-ion battery packs deployed in electric vehicles (EVs) entails enormous economic potential for used EV batteries to be redeployed in a second life application, e.g., for behind-the-meter stationary energy storage. To examine this potential, we develop a generic economic valuation model for used capacity assets in which second life usage requires repurposing costs and delays the receipt of recycling payoffs. Our model estimates point to a robust economic case for repurposing battery packs with iron-based cathodes (LFP batteries). Specifically, we project that the fair market value of LFP batteries exiting from electric vehicles generally exceeds 40% of the market value of a new battery. The value retention shares of used LFP packs are substantially higher in the U.S. market than in China, owing to the fact that new batteries are traded at higher market prices in the U.S. In contrast, our findings point only to a marginal economic case for repurposing batteries with nickel-cobalt-based cathodes (NCX batteries) in the context of the U.S. market. This finding reflects the relatively large recycling payoffs available from nickel and cobalt as well as the relatively short life cycle of NCX cathodes. For the Chinese market, we obtain the unambiguous conclusion that owners of NCX batteries are better off not incurring the requisite repurposing costs but instead immediately collecting the available recycling payoff.

Keywords: Electric Vehicles, Used Batteries, Second Life Applications, Recycling

1 Introduction

Energy storage in batteries is poised to play a central role in the transition to a decarbonized energy economy. The growing importance of lithium-ion batteries has become particularly transparent in connection with the adoption of electric vehicles (EVs). According to the International Energy Agency, electric vehicle registrations grew globally by 60% in 2022, thereby exceeding the threshold of 10 million vehicles (IEA, 2023) for the first time. While this growth rate was not sustained in 2023, analysts nonetheless pointed to the total number of registered EVs and plug-in hybrids increasing from 14.2 to 16.6 million cars in 2024 (IEA, 2023; King, 2024).

Concurrent with the recent growth in EV registrations, renewable energy sources in the form of solar PV and wind power are reaching ever higher penetration levels in many regions worldwide. It is widely accepted that the variability and intermittency of these power sources create a growing need for large-scale energy storage. Lithium-ion batteries are also becoming an increasingly attractive energy storage medium for stationary applications (EIA, 2024), both at the grid level and behind the meter in commercial and residential settings. This paper examines the potential economic synergies that arise from lithium-ion batteries serving the dual purpose of powering electric vehicles (EVs) before being redeployed in a stationary second-life application, e.g., installation behind the meter in homes or commercial buildings outfitted with a solar PV rooftop.[1]

Earlier studies have pointed to the potential of repurposed used EV batteries in stabilizing the electricity grid (Anderson, 2020; Moy and Onori, 2023; Xu et al., 2023; Zhu et al., 2021). Due to the current low volume of battery packs extracted from EVs, the fair market value of these repurposed storage devices remains highly uncertain as of today. However, as millions of used EV batteries will become available either for recycling or for second-life applications in the coming years, a sizeable marketplace for used EV batteries is likely to form. The projected market value of these used assets is of immediate significance for consumers as well as the manufacturers of EVs and battery packs.

In estimating the fair-market value of used lithium-ion battery packs, we rely on a generic economic model for valuing used capacity assets in the vein of Arrow (1964) and Rogerson (2008). Accordingly, assets provide productive capacity for delivering goods and services (For instance, energy storage services in the context of our analysis). An asset's capacity is assumed to degrade

[1] McKinsey (2023) projects that by 2030, the largest demand for Li-ion batteries will come from the mobility sector, while the second largest source of demand will be the stationary energy storage segment.

depending on its usage. Given a particular usage pattern, degradation can then be expressed as a function of calendar time. The crucial concept in valuing used assets is the so-called *user cost of capital*. It reflects the minimum price an investor in new assets would need to obtain for *one unit of capacity made available for one period of time*. The fair market value of a used asset is then given by the discounted future revenues that derive from the asset's remaining capacity in future time periods valued at the user cost of capital in those future time periods. The resulting stream of revenues is to be adjusted for any recycling values attainable at the end of the asset's useful life as well as any repurposing costs incurred in case the used asset is repurposed for its second-life application.

Figure 1 illustrates our adaptation of the generic asset valuation model in the context of used EV batteries. Our model framework presumes the existence of a marketplace in which Rental Equipment Providers (REPs) make battery packs available to customers. These battery packs include items that are dedicated to the (stationary) second life application throughout their economic lives as well as "cross-overs" that were first deployed in EVs. The rental market for used battery packs is assumed to be competitive insofar as REPs break even on their investments, that is, they achieve a net present value of zero for their acquisitions of new and used batteries. Customers, in turn, are assumed to rationally anticipate the trajectory of future new battery prices and the corresponding user costs of capital. Importantly, customers are presumed to be indifferent between short- and long-term contracts for energy storage services provided by the battery packs.

We consider two different cathode chemistries for batteries: Lithium-iron-phosphate (LFP) and Nickel-cobalt (NCX).[2] LFP batteries have been rapidly gaining traction (IEA, 2022) in recent years compared to more expensive NCX batteries. Yet, NCX batteries have a higher energy density, a shorter overall life cycle and more expensive raw materials, which have the potential for significant recycling payoffs.

Our competitive valuation model takes into account that the market prices of new batteries have steadily declined in the past, and are expected to continue to do so in the future. Anticipating an annual decline rate of 3% in the market prices of new lithium-ion batteries, we estimate the fair market value of used EV batteries, at the time they transition to a stationary second life.

[2] Here, X either refers to Manganese or Aluminum. The corresponding battery chemistries are then referred to as NCM or NCA, respectively.

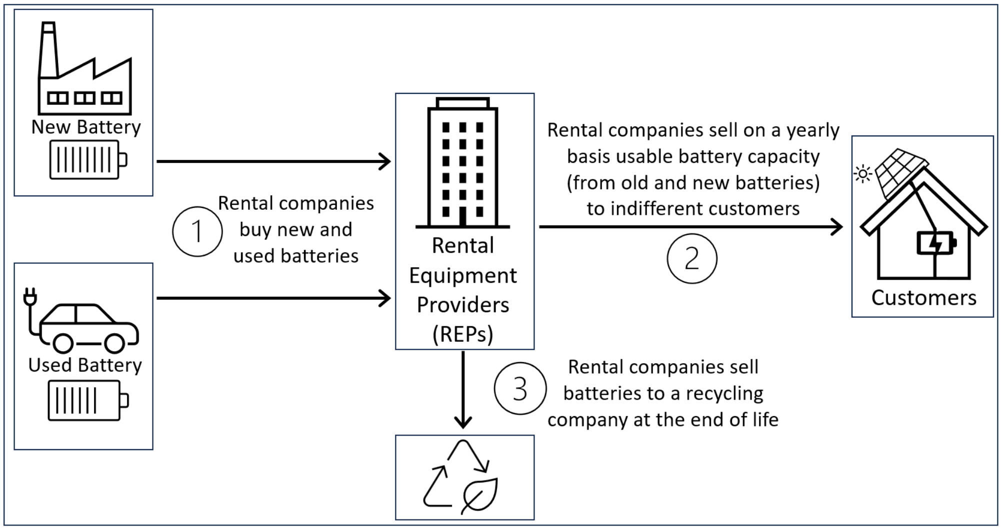


Figure 1: Rental market for battery energy capacity

We analyze these fair market values for both LFP and NCX batteries in two market locations: the U.S. and China. Currently new lithium-ion batteries trade at substantially lower prices in China compared to the U.S. market. This price differential has significant implications for our basic question of whether it is economically preferable to repurpose used EV batteries at a cost, or instead to avoid that cost and immediately collect a recycling payoff.

Our numerical estimates point to significant and robust fair market valuations for LFP battery packs in both the U.S. and the Chinese markets. For these battery chemistries, it makes economic sense to incur the repurposing costs required prior to redeploying the used batteries in their second-life application. Because LFP batteries have relatively long life cycles in terms of the total number of equivalent full charge/discharge cycles, we obtain significant value retention shares i.e., the fair market value of the used battery in relation to the market value of a new battery in a particular year.

For the U.S. market, specifically, the value retention shares of LFP batteries range anywhere from about 40 - 75% depending on the state of health (energy storage capacity) and the assumed degradation rate of the battery in the second-life application. Currently, new LFP batteries are considerably cheaper in the Chinese market than in the U.S. and this differential is expected to persist in the future. For used LFP battery packs in China, we project value retention shares anywhere between 1 - 50%.[3] Nonetheless, we obtain the robust conclusion that in the Chinese market, the repurposing of used LFP battery packs for a second-life application is also preferred to immediate recycling.

Our findings for NCX batteries are more nuanced. More varied conclusions emerge not only because of the significant recycling values of the raw materials in NCX cathodes but also because NCX battery packs have considerably shorter useful lives in terms of the total number of possible charging cycles. For the U.S. market, we estimate NCX value retention shares in the range of 6 - 40%. However, if at the beginning of the second-life application the battery's state of health is only 70%, then, starting in 2030, immediate recycling will become the preferred alternative for such battery packs, provided they are expected to degrade relatively quickly in the future. In contrast, we obtain rather unambiguous findings for used NCX battery packs in China: owners there will generally obtain a higher payoff from immediate recycling compared to a second-life redeployment after incurring the requisite cost of repurchasing the pack.

Our findings contribute to multiple branches of the literature on the economics of batteries and electric vehicles. In particular, we extend earlier studies on the value of battery packs that have had a first automotive life. Prior academic literature and industry reports suggest a wide range of value estimates. This relatively wide range of estimates reflects different battery health assumptions, different cathode chemistries being analyzed, and multiple estimation approaches.[4]

The fair market value methodology underlying our study relates directly to earlier studies by Sun et al. (2018), Steckel et al. (2021), Börner et al. (2022) and Neubauer and Pesaran (2011). Most closely to our competitive pricing approach, Sun et al. (2018) propose a model for estimating supply and demand curves for second-life batteries and predicting the emerging equilibrium prices. Steckel et al. (2021) estimate the levelized cost of storage for new and used batteries based on a range of market prices for used batteries. Börner et al. (2022) also emphasize the need for used battery packs to be priced competitively in the secondary market. Finally, Neubauer and Pesaran (2011) investigate the impact of second-life usage on the initial pricing of EV batteries.

[3] Since the value retention shares are calculated as ratios, one might expect them to be invariant to the market value of new batteries. However, the numerator in this ratio is reduced by a fixed additive amount, given by the cost of repurposing the battery.

[4] Prices for second-life batteries have either been reported, calculated, or predicted. Reported data can be found in Capgemini (2019), Melin (2022) and Reid and Julve (2016). Predicted and calculated data are available from Neubauer and Pesaran (2011), Gur et al. (2018), Neubauer et al. (2012), Lih et al. (2012), Song et al. (2019), Mathews et al. (2020), Han et al. (2018), and Madlener and Kirmas (2017).

More broadly, our study speaks to the rapidly changing economics of EVs. Reliable estimates regarding the fair market values of used batteries are important for the purchasing decision of EVs in the first place. These estimates have further implications for the economic positioning of EVs with regard to insurance, leasing and lending agreements. Our findings also contribute to the understanding of the environmental impacts of batteries. The manufacture of batteries is material, energy, and water-intensive (Barnhart and Benson, 2013). Second-life usage and battery recycling can reduce life-cycle environmental impacts.[5] Adding a second life to an energy storage device can significantly lower its assessed product carbon footprint per charge/discharge cycle, as the carbon emissions from the manufacturing process are divided over a larger number of charging cycles (Lu et al., 2022; Philippot et al., 2019; Pellow et al., 2015).

The remainder of this paper is organized as follows. Section 2 develops the model framework for used capacity assets. Applications of this model in the context of used LFP batteries are presented in Section 3, while applications to used NCX batteries are examined in Section 4. Our findings are discussed and integrated in Section 5. Section 6 concludes the paper.

2 Model Framework

We adopt a generic economic model for valuing used capacity assets in order to derive the fair market value of used batteries entering their second life. In the context of our model, both new and used assets provide potentially valuable productive capacity. Used capacity assets are assumed to be traded in a competitive rental market in which customers are indifferent between owning an asset (new or used) and renting it on an annual basis for multiple years.

A central concept in valuing used capacity assets is the so-called *user cost of capital*; see for example Arrow (1964), Rogerson (2008) and Rajan and Reichelstein (2009). The user cost of capital refers to the competitive revenue that a Rental Equipment Provider (REP) would need to obtain for one unit of capacity that is rented out to a customer for one period of time. The user cost of capital reflects anticipated price declines for new assets, the rate at which capacity degrades over time, and the anticipated recycling value that the REP is to receive at the end of the asset's useful life. Importantly, the sequence of declining values for the user cost of capital is determined

[5] For example, replacing lithium sourced from raw materials with recycled lithium results in a significant reduction in the mass of material required (Meshram et al., 2014).

implicitly by a zero economic profit condition: if new assets are rented out in each period at the rental rate given by the current user cost of capital, REPs will exactly break even in expectation on their investments in new assets. This break-even criterion will be met for a given discount rate and a given anticipated recycling value.

Dates and time periods are indexed by t, with period t beginning at date $t-1$ and ending at date t. The REP and the rental customers of capacity assets have an infinite planning horizon and discount future expected payoffs at the common discount rate, r. The market prices of new assets (batteries with a particular chemistry) are assumed to decline over time at a constant rate η so that the market price at date t is $\eta^t \cdot v$ per unit of the asset. Degradation of new assets is represented by the State of Health (SOH) parameter x_t, with $x_1 = 1$, $x_t > x_{t+1}$ and $x_{T+1} = 0$. Thus, an asset that was acquired at date 0 and comes into use at date 1 reaches the end of its useful life (its aging knee) at date T. In our empirical analysis of used batteries, we argue that battery degradation is not driven by calendar time, but by usage. Given the assumed usage pattern of a battery in each year of its second life, there will then be a 1-1 mapping between time- and usage-driven degradation.

Abstracting from any recycling values attainable at the end of an asset's useful life, earlier studies by Arrow (1964), Rogerson (2008) and Rajan and Reichelstein (2009) have identified the following user cost of capital in period t:

$$c_t = \frac{\eta^t \cdot v}{\sum_{i=1}^{T} \eta^i \cdot x_i \cdot (1+r)^{-i}}. \tag{1}$$

To identify the user cost of capital in accordance with equation (1), the earlier studies have shown that if the REP acquires new assets in each period and rents out new and used batteries at the current user cost of capital, c_t, for a $t = 1, 2...$, then the REP will exactly break even. Specifically, the present value of rental revenues will be exactly equal to the present value of all investment expenditures in new assets. Furthermore, this equality holds independently of the REP's investment pathway in new capacity investments.

Our model extends the earlier studies on the market value of used assets by including the possibility of a recycling value that the REP receives at the asset's terminal date T. This recycling value is assumed to be a constant share, represented by the parameter u, with $0 \leq u \leq 1$, of the initial acquisition price v. Thus, an asset acquired at date t that reaches the end of its useful life at date $t+T$ still has a recycling value of $v \cdot u$ at date $t+T$. Appendix A demonstrates the following expression for the user cost of capital in the presence of recycling values.

Claim 1. *Suppose the acquisition value of new assets declines geometrically at rate η and the recycling value of an asset at the end of its useful life is a fixed proportion, u, of the initial acquisition value of new assets, v. The user cost of capital is then given by:*

$$c_t^* = \frac{\eta^t \cdot v}{\sum_{i=1}^{T} \eta^i \cdot x_i \cdot (1+r)^{-i}} - \frac{u \cdot v \cdot (1+r)^{-T}}{\sum_{i=1}^{T} x_i \cdot (1+r)^{-i}}. \tag{2}$$

Suppose now that at the beginning of period t, i.e., at date $t-1$, the state of health equal of a used asset is x_i, for $1 \leq i \leq T$. The REP will then be able to obtain a rental payment of

$$RP_t(x_i) = x_i \cdot c_t^*$$

in period t. The attainable rental payment in period $t+1$ becomes $RP_{t+1}(x_i) = x_{i+1} \cdot c_{t+1}^*$, and so forth. Therefore at the beginning of period t the future rental payments for a used asset with SoH equal to x_i will be equal to:

$$FRP_t(x_i) = \sum_{j=0}^{T-i} c_{t+j}^* \cdot x_{i+j} \cdot (1+r)^{-(j+1)}. \tag{3}$$

From the perspective of period t, the future recycling value of the used battery with a state of health equal to x_i is given by:

$$FRV_t(x_i) = v \cdot u \cdot (1+r)^{-(T-i+1)}. \tag{4}$$

If an asset is transferred from its original first-life application to its second-life use, the REP is assumed to incur repurposing costs, REC, at that time. For simplicity, we assume repurposing costs are time-invariant. Hence, if a repurposed asset with a state of health equal to x_i entering its second life application is utilized up to the end of its useful life, its fair market value in period t is:

$$FMV_t^o(x_i) = FRP_t(x_i) + FRV_t(x_i) - REC. \tag{5}$$

We note that the term $FRV_t(x_i)$ depends on the state of health, that is, x_i, at date t, because x_i determines how many years into the future the used asset will reach its terminal age.

In the presence of recycling values, equation (5) only provides a lower bound on the fair market value of the used asset. This is because the REP might potentially save on the repurposing costs and immediately recycle the asset. We therefore define the fair market value of a used asset with a current state of health equal to x_i in period t as:

$$FMV_t(x_i) = \max\{FMV_t^o(x_i), v \cdot u\}. \tag{6}$$

Depending on the underlying parameter values, it is also conceivable that the REP may incur the repurposing cost and yet not utilize the asset to the end of its useful life in order to collect the recycling payoff at an earlier point in time. In the context of lithium-ion batteries, our calculations below show that such in-between scenarios are always dominated by one of the two boundary values on the right-hand side of equation (6).

3 Model Application: Used LFP Batteries

3.1 Parameter Calibration

This subsection calibrates the preceding model in the context of EV batteries that transition to a stationary application. To that end, we begin with market data for the prices of new batteries and the anticipated future decline in those prices. The expected pathway of battery degradation rates in the second-life application is estimated based on multiple studies and data sources. The resulting user cost of capital estimates and fair market valuations for used LFP batteries are reported in the following subsection 3.2. Fair market values and additional parameter calibration of NCX batteries are in section 4.

Battery Chemistry

The vast majority of lithium-ion batteries that have been depoloyed up to now in EVs are based either on lithium iron phosphate (LFP), or Nickel-cobalt-X (NCX) chemistries (IEA, 2022). LFP batteries have a comparative advantage in longevity (Preger et al., 2020; Li et al., 2020), thermal stability (El Moutchou et al., 2022; Li et al., 2020) and manufacturing costs. NCX batteries, in contrast, have higher energy density and significant recycling values due to the nickel and cobalt content in the battery cathode.

At the beginning of 2022, LFP cells were used in 3% of EV batteries in North America, 6% in the European Union, and 44% in China (Jin and Lienert, 2022). In the first quarter of 2022, Tesla equipped nearly half of its globally produced vehicles with an LFP battery, though the company relied predominantly on NCX lithium-ion batteries up to that point in time (Tesla, 2022). The rising adoption of LFP chemistry by Tesla may herald a tipping point for other European and U.S. carmakers to rely increasingly on LFP batteries. Wood Mackenzie highlights the growing market share of LFP batteries and their relative benefits in cost, longer lifecycle, and high safety performance (Mackenzie, 2022). The combination of improved energy density, reduced reliance on volatile raw material prices (Campbell et al., 2022) and lower costs suggests a rising percentage of LFP batteries in EVs in the future vehicle mix. This perspective is consistent with recent assessments by the International Energy Agency (IEA, 2022).

New Battery Prices

The term $v \cdot \eta^t$ in our model refers to the acquisition price of the entire battery pack in year t. This price includes the power component and the battery management system in addition to the battery cells. We initially rely on US battery prices from data reports sponsored by the U.S. Department of Energy (Cole et al., 2021; Viswanathan et al., 2022). Specifically, we adopt an estimated market price of $v = \$389$ per kWh for new LFP battery packs in 2024. These are assumed to have a duration of 3.7 hours.[6] The power component of the battery pack will then be appropriate for both mobile automotive and stationary behind-the-meter applications.

The model parameter η refers to the rate at which new battery prices are expected to decline in future years. Earlier studies have examined the decline in the cost of new batteries as a function of the cumulative production volume delivered by the entire industry. Such learning-by-doing models have estimated learning rates in the range of 16-24%, meaning that with every doubling

[6] The duration of a battery is given by the energy-to-power ratio. It therefore represents the number of hours the battery can be discharged at maximum power output.

of cumulative volume the acquisition costs would drop to somewhere between 76% and 84% of its previous value (Glenk et al., 2021; Kittner et al., 2017; Schmidt et al., 2017; Ziegler and Trancik, 2021). Based on data reports by (Cole et al., 2021; Viswanathan et al., 2022), we forecast future prices for new battery packs as a function of time and estimate an annual battery price decline of 3%, that is, $\eta = 0.97$.[7] Applying this price decline pattern over the next decade, comparable new LFP battery packs are expected to trade for $v \cdot \eta^{11} = \$278$ per kWh in the year 2035.

Degradation

The model described in Section 2 presumes that an asset's productive capacity declines as a function of time, represented through the declining sequence $0 \leq x_T \leq x_{T-1} \leq ... \leq x_1$. For a given battery chemistry, the rate of decline in the state of health is arguably driven by three factors: (i) the number of annual cycles, N, (ii) the average depth of discharge, DoD and iii) the total number of possible charge/discharge cycles.[8] Specifically, the state of health, x_t, of a battery is modeled here as:

$$x_t = \left(1 - \frac{N \cdot \text{DoD}}{EFC_{\text{Theoretical}}}\right)^{t-1}, \text{ for } t \geq 1,$$

where $EFC_{\text{Theoretical}}$ refers to the (theoretical) total number of equivalent full charge- and discharge cycles that the battery can perform over its useful life. One EFC corresponds to charging and discharging the battery in the amount of the original usable energy capacity, without any degradation up to this point in time.[9]

A battery's state of health (SoH) in its second life application depends on the battery chemistry, the cycling demands in the second-life application and the battery's state of health, x_i (with $i < t$), when entering its second life. The parameter, x_i, in turn, depends on the usage pattern in the first life. Our analysis allows for potential variation in the first-life usage profile by considering three different SoH values for x_i: 70, 80 and 90%. Maintaining the assumption of a geometric decline pattern in the second life, we obtain:

[7] In the context of the global market for solar PV modules, Reichelstein and Sahoo (2018) estimate the declining long-run marginal cost, and competitive market price of solar panels if the cost of production capacity declines at a constant annual rate.

[8] As the name suggests, depth of discharge refers to the percentage of remaining energy capacity that is charged or discharged in each cycle.

[9] Our model ignores so-called calendar aging, that is, the possibility of batteries degrading over time, even if they are not utilized.

$$x_t = x_i \cdot \left(1 - \frac{N \cdot \text{DoD}}{EFC_{\text{Theoretical}}}\right)^{t-i}, \text{ for } t \geq i. \quad (7)$$

The decline pattern in equation (7) essentially presumes a "Markov" structure: given the state of health at the beginning of the second life, i.e., x_i, the usage pattern in the first life does not matter.

Our calculations for stationary second-life calculations presume daily cycles, that is $N = 365$, and a DoD factor of 80%, a value that is commonly assumed to avoid excessive degradation. In addition, we consider fast, medium and slow degradation scenarios by allowing for theoretical EFCs of 10,000, 20,000 and 30,000 for LFP batteries. The medium degradation scenario is based on Figure 2a of Preger et al. (2020), while the fast and slow degradation scenarios are included here as a sensitivity analysis.

Finally, our calculations reflect the concept of the "aging knee" by supposing that equation (7) is applicable only up to a critical state of health value, while x_{t+i} drops to zero thereafter. We assume that battery life for the LFP chemistry battery life ends at the end of the year when the energy charge capacity reaches the aging knee, set at 50% of the theoretical EFC.

In calibrating the trajectory of the state of health parameter for the stationary applications, we rely on three different data sources: i) Data from Stanford University's battery lab (Zhuang et al., 2024); ii) crowd-sourced real-life data from electric car drivers (Lambert, 2018); iii) prior academic publications relying on simulated usage.

In assessing the quality of our prediction model for second-life battery degradation, we note that the lab data of Zhuang et al. (2024), calculated at the battery pack level, is based on a simulation tool that tests the impact of varying numbers of cycles on the degradation rate.[10] However, real-world applications with a thermal management system may result in different predictions than laboratory tests, as the latter typically do not include active battery cell cooling. Hence, the crowd-sourced data (see, e.g., Lambert (2018)) complements our laboratory data, allowing us to

[10] Most prior literature relies on laboratory tests or selected field data, as wide-scale data on real-life automotive usage is scarce. Recent contributions to the literature include Wassiliadis et al. (2022) who perform an accelerated aging test of lithium-ion battery cells without an active cooling system and an NMC battery of a Volkswagen ID.3 Pro Performance. They find a reduced aging rate compared to prior literature, with graphs pointing towards an SoH of around 85-95% after 8 years or 160,000 km. Preger et al. (2020) conduct a multi-year cycling study of LFP, NMC, and NCA batteries and find a remaining 80% SoH with around 4,000 EFC for LFP, 1,000 EFC for NMC, and 600 EFC for NCA.

observe real-life degradation levels for EV batteries.[11] At the same time, the latter data may be afflicted by a self-reporting selection bias and the mixture of different cell chemistries across car models.

Repurposing Costs

Prior to deployment in a stationary second-life application, the EV battery must be repurposed at a cost. Earlier literature estimates these repurposing costs at 32 \$/kWh (Neubauer et al., 2012), 21-50 \$/kWh (Neubauer et al., 2015),[12] 25-50 €/kWh (Reid and Julve, 2016), and 65.3 \$/kWh (Cready et al., 2003).[13] In line with the literature estimates, we assess the cost of repurposing an EV battery, REC, for deployment in a stationary second-life application at 45 \$/kWh.[14] This value is approximately the average of the above literature estimates, including currency conversion. Lower values could be achieved with local battery sourcing and economies of scale as elaborated in Neubauer et al. (2015). A study by McKinsey (2019) predicts that the cost of manufacturing new batteries will fall faster than repurposing costs over the coming decades. If accurate, this prediction points to a growing relevance of repurposing costs for the fair market value of used batteries. Consistent with Steckel et al. (2021), our calculations reflect that any shift in repurposing costs changes the fair market value of a used battery on a dollar-for-dollar basis.

Recycling Value

The accelerated pace of EV adoptions presents both waste-management challenges and opportunities to recover valuable metals at the end of battery life (Harper et al., 2019). In response to these opportunities, a nascent EV battery recycling industry has emerged which has yet to achieve significant scale economies. As recycling technologies advance and economies of scale are realized, the economic value of recycling is expected to increase in parallel with the growing volume of end-of-life batteries requiring processing in the coming years.

The model described in Section 2 posits that recycling profits, that is, recycling revenues less applicable transportation and processing costs, are a constant percentage of the price of a battery

[11] Crowd-sourced data is available from a group of Tesla owners of the Dutch-Belgium Tesla forum that gathered data from over 350 Tesla vehicles worldwide with nickel-cobalt-based chemistry and published this data in 2018. A fitted trendline suggests that around 90% of usable battery energy capacity is left after 300,000 km.

[12] Figure 27 of Neubauer et al. (2015).

[13] Sum of costs excluding battery price taken from Figure 7 of Cready et al. (2003).

[14] Higher thermal stability of LFP batteries could further reduce these repurposing costs in the future compared to NCX batteries.

pack in the year 2024. In contrast to NCX batteries, there is no evidence that LFP batteries entail positive recycling profits. In other words, recycling companies will break even if they obtain dead LFP batteries for free and sell the recycled raw materials at a price that covers their transportation and processing costs. Accordingly, we set $u = 0$ in our calculations for LFP chemistries.

3.2 Valuation of Used LFP Batteries

To calculate the user cost of capital, c_t^*, we rely on the parameters compiled in subsection 3.1 and listed in Table 7. Our calculations assume an interest rate (cost of capital) of r =5%. Inserting these parameter values into Equation 2 yields the following values for the user cost of capital.

Table 1: User cost of capital for LFP batteries (in \$/kWh) in the U.S.

Chemistry	Degradation	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
LFP	Fast	44.0	42.7	41.4	40.2	39.0	37.8	36.7	35.6	34.5	33.5	32.5	31.5
	Medium	36.1	35.0	34.0	33.0	32.0	31.0	30.1	29.2	28.3	27.5	26.6	25.8
	Slow	34.4	33.3	32.3	31.4	30.4	29.5	28.6	27.8	26.9	26.1	25.4	24.6

Consistent with the expression for the user cost of capital in Claim 1, the values for c_t^* in Table 1 decrease at the rate of η =3%, regardless of the assumed rate of degradation in the second-life. This 3% decline pattern reflects our specification that, in contrast to NCX batteries, LFP batteries have no significant recycling value. As one would expect, a relatively slow degradation scenario yields more remaining usable battery cycles and therefore decreases the user cost of capital, c_t^*. From the formula for c_t^* in Claim 1, it is readily seen that an increase in either the cost of capital r or the battery base price v will result in an increase in c_t^*,[15] while an increase in the recycling value u decreases c_t^*. Changes in the price decline factor η, have a non-montonic effect on the user cost of capital. Higher values of the price decline factor η increase both the numerator and the denominator in the expression for c_t^* in the long term. For the parameter values considered in this paper, the overall effect is such that lower values of η, i.e., a faster decline in the price of new batteries, result in a higher user cost of capital early on, an effect that is subsequently reversed in later years.

The user cost of capital values for LFP battery packs allows us to estimate the fair market values in accordance with equation (6). Regarding the SoH of the used battery at its second-life

[15] For example, an interest rate increase from 5% to 7% increases the user cost of capital by 20% for LFP batteries in the medium degradation scenario.

inception, we consider the three alternative scenarios of 70, 80, and 90%. Depending on the initial SOH of a used LFP battery entering its second life and the assumed future degradation rate, Table 2 shows the FMVs for nine alternative scenarios as a percentage of the new battery prices in each future year. We refer to these percentages as *value retention shares (VRS)*. In terms of the notation introduced in Section 2, we formally define:

$$VRS_t(x_i) = \frac{FMV_t(x_i)}{MV_t(x_1 = 1)},$$

where $MV_t(x_1 = 1)$ denotes the market value of a new battery with an initial SOH equal to 100%.

Table 2: Value Retention Shares of used LFP batteries in the U.S.

Chemistry	Degradation	Initial SOH	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
LFP	New battery	100%	389.0	377.3	366.0	355.0	344.4	334.0	324.0	314.3	304.9	295.7	286.9	278.3
	Fast Degradation Scenario	90%	74.7%	74.3%	74.0%	73.6%	73.2%	72.8%	72.4%	71.9%	71.5%	71.0%	70.6%	70.1%
		80%	59.9%	59.5%	59.2%	58.8%	58.4%	58.0%	57.6%	57.2%	56.7%	56.3%	55.8%	55.3%
		70%	43.9%	43.5%	43.1%	42.8%	42.4%	42.0%	41.5%	41.1%	40.7%	40.2%	39.7%	39.3%
	Medium Degradation Scenario	90%	77.4%	77.0%	76.7%	76.3%	75.9%	75.5%	75.1%	74.7%	74.2%	73.8%	73.3%	72.8%
		80%	65.5%	65.2%	64.8%	64.4%	64.0%	63.6%	63.2%	62.8%	62.3%	61.9%	61.4%	60.9%
		70%	51.4%	51.1%	50.7%	50.3%	49.9%	49.5%	49.1%	48.7%	48.2%	47.8%	47.3%	46.8%
	Slow Degradation Scenario	90%	77.4%	77.1%	76.7%	76.3%	75.9%	75.5%	75.1%	74.7%	74.2%	73.8%	73.3%	72.8%
		80%	67.5%	67.2%	66.8%	66.4%	66.0%	65.6%	65.2%	64.8%	64.3%	63.9%	63.4%	62.9%
		70%	56.3%	55.9%	55.6%	55.2%	54.8%	54.4%	54.0%	53.5%	53.1%	52.6%	52.2%	51.7%

Our findings point to significant value retention shares for used LFP batteries anywhere between approximately 40% and 75%. Higher initial SOH values and a slow degradation rate are projected to result in a remarkably high retention share of 77%, while at the opposite end of the spectrum fast degradation and a relatively low SOH=70% would result in a retention share of only 39% for the nine alternative scenarios considered in Table 2, the SOH at the beginning of the second-life application has a considerably stronger impact on the retention shares than the degradation rate. In all scenarios, retention shares decline over time because the user cost of capital, and thereby the attainable rental payments for used batteries, declines with falling new battery prices, yet repurposing costs are assumed to be time-invariant.

In absolute value terms, suppose a used LFP battery enters its second life with a SOH of 80% and capacity degrades at a medium rate in the future, a medium-sized car with a 50 kWh battery pack has a fair market value of around \$10,200 (approximately \$205 per kWh equal to 63.2% of \$324) in 2030. These surprisingly high FMV values reflect the anticipated long useful lives of LFP batteries, possibly exceeding 20 years. Our valuation estimates are relevant for multiple stakeholders, including battery and automotive manufacturers, consumers and recycling companies.

The above calculations were based on US battery pricing data. A report by BloombergNEF (2024) indicates that Chinese prices for new LFP batteries for a 2-hour duration system have declined to v =$115 per kWh in February 2024. Table 3 replicates the analysis in Table 2, except that the initial price of new batteries in 2024 is benchmarked at $115 per kWh.

Table 3: Value Retention Shares of used LFP batteries in the Chinese market.

Chemistry	Degradation	Initial SOH	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
LFP	New battery	100%	115.0	111.6	108.2	105.0	101.8	98.8	95.8	92.9	90.1	87.4	84.8	82.3
	Fast Degradation Scenario	90%	47.1%	45.9%	44.7%	43.4%	42.1%	40.7%	39.3%	37.8%	36.3%	34.8%	33.2%	31.5%
		80%	32.3%	31.1%	29.9%	28.6%	27.3%	25.9%	24.5%	23.0%	21.5%	20.0%	18.4%	16.8%
		70%	16.3%	15.1%	13.8%	12.6%	11.2%	9.9%	8.5%	7.0%	5.5%	4.0%	2.4%	0.7%
	Medium Degradation Scenario	90%	49.8%	48.6%	47.4%	46.1%	44.8%	43.4%	42.0%	40.5%	39.0%	37.5%	35.9%	34.3%
		80%	38.0%	36.8%	35.5%	34.2%	32.9%	31.5%	30.1%	28.7%	27.2%	25.6%	24.0%	22.4%
		70%	23.9%	22.7%	21.4%	20.1%	18.8%	17.4%	16.0%	14.6%	13.1%	11.5%	9.9%	8.3%
	Slow Degradation Scenario	90%	49.9%	48.6%	47.4%	46.1%	44.8%	43.4%	42.0%	40.6%	39.1%	37.5%	35.9%	34.3%
		80%	40.0%	38.8%	37.5%	36.2%	34.9%	33.5%	32.1%	30.7%	29.2%	27.6%	26.0%	24.4%
		70%	28.7%	27.5%	26.3%	25.0%	23.7%	22.3%	20.9%	19.4%	17.9%	16.4%	14.8%	13.2%

We find that if the prices for new LFP batteries trade at about one-third of U.S. prices, it is still profitable to repurpose used EV batteries for a second-life application, though the value retention shares drop dramatically relative to the U.S. market scenario. In the context of the Chinese market, we observe retention shares ranging from 1% to 50% of the value of new LFP batteries. As before, the initial SOH is the main driver of the actual value retention share. We recall that fair market valuations of LFP batteries are calculated as the difference between discounted future rental payments minus the fixed upfront cost of repurposing. With lower prices for new batteries, the value retention shares of future rental payments remain constant, but the fixed effect of the repurposing lowers the overall value retention shares. Further, this effect will become more pronounced in the years with the lowest new battery prices. Thus, the retention shares shown in Table 3 drop into the single digits, particularly for low initial SOH values. In the extreme scenario of 70% SOH and fast degradation, it essentially becomes a toss-up between repurposing the used battery or saving the repurposing cost and discarding the LFP battery.

4 Model Application: Used NCX Batteries

4.1 Parameter Calibration

Because of their higher energy density, NCX batteries are particularly attractive in EV markets that put a premium on the achievable range and acceleration capability of EVs. In contrast, LFP batteries have gained a large market share in markets like China that are willing to trade off range and performance for lower cost. Both battery chemistries are now suitable for mass-market EV models. For example, the standard version of the European Tesla Model 3 relies on LFP chemistry, while the long-range Model 3 version relies on NCX chemistry.

Regarding new battery prices for NCX batteries and the anticipated changes, we again relied on data reports sponsored by the U.S. Department of Energy (Cole et al., 2021; Viswanathan et al., 2022). Accordingly, our calculations start with a U.S. market price of $v = \$434.6$ per kWh for new NCX battery packs in 2024.

We adopt the same framework to model the second-life degradation of NCX batteries. To reflect that the NCX chemistry entails shorter life cycles, we base our three degradation scenarios for fast, medium and slow degradation on Equivalent Full Cycles of 2,500, 5,000 and 7,500, respectively. In line with Zhuang et al. (2024), the aging knee for NCX batteries is assumed to occur once the SOH reaches 60%, in contrast to the 50% for LPF chemistries. Finally, for NCX batteries we again assume \$45 per kWh charge to repurpose the battery pack for its stationary application.

Estimates by Lander et al. (2021) show positive recycling profits for nickel-based EV batteries in most jurisdictions. Our calculations assume that due to their high nickel and cobalt content, NCX batteries can be sold to a recycling company for a time-invariant fee of $u \cdot v = 0.05 \cdot \$434.6 = \$21.73$ per kWh. Clearly, this estimate is sensitive to variations in metal prices, recycling processes, as well as transportation and disassembly costs (Slattery et al., 2021).[16] Our estimate of u is consistent with the claim by Elon Musk, CEO of Tesla, in April 2022: "Even a dead battery pack is worth about a thousand dollars" (TED, 2022) as a 50 kWh battery pack would have a recycling profit of $50 \cdot \$21.73 = \$1{,}086$ in our calculations. The attainability of positive recycling values for NCX batteries is important in alleviating concerns about unrecycled battery waste.

[16] Prices for battery metals sharply increased between 2021 and the spring of 2022. Yet the prices for materials such as lithium subsequently declined again substantially.

4.2 Valuation of Used NCX Batteries

In terms of their user cost of capital, NCX batteries have the advantage of positive recycling values, as reflected in the expression for c_t^* in (2). At the same time, new NCX batteries are more expensive and degrade faster due to a smaller overall number of equivalent full cycles. Table 4 shows that the latter two effects clearly dominate the former, resulting in user cost of capital values that are substantially larger for NCX chemistries than those for LFP batteries, as shown in Table 4.

Table 4: User cost of capital for NCX batteries (in \$/kWh) in the U.S.

Chemistry	Degradation	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
NCX	Fast	121.1	117.4	113.7	110.1	106.7	103.4	100.1	97.0	93.9	91.0	88.1	85.3
	Medium	77.4	75.0	72.7	70.4	68.3	66.1	64.1	62.1	60.2	58.3	56.5	54.7
	Slow	61.2	59.3	57.5	55.7	54.0	52.3	50.7	49.1	47.6	46.2	44.7	43.3

In calculating the fair market value of used NCX batteries, it is important to recall that the logic of our rental equipment model requires future rental payments to be based on the lowest available user cost of capital. Put differently, because used NCX batteries must compete with LFP batteries, the rental payments attainable for NCX batteries must be based on the lower user cost of capital. Our calculations above have shown that the competitive user cost of capital is determined by the NCX technology.

Table 5: Value Retention Shares of used NCX batteries in the U.S. Yellow fields indicate immediate recycling.

Chemistry	Degradation	Initial SOH	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
NCX	New battery	100%	434.6	421.6	408.9	396.6	384.7	373.2	362.0	351.1	340.6	330.4	320.5	310.9
	Fast Degradation Scenario	90%	21.3%	21.1%	20.9%	20.7%	20.5%	20.2%	20.0%	19.8%	19.5%	19.3%	19.0%	18.8%
		80%	14.0%	13.9%	13.7%	13.5%	13.3%	13.0%	12.8%	12.6%	12.4%	12.1%	11.9%	11.6%
		70%	7.0%	6.9%	6.7%	6.5%	6.3%	6.1%	6.0%	6.2%	6.4%	6.6%	6.8%	7.0%
	Medium Degradation Scenario	90%	28.8%	28.6%	28.4%	28.1%	27.9%	27.7%	27.4%	27.2%	26.9%	26.7%	26.4%	26.1%
		80%	19.1%	18.9%	18.7%	18.5%	18.3%	18.0%	17.8%	17.6%	17.3%	17.1%	16.8%	16.5%
		70%	9.2%	9.0%	8.8%	8.6%	8.4%	8.2%	8.0%	7.8%	7.5%	7.3%	7.1%	7.0%
	Slow Degradation Scenario	90%	38.5%	38.2%	38.0%	37.7%	37.5%	37.2%	37.0%	36.7%	36.4%	36.1%	35.8%	35.5%
		80%	27.4%	27.2%	27.0%	26.8%	26.5%	26.3%	26.0%	25.8%	25.5%	25.2%	24.9%	24.6%
		70%	12.4%	12.2%	12.0%	11.8%	11.6%	11.4%	11.1%	10.9%	10.7%	10.4%	10.2%	9.9%

The value retention shares shown in Table 5 show that in the context of the U.S. market NCX batteries are far less attractive for second-life applications than their LFP counterparts. This finding is primarily a consequence of the relatively high acquisition cost of new NCX batteries and, at the same time, the relatively low future rental payments that derive from the competitive user cost of capital based on LFP chemistry. In the scenario of a 70% initial SOH combined with fast degradation, we find that starting in 2030 it would be preferable to collect the recycling value of the used NCX battery immediately rather than collect the limited future rental payments after incurring the repurposing costs. All cells marked in yellow indicate scenarios and points in time where instant recycling becomes the preferred alternative. The corresponding value retention shares for immediate recycling increase over time simply because new NCX battery prices are assumed to decline at the rate of 3% while the absolute recycling value is time-invariant. In general, immediate recycling becomes economically preferable to a second life deployment over time, with faster degradation and a lower initial SoH.

The preceding findings are further reinforced in an environment with relatively low market prices for new battery packs. To illustrate this point, we finally recalculate the FMV of used NCX batteries in the context of the Chinese market in Table 6.

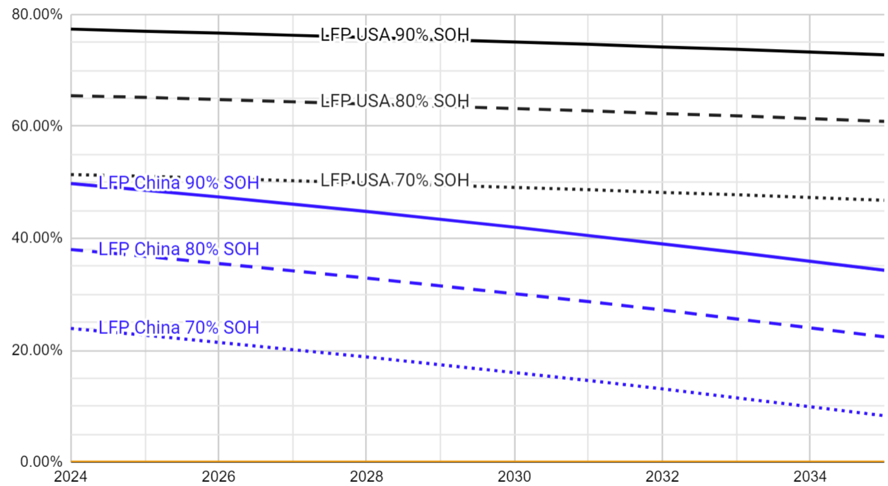
Table 6: Value Retention Shares of used NCX batteries in the Chinese market. Yellow fields indicate immediate recycling.

Chemistry	Degradation	Initial SOH	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
NCX	New battery	100%	128.5	124.6	120.9	117.2	113.7	110.3	107.0	103.8	100.7	97.7	94.7	91.9
	Fast Degradation Scenario	90%	16.9%	17.4%	18.0%	18.5%	19.1%	19.7%	20.3%	20.9%	21.6%	22.2%	22.9%	23.6%
		80%	16.9%	17.4%	18.0%	18.5%	19.1%	19.7%	20.3%	20.9%	21.6%	22.2%	22.9%	23.6%
		70%	16.9%	17.4%	18.0%	18.5%	19.1%	19.7%	20.3%	20.9%	21.6%	22.2%	22.9%	23.6%
	Medium Degradation Scenario	90%	16.9%	17.4%	18.0%	18.5%	19.1%	19.7%	20.3%	20.9%	21.6%	22.2%	22.9%	23.6%
		80%	16.9%	17.4%	18.0%	18.5%	19.1%	19.7%	20.3%	20.9%	21.6%	22.2%	22.9%	23.6%
		70%	16.9%	17.4%	18.0%	18.5%	19.1%	19.7%	20.3%	20.9%	21.6%	22.2%	22.9%	23.6%
	Slow Degradation Scenario	90%	20.7%	20.0%	19.2%	18.5%	19.1%	19.7%	20.3%	20.9%	21.6%	22.2%	22.9%	23.6%
		80%	16.9%	17.4%	18.0%	18.5%	19.1%	19.7%	20.3%	20.9%	21.6%	22.2%	22.9%	23.6%
		70%	16.9%	17.4%	18.0%	18.5%	19.1%	19.7%	20.3%	20.9%	21.6%	22.2%	22.9%	23.6%

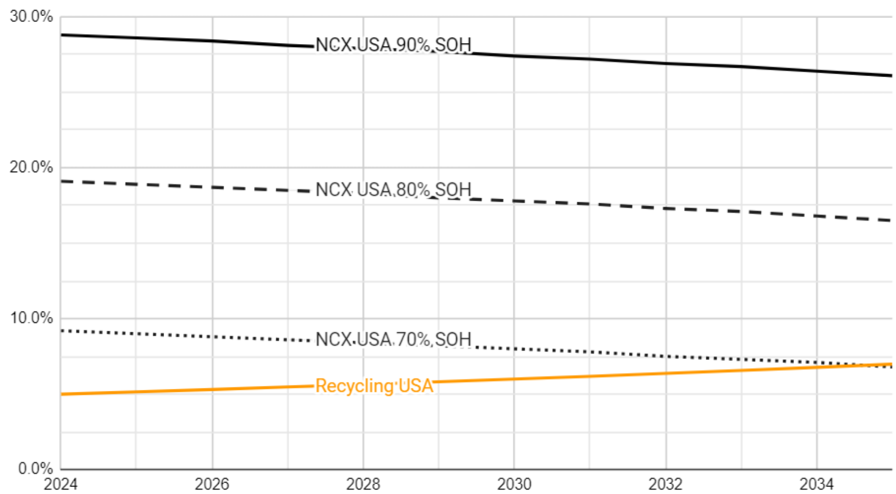
The findings in Table 6 lead to an unequivocal conclusion for NCX batteries in the market environment of China. The payoff from immediate recycling combined with the avoided cost of recycling makes repurposing a used NCX battery unattractive unless future degradation is slow and the candidate battery still has 90% of its initial energy storage capacity. Further, even for this rather favorable scenario our results point to repurposing as the preferred alternative only up to the year 2026.

5 Discussion

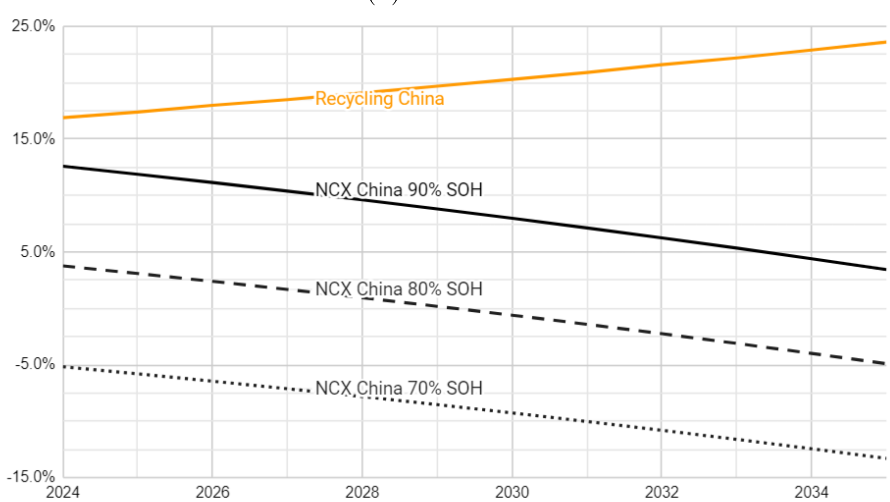
Our findings in the previous sections point to a sizeable market for repurposed LFP battery



(a) LFP USA and China



(b) NCX USA



(c) NCX China

Figure 2: Value Retention Shares of used NCX batteries in the medium degradation scenario.

packs that have had a first automotive life. For used NCX batteries, in contrast, immediate recycling is becoming the preferred alternative for a growing number of scenarios regarding market context, state of health and assumed future degradation.

To display our findings visually, Figure 2 plots the value retention shares from repurposing, defined as:

$$VRS_t^{rep}(x_i) \equiv \frac{FMV_t^o(x_i)}{MV_t(x_1 = 1)},$$

and the value retention shares from immediate recycling, defined as:

$$VRS_t^{rec} \equiv \frac{u \cdot v}{MV_t(x_1 = 1)},$$

for LFP and NCX batteries in both the U.S. and China. Here, the black and blue curves represent the value retention shares from repurposing, while the orange curves represent the value retention shares from immediate recycling. The value retention percentages shown in Tables 2-3 and 5-6 are then obtained as the larger of the two values:

$$VRS_t(x_i) = \max\{VRS_t^{rep}(x_i), VRS_t^{rec}\}.$$

In all scenarios considered in our analysis, $VRS_t^{rep}(x_i)$ is a decreasing function of time, while VRS_t^{rec} is increasing over time.

Since LFP batteries are assumed to result in a net-zero recycling payoff irrespective of market location, the orange line in panel 2a of Figure 2 coincides with the x-axis. The $VRS_t^{rep}(x_i)$ of used LFP batteries in the USA and China do not overlap in 2a, regardless of the assumed SOH at the beginning of the second life. This conclusion must be attributed to the significant price differential for new batteries between the U.S. and China. Tables 2 and 3 have shown that for the fast degradation scenario the corresponding black and blue curves in 2a would dip into the single-digit percentage values, but they would still not cross the x-axis, i.e., $VRS_t^{rep}(x_i) > 0$ for the nine scenarios considered in Tables 2 and 3.

Panel 2b illustrates that for NCX batteries in the U.S. the year 2035 will be the "tipping point" at which immediate recycling becomes preferable, at least in the medium degradation scenario and a 70% state of health at the time the battery would enter its second life application. Naturally, this tipping point will occur at an earlier point in time in a fast battery degradation scenario.

Panel 2c in Figure 2 confirms that in the scenario of medium degradation immediate recycling is the preferred alternative for NCX batteries in China, regardless of the initial state of health. The panel further shows that unless the used battery still has an SOH of around 90%, repurposing a used NCX battery is unprofitable on its own. Thus, repurposing would not make economic sense even if one were to ignore the opportunity cost associated with not receiving the recycling payoff immediately.

6 Conclusion

The analysis in this paper speaks to the emergence of a global market for used EV battery packs that will become available over the next decade. To estimate the fair market value of these assets, our study has examined a generic competitive pricing model in which used assets not only have a recycling value but their redeployment in a second life application requires a repurposing cost. Our fair market value estimates are contingent on several key parameters, including the charge/discharge capacity (state of health) of the battery entering its second life, its future rate of degradation, repurposing costs, battery chemistry, and the expected trajectory of future prices for new batteries.

Our findings present a robust case for repurposing and redeploying LFP batteries in applications with daily cycles, such as storing excess power from renewables either behind the meter or at the grid level. Further, the value retention shares associated with used LFP batteries in the U.S. are generally above 40%, even if the beginning state of health is relatively low and high future degradation rates limit the overall useful life of the battery. Competition between the two types of chemistries implies that the user cost of capital for NCX batteries – the rate at which one unit of energy storage capacity is rented out for one year – is also determined by that for LFP batteries. This effect makes immediate recycling of NCX batteries the preferred alternative in the context of the Chinese market. For the U.S. market, our findings project limited opportunities for repurposing NCX battery packs, and these opportunities are likely to diminish further in the coming decade.

For NCX batteries, it would be instructive in future research to trace out the exact frontier of parameter configurations that separate the recommendation for recycling from that for repurposing.[17] It would also be instructive to document how quickly the available value retention shares increase as one moves away from the frontier separating the two decision alternatives. Similar analyses could be conducted for other battery chemistries such as sodium-ion batteries. Leading global battery manufacturers, such as BYD and CATL, are beginning to mass-produce sodium-ion batteries for automotive applications (Zhang, 2023). The recent work of Yao et al. (2024) suggests that sodium-ion batteries may become competitive with LFP batteries within a decade.

Moving further afield, we recall that our valuation model relies on the assumption of a competitive rental market for energy storage capacity. Additional transaction costs, not recognized in our study, may motivate potential buyers to favor ownership over renting used assets. That would naturally suggest that the seller accompany the sale of the used battery with a warranty provision. Our competitive valuation framework lends itself to quantifying inherent trade-offs in the sale of a used battery and the terms of an accompanying warranty that provides the buying side with performance protection, yet allows the seller to earn a zero economic profit in expectation.

More broadly, our study raises the question of how EV owners can monetize the intrinsic value of used battery packs. Potentially, car manufacturers could offer a lower upfront sales price for EVs, in return for all residual rights to the car's used battery at a certain point in time. Such arrangements might resemble NIO's (Zhang, 2024) rental model for EV batteries.

[17] Future research could also examine the sensitivity of our results to different charge cycles in other second life applications, e.g., frequency regulation or EV charging stations (Zhuang et al., 2024). In that context, we note that some studies, such as Börner et al. (2022), argue that not all EV batteries are suitable for daily cycles in stationary storage applications.

Variable	Explanation	Value
t	Time period (in years)	-
i	Age of battery	-
T	End of battery life (in years)	-
v	System price of new battery ($ per kWh) including power component (energy-to-power ratio of 3.7)	varies
η	Price decline new batteries per year (scalar) (3% price decline)	0.97
c_t	User cost of capital in t	endogenous
SoH_t / x_i	Battery State of Health energy capacity in t	endogenous
u	Recycling profit for NCX batteries (as a percentage of initial acquisition cost, v)	5%
r	Discount rate	5%
FMV	Fair market value used battery ($ per kWh)	endogenous
RP	Rental Payment for usable energy capacity	-
FRP	Present value of future rental payments	-
FRV	Present value of future recycling value	-
VRS	Value retention share: The FMV of the used battery in relation to the market value of a new battery	-
REC	Repurposing costs for used battery ($ per kWh)	45
N	Number of charge and discharge cycles per year (scalar)	365
DoD	Depth of discharge (Battery state of charge operating range)	0.8
$\text{EFC}_{\text{Theoretical}}$	Theoretical EFC (fast degradation scenario) to 0% SoH (LFP/NCX)	10000 / 2500
$\text{EFC}_{\text{Theoretical}}$	Theoretical EFC (medium degradation scenario) to 0% SoH (LFP/NCX)	20000 / 5000
$\text{EFC}_{\text{Theoretical}}$	Theoretical EFC (slow degradation scenario) to 0% SoH (LFP/NCX)	30000 / 7500
$\text{EFC}_{\text{Usable}}$	Total usable EFC as a percentage of the theoretical EFC (LFP/NCX)	60% / 50%

Table 7: Summary of variables

Appendix A. Proof of Claim 1

Suppose the REP invests in new asset capacity according to the schedule

$$\mathbf{I} = (\mathrm{I}_0, \mathrm{I}_1, \mathrm{I}_2, \ldots),$$

where I_t refers to the units of capacity invested in year t. To validate the "user cost of capital", we show that if the rental value per unit of capacity (kWh) is given by:

$$c_t^* = \frac{\eta^t \cdot v}{\sum_{i=1}^T \eta^i \cdot x_i \cdot (1+r)^{-i}} - \frac{u \cdot v \cdot (1+r)^{-T}}{\sum_{i=1}^T x_i \cdot (1+r)^{-i}},$$

then, for any $\mathbf{I}$, the REP will exactly break-even in terms of discounted cash flows. The investment expenditures of the REP are given:

$$\sum_{i=0}^{\infty} v \cdot \eta^i \cdot I_i \cdot (1+r)^{-i} \,. \tag{6}$$

The corresponding discounted cash-inflows (revenues) are given by:

$$\sum_{i=1}^{\infty} c_i^* \cdot K_i(\mathbf{I}) \cdot (1+r)^{-i} + \sum_{i=1}^{\infty} RV_i(\mathbf{I}) \cdot (1+r)^{-i} \,. \tag{7}$$

Here, $K_i(\mathbf{I})$ denotes the capacity stock available in period i, given the investment sequence $\mathbf{I}$. Thus,

$$K_i(\mathbf{I}) = \sum_{j=1}^{i} x_i \cdot I_{i-j} \qquad \text{for } i \leq T,$$

and

$$K_i(\mathbf{I}) = \sum_{j=1}^{T} x_j \cdot I_{i-j} \qquad \text{for } i > T.$$

The payoffs from recycling, $RV_i(\mathbf{I})$, are given by

$$RV_i(\mathbf{I}) = 0 \qquad \text{for } i < T$$

and

$$RV_i(\mathbf{I}) = u \cdot v \cdot I_{i-T} \qquad \text{for } i \geq T.$$

To demonstrate that (6) = (7) for any **I**, we show that the coefficients multiplying each I_i are the same in (6) and (7). Thus, for I_0 the requirement becomes:

$$v = \sum_{i=1}^{T} c_i^* \cdot x_i \cdot (1+r)^{-i} + (1+r)^{-T} \cdot u \cdot v \,. \tag{8}$$

Recalling the definition of c_i^*, equation (8) can be restated as:

$$v = \sum_{i=1}^{T} \frac{\eta^i \cdot v \cdot x_i \cdot (1+r)^{-i}}{\sum_{j=1}^{T} \eta^j \cdot x_j \cdot (1+r)^{-j}} - \sum_{i=1}^{T} \frac{x_i \cdot (1+r)^{-i} \cdot u \cdot v \cdot (1+r)^{-T}}{\sum_{j=1}^{T} x_j \cdot (1+r)^{-j}} + (1+r)^{-T} \cdot u \cdot v, \tag{9}$$

which obviously holds true.

Proceeding to the coefficients multiplying I_1 in (6) and (7), it remains to verify that

$$\eta \cdot v \cdot (1+r)^{-1} = \sum_{i=2}^{T+1} c_i^* \cdot x_{i-1} \cdot (1+r)^{-i} - (1+r)^{-(T+1)} \cdot u \cdot v \,. \tag{10}$$

The left- and right-hand side of (10) are indeed the same because

$$\sum_{i=2}^{T+1} c_i^* \cdot x_{i_1} \cdot (1+r)^{-i} = \sum_{i=2}^{T+1} \frac{\eta^i \cdot v \cdot x_{i-1} \cdot (1+r)^{-i}}{\sum_{j=1}^{T} \eta^j \cdot x_j \cdot (1+r)^{-j}} - \sum_{i=2}^{T+1} \frac{x_{i-1} \cdot (1+r)^{-i} \cdot u \cdot v \cdot (1+r)^{-T}}{\sum_{j=1}^{T} x_j \cdot (1+r)^{-j}},$$

and

$$\sum_{i=2}^{T+1} \frac{\eta^i \cdot v \cdot x_{i-1} \cdot (1+r)^{-i}}{\sum_{j=1}^{T} \eta^j \cdot x_j \cdot (1+r)^{-j}} = \eta \cdot v \cdot (1+r)^{-1},$$

while

$$\sum_{i=2}^{T+1} \frac{x_{i-1} \cdot (1+r)^{-i} \cdot u \cdot v \cdot (1+r)^{-T}}{\sum_{j=1}^{T} x_j \cdot (1+r)^{-j}} = u \cdot v \cdot (1+r)^{-(T+1)}.$$

Proceeding to the coefficients multiplying I_t in (6) and (7), it remains to verify that

$$\eta^t \cdot v \cdot (1+r)^{-t} = \sum_{i=t+1}^{T+t} c_i^* \cdot x_{i-t} \cdot (1+r)^{-i} - (1+r)^{-(T+t)} \cdot u \cdot v \,. \tag{11}$$

Substitution of the expressions for the user cost of capital c_i^* again yields the equality of the left and right-hand side of (11). $\square$

References

Anderson, M. (2020). Used ev batteries could power tomorrow's solar farms.

Arrow, K. (1964). Optimal capital policy, the cost of capital, and myopic decision rules. *Ann Inst Stat Math 16*(1), 21–30.

Barnhart, C. and S. Benson (2013). On the importance of reducing the energetic and material demands of electrical energy storage. *Energy & Environmental Science 6*(4), 1083–1092.

BloombergNEF (2024). Global energy storage market records biggest jump yet. https://about.bnef.com/blog/global-energy-storage-market-records-biggest-jump-yet/.

Börner, M., M. Frieges, B. Späth, K. Spütz, H. Heimes, D. Sauer, and W. Li (2022). Challenges of second-life concepts for retired electric vehicle batteries. *Cell Reports Physical Science 3*(10), 1–19.

Campbell, P., J. Miller, and J. Song (2022). Surging price of battery materials complicates carmakers' electric plans. https://www.ft.com/content/17d2d027-22c1-4ecc-8f92-d70268c8a4ac.

Capgemini (2019). The second life battery cycle: After about 10 years in vehicle, lithium-ion batteries can be reused for another purpose and thereby begin a "second life". https://www.capgemini.com/us-en/2019/04/second-life-batteries-a-sustainable-business-opportunity-not-a-conundrum.

Cole, W., A. Frazier, and C. Augustine (2021). Cost projections for utility-scale battery storage: 2021 update. Technical report, National Renewable Energy Laboratory (NREL), Golden, CO (United States).

Cready, E., J. Lippert, J. Pihl, I. Weinstock, and P. Symons (2003). Technical and economic feasibility of applying used ev batteries in stationary applications. Technical report, Sandia National Laboratories.

EIA (2024). U.s. battery storage capacity expected to nearly double in 2024. https://www.eia.gov/todayinenergy/detail.php?id=61202.

El Moutchou, S., H. Aziam, M. Mansori, and I. Saadoune (2022). Thermal stability of lithium-ion batteries: Case study of nmc811 and lfp cathode materials. *Materials Today: Proceedings 51*, A1–A7.

Glenk, G., R. Meier, and S. Reichelstein (2021). Cost dynamics of clean energy technologies. *Schmalenbach Journal of Business Research 73*(2), 179–206.

Gur, K., D. Chatzikyriakou, C. Baschet, and M. Salomon (2018). The reuse of electrified vehicle batteries as a means of integrating renewable energy into the european electricity grid: A policy and market analysis. *Energy Policy 113*, 535–545.

Han, X., Y. Liang, Y. Ai, and J. Li (2018). Economic evaluation of a pv combined energy storage charging station based on cost estimation of second-use batteries. *Energy 165*, 326–339.

Harper, G., R. Sommerville, E. Kendrick, L. Driscoll, P. Slater, R. Stolkin, A. Walton, P. Christensen, O. Heidrich, S. Lambert, et al. (2019). Recycling lithium-ion batteries from electric vehicles. *Nature 575*(7781), 75–86.

IEA (2022). Global ev outlook 2022. https://iea.blob.core.windows.net/assets/ad8fb04c-4f75-42fc-973a-6e54c8a4449a/GlobalElectricVehicleOutlook2022.pdf.

IEA (2023). As their sales continue to rise, suvs' global co2 emissions are nearing 1 billion tonnes. https://www.iea.org/commentaries/as-their-sales-continue-to-rise-suvs-global-co2-emissions-are-nearing-1-billion-tonne.

Jin, H. and P. Lienert (2022). Insight: Iron man elon musk places his tesla battery bets. https://www.reuters.com/business/autos-transportation/iron-man-elon-musk-places-his-tesla-battery-bets-2022-04-27/.

King, N. (2024). Global ev growth forecast in 2024, but challenges remain. https://ev-volumes.com/news/ev/global-ev-growth-forecast-in-2024-but-challenges-remain/.

Kittner, N., F. Lill, and D. Kammen (2017). Energy storage deployment and innovation for the clean energy transition. *Nature Energy 2*(9), 17125.

Lambert, F. (2018). Tesla battery degradation at less than 10% after over 160,000 miles, according to latest data. https://electrek.co/2018/04/14/tesla-battery-degradation-data/.

Lander, L., T. Cleaver, M. Rajaeifar, V. Nguyen-Tien, R. Elliott, O. Heidrich, E. Kendrick, J. Edge, and G. Offer (2021). Financial viability of electric vehicle lithium-ion battery recycling. *iScience 24*(7), 102787.

Li, W., Y. Cho, W. Yao, Y. Li, A. Cronk, R. Shimizu, M. Schroeder, Y. Fu, F. Zou, V. Battaglia, et al. (2020). Enabling high areal capacity for co-free high voltage spinel materials in next-generation li-ion batteries. *Journal of Power Sources 473*, 228579.

Lih, W., J. Yen, F. Shieh, and Y. Liao (2012). Second use of retired lithium-ion battery packs from electric vehicles: technological challenges, cost analysis and optimal business model. In *2012 International Symposium on Computer, Consumer and Control*, pp. 381–384. IEEE.

Lu, S., G. Serafein, and M. W. Toffel (2022). Driving decarbonization at bmw. *Harvard Business School Case 123-008*.

Mackenzie, W. (2022). Global lithium-ion battery capacity to rise five-fold by 2030. https://www.woodmac.com/press-releases/global-lithium-ion-battery-capacity-to-rise-five-fold-by-2030/.

Madlener, R. and A. Kirmas (2017). Economic viability of second use electric vehicle batteries for energy storage in residential applications. *Energy Procedia 105*, 3806–3815.

Mathews, I., B. Xu, W. He, V. Barreto, T. Buonassisi, and I. Peters (2020). Technoeconomic model of second-life batteries for utility-scale solar considering calendar and cycle aging. *Applied Energy 269*, 115127.

McKinsey (2019). Second-life ev batteries: The newest value pool in energy storage.

McKinsey (2023). Resilient, sustainable, and circular. https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/battery-2030-resilient-sustainable-and-circular.

Melin, H. E. (2022). Twitter post: 17th of november 2022. https://twitter.com/hanseric/status/1593261129706479622.

Meshram, P., B. Pandey, and T. Mankhand (2014). Extraction of lithium from primary and secondary sources by pre-treatment, leaching and separation: A comprehensive review. *Hydrometallurgy 150*, 192–208.

Moy, K. and S. Onori (2023). Synthetic grid storage duty cycles for second-life lithium-ion battery experiments.

Neubauer, J. and A. Pesaran (2011). The ability of battery second use strategies to impact plug-in electric vehicle prices and serve utility energy storage applications. *Journal of Power Sources 196*(23), 10351–10358.

Neubauer, J., A. Pesaran, B. Williams, M. Ferry, and J. Eyer (2012). Techno-economic analysis of pev battery second use: Repurposed-battery selling price and commercial and industrial end-user value. Technical report, National Renewable Energy Laboratory (NREL).

Neubauer, J., K. Smith, E. Wood, and A. Pesaran (2015). Identifying and overcoming critical barriers to widespread second use of pev batteries. Technical report, National Renewable Energy Laboratory (NREL).

Pellow, M. A., C. J. Emmott, C. J. Barnhart, and S. M. Benson (2015). Hydrogen or batteries for grid storage? a net energy analysis. *Energy & Environmental Science 8*(7), 1938–1952.

Philippot, M., G. Alvarez, E. Ayerbe, J. Van Mierlo, and M. Messagie (2019). Eco-efficiency of a lithium-ion battery for electric vehicles: influence of manufacturing country and commodity prices on ghg emissions and costs. *Batteries 5*(1), 23.

Preger, Y., H. Barkholtz, A. Fresquez, D. Campbell, B. Juba, J. Romàn-Kustas, S. Ferreira, and B. Chalamala (2020). Degradation of commercial lithium-ion cells as a function of chemistry and cycling conditions. *Journal of The Electrochemical Society 167*(12), 120532.

Rajan, M. V. and S. Reichelstein (2009). Depreciation rules and the relation between marginal and historical cost. *Journal of Accounting Research 47*(3), 823–865.

Reichelstein, S. and A. Sahoo (2018). Relating product prices to long-run marginal cost: Evidence from solar photovoltaic modules. *Contemporary Accounting Research 35*(3), 1464–1498.

Reid, G. and J. Julve (2016). Second life-batteries as flexible storage for renewables energies.

Rogerson, W. P. (2008). Intertemporal cost allocation and investment decisions. *Journal of Political Economy 116*(5), 931–950.

Schmidt, O., A. Hawkes, A. Gambhir, and I. Staffell (2017). The future cost of electrical energy storage based on experience rates. *Nature Energy 2*(8), 17110.

Slattery, M., J. Dunn, and A. Kendall (2021). Transportation of electric vehicle lithium-ion batteries at end-of-life: A literature review. *Resources, Conservation and Recycling 174*, 105755.

Song, Z., S. Feng, L. Zhang, Z. Hu, X. Hu, and R. Yao (2019). Economy analysis of second-life battery in wind power systems considering battery degradation in dynamic processes: Real case scenarios. *Applied Energy 251*, 113411.

Steckel, T., A. Kendall, and H. Ambrose (2021). Applying levelized cost of storage methodology to utility-scale second-life lithium-ion battery energy storage systems. *Applied Energy 300*, 117309.

Sun, S. I., A. J. Chipperfield, M. Kiaee, and R. G. Wills (2018). Effects of market dynamics on the time-evolving price of second-life electric vehicle batteries. *Journal of Energy Storage 19*, 41–51.

TED (2022). Elon musk talks twitter, tesla and how his brain works – live at ted2022. https://www.youtube.com/watch?v=cdZZpaB2kDM&t=2530s&ab_channel=TED.

Tesla (2022). Tesla quarterly shareholder deck update for q1 2022 earnings call. https://tesla-cdn.thron.com/static/IOSHZZ_TSLA_Q1_2022_Update_G9MOZE.pdf?xseo=&response-content-disposition=inline%3Bfilename%3D%22TSLA-Q1-2022-Update.pdf%22.

Viswanathan, V., K. Mongird, R. Franks, and R. Baxter (2022). 2022 grid energy storage technology cost and performance assessment. https://www.pnnl.gov/sites/default/files/media/file/ESGC%20Cost%20Performance%20Report%202022%20PNNL-33283.pdf.

Wassiliadis, N., M. Steinsträter, M. Schreiber, P. Rosner, L. Nicoletti, F. Schmid, M. Ank, O. Teichert, L. Wildfeuer, J. Schneider, et al. (2022). Quantifying the state of the art of electric powertrains in battery electric vehicles: Range, efficiency, and lifetime from component to system level of the volkswagen id. 3. *Etransportation 12*, 100167.

Xu, C., P. Behrens, P. Gasper, K. Smith, M. Hu, A. Tukker, and B. Steubing (2023). Electric vehicle batteries alone could satisfy short-term grid storage demand by as early as 2030. *Nature Communications 14*(1), 119.

Yao, A., S. M. Benson, and W. C. Chueh (2024). How quickly can sodium-ion learn? assessing scenarios for techno-economic competitiveness against lithium-ion batteries. *arXiv preprint arXiv:2403.13759*.

Zhang, P. (2023). Catl, byd's sodium-ion batteries both to be in mass production within this year, report says. https://cnevpost.com/2023/04/20/catl-byd-sodium-ion-batteries-mass-production-this-year-report/.

Zhang, P. (2024). Nio revamps baas, a key car-buying option for reducing initial costs, amid fierce price war. https://cnevpost.com/2024/03/14/nio-revamps-baas-option-amid-fierce-price-war/.

Zhu, J., I. Mathews, D. Ren, W. Li, D. Cogswell, B. Xing, T. Sedlatschek, S. Kantareddy, M. Yi, T. Gao, Y. Xia, Q. Zhou, T. Wierzbicki, and M. Z. Bazant (2021). End-of-life or second-life options for retired electric vehicle batteries. *Cell Reports Physical Science 2*(8), 100537.

Zhuang, J., A. Bach, B. van Vlijmen, S. Reichelstein, W. Chueh, S. Onori, and S. Benson (2024). A decision-making model for retired li-ion batteries. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4484966.

Ziegler, M. S. and J. E. Trancik (2021). Re-examining rates of lithium-ion battery technology improvement and cost decline. *Energy & Environmental Science 14*(4), 1635–1651.