Fair Market Valuation of Electric Vehicle Batteries in the Circular Economy

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Abstract:

Electric vehicle registrations are growing worldwide. At the end of the vehicle life, used lithium-ion batteries can be reused or recycled. This study presents an economic analysis of used lithium-ion batteries that can be repurposed for a second life to store renewable energy. We employ a valuation methodology that determines at the time of retirement the fair market value of used batteries based on their cathode chemistry, actual state of health, recycling values and battery market characteristics. Our findings reveal that current market characteristics result in positive market values for both nickel-cobalt-based and iron-based cathode batteries. Iron-based cathode batteries exhibit higher values primarily due to longer cycle lives. Additionally, we predict that a larger percentage of used nickel-cobalt-based batteries will be recycled due to an expected decline in used battery prices. Our results have implications for lifetime carbon footprint and total cost of ownership calculations of electric vehicles.

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1. Introduction

Global electric vehicle (EV) registrations are increasing amid favorable regulatory actions and improving cost competitiveness. While the new car market declined in 2022, new electric vehicle registrations increased by around 60% to more than 10 million units (IEA, 2023). This trend points towards a fast adoption of electric cars. Countries that implemented early incentives for electric vehicles, such as Norway, provide insight into possible trends, as evidenced by the growth in EV registrations from a mere 1% in 2011 to an impressive 72% in 2021 (IEA, 2020; IEA, 2022a). Once those EVs reach their end-of-life[1], large amounts of used battery packs will become available. The ambiguity surrounding the capacity to recycle used batteries raises concerns about potential electric waste. Nevertheless, it is not apparent that electric batteries must be immediately recycled following their initial use in electric vehicles (e.g., Gur et al., 2018).

Reusing batteries has been proposed to reduce waste, save money, and reduce EV lifecycle impacts (Harper et al., 2019). Depending on the number of charge cycles during reuse, the carbon intensity of batteries can be improved 2-3-fold with a second life (Pellow et al., 2016). A potential second-life application for batteries is the deployment in a stationary energy storage solution (Moy and Onori, 2023; Zhu et al., 2021), for example, a behind-the-meter deployment combined with solar power (Anderson, 2020). Achieving a high reuse rate of electric vehicle batteries for grid storage applications would be adequate to address the worldwide demand for short-term energy storage by 2050. (Xu et al., 2023). Nonetheless, a large-scale, operational marketplace for repurposing batteries has yet to materialize. Therefore, it becomes imperative to examine the economic viability of reusing batteries no longer suitable for primary mobile applications and their respective fair market value.

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[1] For example, once the vehicle body is not suitable for further usage due to severe defects and shortcomings such as rost or a car crash. In addition, used EV batteries may get available once the battery warranty period ends.

Not all electric batteries are the same. Many electric cars include high-energy-dense batteries based on a nickel-cobalt cathode. In recent years, less energy-dense iron-based (cobalt-free) cathode batteries gained rapid market share (IEA, 2022b). The economics of a second life may differ substantially between different chemistries due to differences in thermal stability, cycle life and production costs.

Prior academic literature primarily focuses on nickel-cobalt-based batteries and relies on diverse approaches for used battery prices. For example, Song et al. (2019) employ industry estimates for battery second-life investment cost and find no economic benefit from reusing batteries in a stationary application. In contrast, Gur et al. (2018) assume second-life battery prices of 30-75% of new batteries and find economically feasible applications for used batteries combined with solar power. This example shows that a precise and adaptive used battery pricing model is essential to estimate the potential of used batteries for decarbonization efforts.

In this paper, we develop an economic model estimating the fair market value of electric car batteries for a second life in a stationary storage solution combined with renewable energy and daily use cycles. This model incorporates differences in battery chemistry, degradation, initial battery state of health (SoH) at the end of the first life and battery market characteristics. Our model determines the battery pack's fair market value at the end of the first application based on a functioning and viable market with indifferent investors and access to new batteries. In addition, we calculate the end-of-life of the used battery based on an equilibrium solution between further usage and recycling or disposal.

Based on current battery market data, we find that used electric batteries offer a positive fair market value in a second life. This value is higher for batteries with a higher state of health at the beginning of the second life, higher new battery prices, lower repurposing costs, and less expected degradation. Then, comparing different chemistries, we find that nickel-cobalt-based cathode batteries (NCX) have lower fair market values than iron-phosphate (LFP) ones due to fewer remaining usage cycles. Currently, a used 60 kWh NCX battery with 90% remaining state of health can achieve a fair market value of around 10,000 $. In the future, we expect falling fair market values for used batteries due to declining new battery prices. At some point until the end of this century, we project that NCX batteries will lose their economic viability for reuse in our second-life application. However, this is not the case for most used LFP batteries. For example, if we assume that an electric car will reach the end of its life in 2030, a used 60 kWh LFP battery pack with 80% state of health is estimated to have a fair market value of 4,200-14,100 $. While NCX batteries have lower reuse values, they include more valuable metals than LFP batteries. Due to those materials, NCX batteries have positive recycling profits. Hence, companies can benefit economically from recycling end-of-life NCX battery packs.

Our paper adds to three different streams of literature. First, we add to the emerging literature[2] investigating second-life applications and prices of used electric batteries. Our fair market valuation models are closely related to Sun et al. (2018), where a methodology is developed to construct supply and demand curves for second-life batteries and predict the average equilibrium price from 2010 to 2050. Furthermore, Steckel et al. (2021) estimate LCOS for new and used batteries based on a range of used battery market prices. We add to this stream of literature by providing a model based on competitive pricing with new battery cells. Furthermore, our model differentiates by cell chemistry and determines the total lifetime endogenously.

Second, our findings add to the literature comparing EVs' economic feasibility. Our study can be integrated with recent work on the financial positioning of EVs versus combustion engine drivetrains (Comello et al., 2021). Earlier studies did not or only inaccurately include a resale value for EV batteries at the end of their first life. One early study by Neubauer and Pesaran (2011) investigates the impact of EV battery second-life usage on the initial cost of

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[2] For more details on literature in this area, please consult Appendix 2.

electric car batteries to automotive consumers and finds relatively minor reductions in upfront costs. It would be informative to examine the sensitivity of earlier life-cycle cost estimates of transportation services by including a resale option in the secondary market. Furthermore, accurate expectations of residual values for used battery packs may be important for the insurance, leasing and car loan sector.

Third, our paper adds to the environmental impact of EV batteries by establishing estimates for lifetime usability with second-life applications. Manufacturing batteries is material, energy, and water-intensive (Barnhart and Benson, 2013). Both second usage and battery recycling[3] can reduce life-cycle environmental impacts. From an energy perspective, extending the life of a battery with a second life can improve the carbon intensity two or three-fold, depending on how much more energy is delivered from the battery over its lifetime (Pellow et al., 2016) as the GHG emissions from the battery manufacturing (Philippot et al., 2019) are divided over more charging cycles. Our paper shows that under certain conditions a reuse is not financially viable for some batteries. Subsidizing these batteries could create positive externalities. Hence, our results may also be relevant to regulators.

2. Results

This section displays our main results for second-life fair market values of used LFP and NCX batteries for the upcoming years. In each table, we employ initial second-life SoH energy capacity values of 70, 80 and 90% (Remaining SoH after the first life). For each initial SoH, we also provide three potential degradation scenarios during the second life (high, medium and low).[4] In case of negative fair market values, batteries are recycled and the seller

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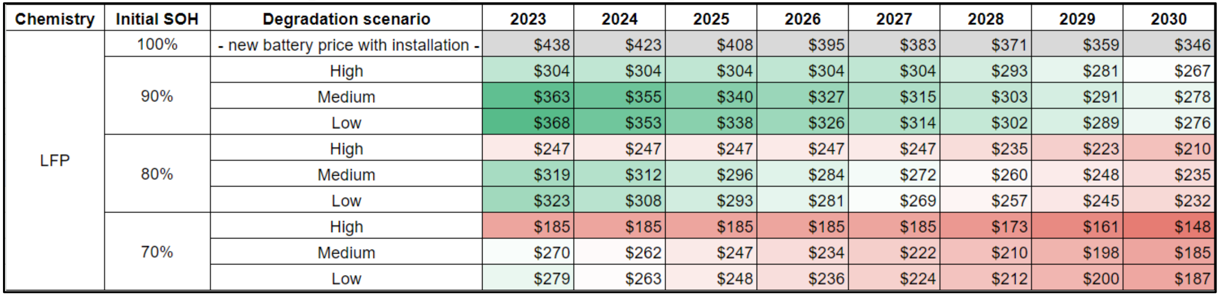
[3] For example, replacing lithium sourced from raw materials with used LIBs results in 10-fold to 30-fold reduction in the mass of material required to supply lithium for new batteries (Meshram et al., 2014).

[4] Different degradation scenarios are included as there is only limited real-world data available for the second life to model the expected degradation accurately. For more details on SoH and degradation scenarios, please consult the discussion section.

receives the recycling profit (see discussion chapter for more details). Table 1 provides fair market values for used LFP batteries based on expected new LFP battery cost declines. All values are positive and range between 148-368 $/kWh. For example, in a medium degradation scenario with 80% initial SoH, a used 60 kWh battery pack is projected to be valued at 14,100 $ (235 $ per kWh) in 2030.

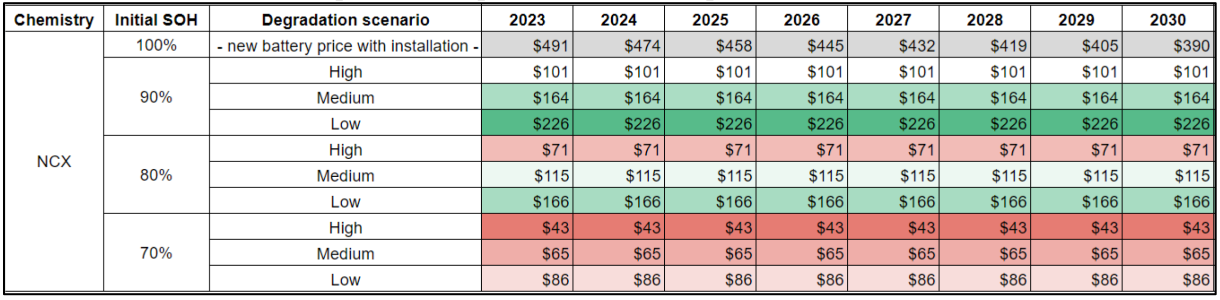
Table 1) Used LFP compared to expected new LFP prices (in $/kWh)



Chemistry	Initial SOH	Degradation scenario	2023	2024	2025	2026	2027	2028	2029	2030
LFP	100%	- new battery price with installation -	$438	$423	$408	$395	$383	$371	$359	$346
	90%	High	$304	$304	$304	$304	$304	$293	$281	$267
		Medium	$363	$355	$340	$327	$315	$303	$291	$278
		Low	$368	$353	$338	$326	$314	$302	$289	$276
	80%	High	$247	$247	$247	$247	$247	$235	$223	$210
		Medium	$319	$312	$296	$284	$272	$260	$248	$235
		Low	$323	$308	$293	$281	$269	$257	$245	$232
	70%	High	$185	$185	$185	$185	$185	$173	$161	$148
		Medium	$270	$262	$247	$234	$222	$210	$198	$185
		Low	$279	$263	$248	$236	$224	$212	$200	$187

Table 2 provides fair market values for used NCX batteries based on expected new NCX (2a) or new LFP (2b) cost declines. All values are positive if fair values for used NCX batteries are calculated based on new NCX prices. However, we argue that more cost-efficient LFP batteries are the proper comparison technology. In this case, used NCX batteries have lower fair market values for reuse. As the decade draws to a close, NCX batteries exhibit negative values, rendering them financially unviable for reuse in our suggested application under the assumptions made.

Table 2a) Used NCX compared to expected new NCX prices (in $/kWh)



Chemistry	Initial SOH	Degradation scenario	2023	2024	2025	2026	2027	2028	2029	2030
NCX	100%	- new battery price with installation -	$491	$474	$458	$445	$432	$419	$405	$390
	90%	High	$101	$101	$101	$101	$101	$101	$101	$101
		Medium	$164	$164	$164	$164	$164	$164	$164	$164
		Low	$226	$226	$226	$226	$226	$226	$226	$226
	80%	High	$71	$71	$71	$71	$71	$71	$71	$71
		Medium	$115	$115	$115	$115	$115	$115	$115	$115
		Low	$166	$166	$166	$166	$166	$166	$166	$166
	70%	High	$43	$43	$43	$43	$43	$43	$43	$43
		Medium	$65	$65	$65	$65	$65	$65	$65	$65
		Low	$86	$86	$86	$86	$86	$86	$86	$86

Table 2b) Used NCX compared to expected new LFP prices (in $/kWh)

Chemistry	Initial SOH	Degradation scenario	2023	2024	2025	2026	2027	2028	2029	2030
LFP	100%	- new battery price with installation -	$438	$423	$408	$395	$383	$371	$359	$346
NCX	90%	High	$101	$101	$101	$101	$101	$89	$77	$64
		Medium	$164	$156	$141	$129	$117	$105	$92	$79
		Low	$216	$201	$186	$174	$162	$150	$138	$124
	80%	High	$71	$71	$71	$71	$71	$60	$48	$35
		Medium	$115	$107	$92	$80	$68	$56	$43	$30
		Low	$157	$142	$126	$114	$102	$90	$78	$65
	70%	High	$43	$43	$43	$43	$43	$32	$19	$6
		Medium	$65	$57	$42	$30	$18	$6	-$6	-$19
		Low	$77	$61	$46	$34	$22	$10	-$2	-$15

Table 3 provides fair market values for used LFP (3a) and NCX (3b) batteries based on expected rapid cost declines for new LFP batteries. Overall, used battery fair market values decrease with decreasing new battery prices. In this scenario, the reuse of NCX batteries becomes largely uneconomical, while most used LFP batteries could be employed in a second life.

Table 3a) Used LFP compared to rapid declining new LFP prices (in $/kWh)

Chemistry	Initial SOH	Degradation scenario	2023	2024	2025	2026	2027	2028	2029	2030
LFP	100%	- new battery price with installation -	$273	$249	$229	$219	$208	$200	$190	$181
	90%	High	$195	$170	$151	$141	$129	$121	$111	$103
		Medium	$205	$181	$161	$151	$140	$132	$122	$113
		Low	$204	$179	$159	$149	$138	$130	$120	$112
	80%	High	$137	$113	$93	$83	$72	$63	$54	$45
		Medium	$162	$138	$118	$108	$97	$88	$79	$70
		Low	$159	$135	$115	$105	$94	$85	$76	$67
	70%	High	$75	$51	$31	$21	$10	$1	-$8	-$17
		Medium	$112	$88	$68	$58	$47	$39	$29	$20
		Low	$114	$90	$70	$60	$49	$40	$31	$22

Table 3b) Used NCX compared to rapid declining new LFP prices (in $/kWh)

Chemistry	Initial SOH	Degradation scenario	2023	2024	2025	2026	2027	2028	2029	2030
LFP	100%	- new battery price with installation -	$273	$249	$229	$219	$208	$200	$190	$181
NCX	90%	High	-$9	-$33	-$53	-$63	-$74	-$82	-$92	-$101
		Medium	$7	-$18	-$38	-$48	-$59	-$67	-$77	-$85
		Low	$52	$28	$8	-$2	-$13	-$22	-$32	-$40
	80%	High	-$38	-$62	-$82	-$92	-$103	-$112	-$121	-$130
		Medium	-$42	-$67	-$87	-$97	-$108	-$116	-$126	-$134
		Low	-$8	-$32	-$52	-$62	-$73	-$82	-$91	-$100
	70%	High	-$66	-$91	-$111	-$121	-$132	-$140	-$150	-$158
		Medium	-$92	-$116	-$136	-$146	-$157	-$166	-$175	-$184
		Low	-$88	-$112	-$132	-$142	-$153	-$162	-$171	-$180

3. Discussion

Second-life application

As a second-life application, we use stationary storage with solar power and daily use cycles without seasonality. Battery reuse in stationary storage was already discussed in academia in 1998 (Pinsky, 1998) and is considered a sustainable approach to battery management (Steckel et al., 2021). The increasing renewable energy share in the grid informs our choice of solar-powered stationary storage. Balancing real-time electric power becomes crucial as countries rapidly deploy renewable energy. Used batteries present a suitable option for renewable energy storage, as this application is relatively insensitive to gravimetric or volumetric energy and the charging and discharging profile is not overly demanding. Lastly, the renewable energy storage market possesses a large capacity to accommodate retired batteries, likely outstripping other applications such as frequency regulation or charging stations.[5]

New battery price development

Our analysis examines two distinct price development scenarios for new batteries. In both cases, lithium-ion battery prices experience a downward trend due to technological advancements and reductions in process costs. This decline in cost can be represented using Wright's Law, where the learning rate indicates the consistent percentage decrease in cost for a particular product as its cumulative production doubles. The learning curve illustrates the remaining costs following each cumulative doubling of production volume. Previous academic research approximates the learning curve for lithium-ion batteries to range from 76% to 84% (Glenk et al., 2021; Kittner et al., 2017; Schmitdt et al., 2017; Ziegler and Trancik, 2021). To support our analysis, we rely on data connected to the U.S. Department of Energy (Cole et al., 2021; Viswanathan et al., 2022). Since new batteries compete with used batteries, we find lower fair market values for used batteries in cases of lower prices for new batteries.

Recycling value

The accelerated adoption of EVs presents waste-management challenges and opportunities for recyclers to recover valuable metal elements at the end of battery life (Harper

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[5] For example, McKinsey & Company (2023) project that in 2030 the second largest demand for Li-Ion batteries stems from the stationary storage market (largest demand from the mobility sector).

et al., 2019). The nascent EV battery recycling industry has yet to achieve significant economies of scale. Nevertheless, 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.

In our model, we employ recycling profits (recycling revenues minus all applicable costs) of 20 $/kWh for NCX and 0 $/kWh for LFP batteries. These estimates draw on a recent academic publication by Lander et al. (2021), demonstrating positive net recycling profits for nickel-based EV batteries in most jurisdictions and recycling methodologies. Conversely, LFP batteries yield negative recycling profits except for direct recycling methods. The authors acknowledge that their results are sensitive to fluctuations in metal prices, recycling processes, transportation and disassembly costs. We also advise caution regarding the point estimates, given that previous literature reveals a wide range of transportation costs associated with EV battery recycling (e.g., Slattery et al., 2021) and metal prices have demonstrated high volatility[6] in recent years.

To corroborate our estimates, we gathered industry insights on the recycling value and profitability of EV batteries. Firstly, J.B. Straubel, CEO and founder of Redwood Materials, stated in September 2021 that battery recycling is already profitable (Randall, 2021). Secondly, Elon Musk, CEO of Tesla, remarked in an April 14, 2022 TED talk that "Even a dead battery pack is worth about a thousand dollars" (TED, 2022). In our model, recycling prices have a minimal impact on the fair market values of used batteries, except for those with values approaching zero. However, a positive recycling profit for NCX batteries aids in addressing concerns about unrecycled battery waste, particularly as our model suggests that a second life may not be economical for some NCX batteries.

Battery chemistries

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[6] Prices for battery metals sharply increased between 2021 and spring of 2022. In 2023, some prices such as lithium substantially declined again.

An essential factor in our model is comparing different battery cathode chemistries as future fair market values of one battery type may depend on the economics of other battery chemistries. A common EV cathode chemistry is nickel-cobalt-X (NCA & NMC or generally NCX) and iron-phosphate (LFP). Nickel-cobalt-based lithium-ion batteries are predominantly employed in developed countries because their higher energy density allows longer EV ranges. In contrast, LFP batteries are cheaper to produce and popular in China. Both chemistries can be employed in regular electric cars. For example, the standard version of the European Tesla Model 3 includes LFP, while the long-range version includes a nickel-cobalt-based battery. In early 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). A recent news release from Wood Mackenzie highlights the growing market share of LFP batteries and their competitive cost, long lifecycle and high safety performance (Wood Mackenzie, 2022). In the first quarter of 2022, Tesla equipped nearly half of its globally vehicles produced with a lithium iron phosphate battery while relying solely on nickel-cobalt-based lithium-ion batteries a few years ago. The rising LFP adoption by Tesla can be viewed as a tipping point for other carmakers to change and adopt more iron-based batteries (Tesla, 2022). Overall, the current market dynamics with advances in energy density for LFP batteries and volatile raw material prices (see, e.g., Campell et al., 2022) indicate a rising percentage of LFP batteries in the future vehicle mix consistent with an outlook provided by the International Energy Agency in May 2022 (IEA, 2022b). From a reusability and recycling perspective, LFP and nickel-cobalt-based batteries differ on multiple factors. First, LFP batteries include fewer valuable metals. Second, LFP batteries have a smaller degradation (e.g., Preger et al, 2020, Li et al., 2020). Third, LFP batteries are more thermal stable (e.g., El Moutchou et al., 2020, Lit et al., 2020) which could reduce repurposing costs for the second life.[7] We contend that when evaluating used nickel-cobalt-based batteries, it is not

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[7] At the moment, we do not model lower repurposing costs for LFP batteries. However, a decrease in repurposing costs would increase the fair market value for a second life.

sufficient to compare them with new nickel-cobalt-based batteries merely. Instead, it is crucial to also consider the more cost-effective lithium iron phosphate (LFP) batteries as a viable alternative. The following figure provides an overview of fair market values including recycling profits of used LFP and NCX batteries with medium degradation, each compared to new LFP batteries. In Figure 1b, all NCX batteries have a fair market value of 20 $/kWh due to the lower bound of recycling profits.

Figure 1a) Fair market value with expected new LFP prices (in $/kWh)

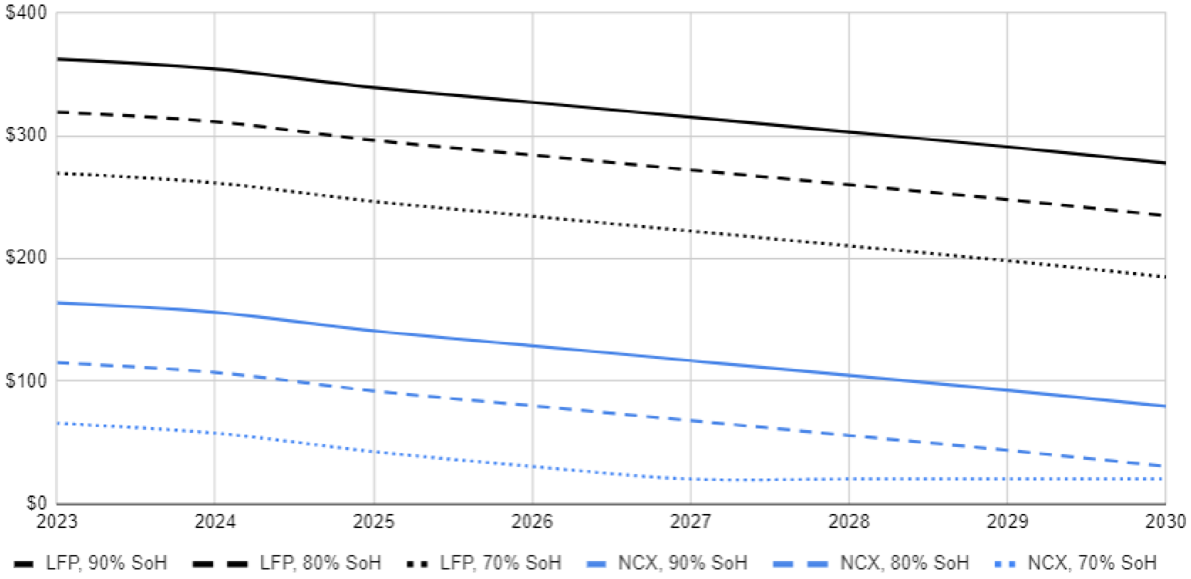

Figure 1b) Fair market value with rapid decline of new LFP prices (in $/kWh)

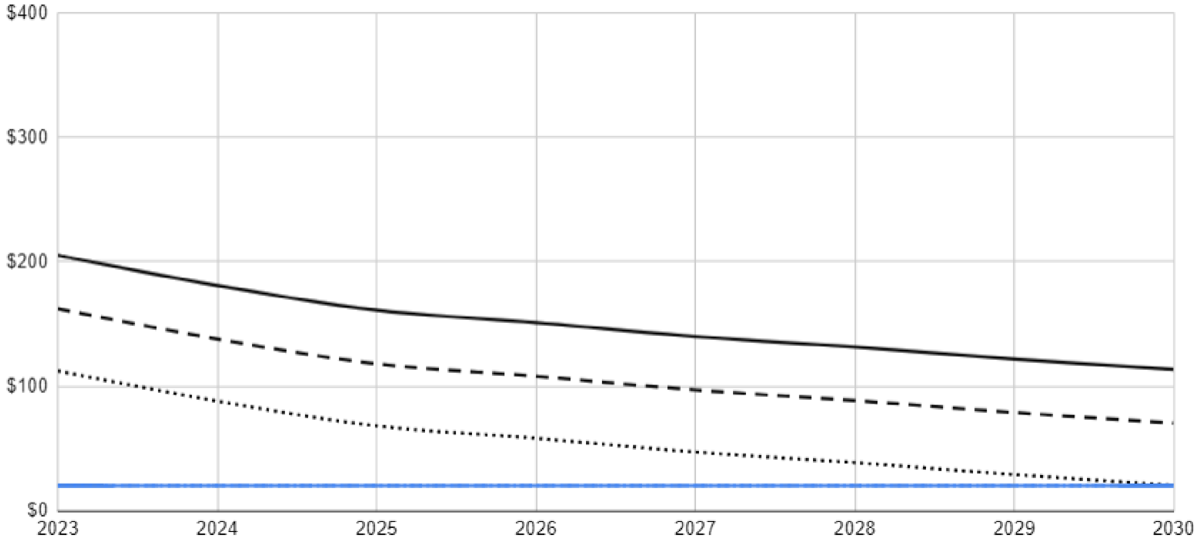

Figure 1a und 1b display fair market values of LFP and NCX batteries with initial SoH of 70, 80 and 90%. Calculations are based on a medium degradation scenario and expected LFP price decline (a) or rapid LFP price decline (b).

State of health, degradation and aging knee

Our model includes three variables affecting the lifetime of used batteries: SoH at the beginning of the second life, the aging knee and future degradation expectations. The state of health measures the battery's condition compared to the original condition.[8] The second life ends once the battery reaches the aging knee, which is considered 50% SoH for LFP and 60% SoH for NCX batteries.[9] Lastly, for degradation expectations, we rely on three different data sources. First, data from the battery lab at Stanford University is based on 2170 NCA Panasonic cells (Zhuang et al., 2023). Second, available real-life data from crowd-sourced electric car drivers (Lambert, 2018). Third, prior academic publications with simulated usage. More details on the data sources are listed in Appendix 3. To allow for variation, we included three scenarios of battery degradation during the second life applicable to new and used batteries simultaneously. The three scenarios differ in the theoretical and actual[10] EFC achievable by the battery chemistry (for more details, see Appendix 1).

Unit revenue

Based on prior literature, the unit revenue (or price premium) per kWh stored is set at 0.16 $ (see Comello & Reichelstein, 2019). This value is the difference between one kWh's selling and purchasing price. Predicting future unit revenues is difficult, as more intermitted renewable energy can increase price differences during the day, while more battery storage solutions could reduce future unit revenues due to more competition. Based on Figure 1a, we show in Figure 2a values for unit revenues of 0.14 $ and in Figure 2b values for unit revenues of 0.18 $. Higher unit revenues (Figure 2b) accelerate fair market value reductions in the upcoming years resulting in lower fair values for used batteries. For lower unit revenues (Figure

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[8] E.g., a battery with initial 100 kWh of usable energy capacity may degrade after 600 equivalent full cycles (or 200.000 miles) to a usable energy capacity of 80 kWh which is equivalent to 20% degradation and an 80% SoH.

[9] The point in time when the battery capacity reaches the aging knee is considered the battery end of life (EOL). We model the aging knee as “Usable EFC“, that are 50% (60%) of “Theoretical EFC” for LFP (NCX).

[10] Actual EFC are the equivalent full cycles a battery can achieve before breaking down (aging knee). Actual EFC are calculated by multiplying theoretical EFC and the aging knee SoH.

2a), fair market values decrease in the near term, but increase in the later years. This change is due to lower revenue streams (stronger in early years) and less competitive new batteries (stronger in late years).

Figure 2a) Fair market value with expected new LFP prices and lower unit revenues (in $/kWh)

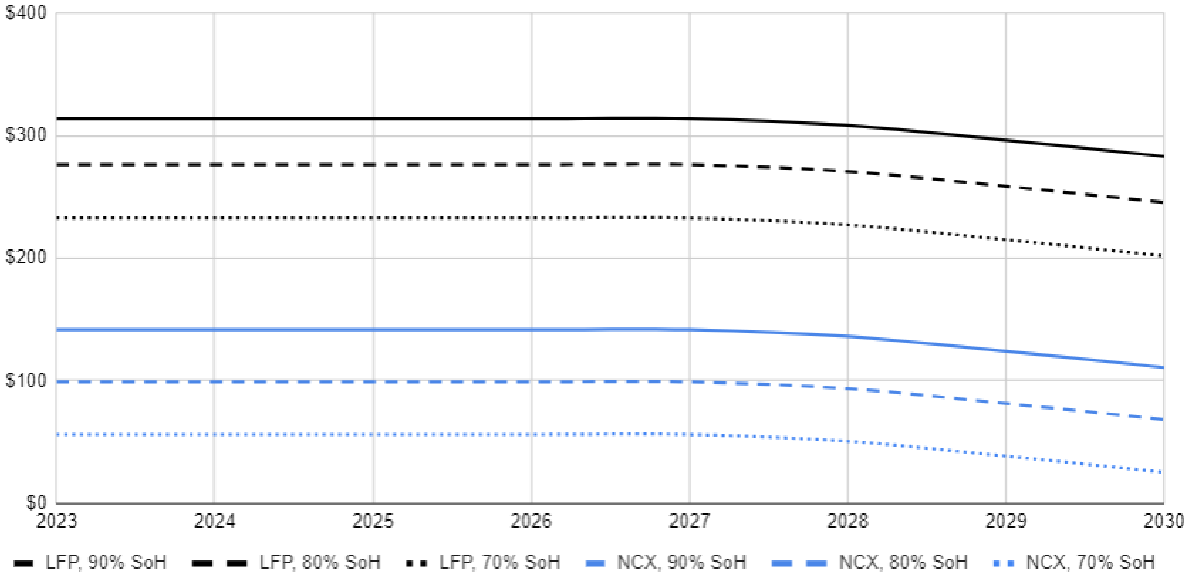
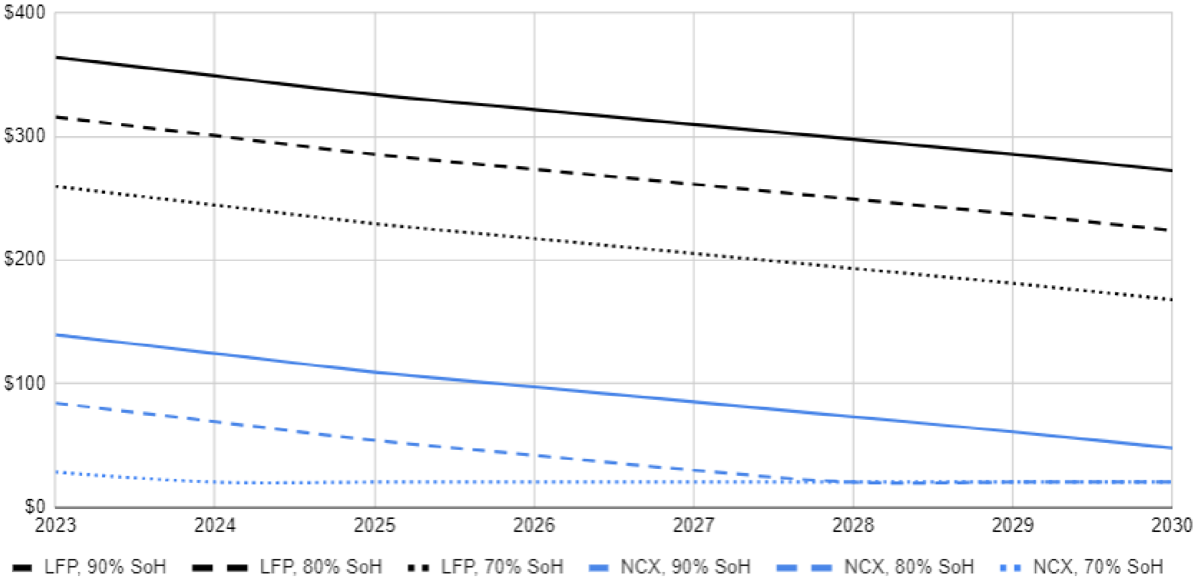


Figure 2b) Fair market value with expected new LFP prices and higher unit revenues (in $/kWh)



Repurposing costs

Repurposing costs are necessary for giving used battery packs a second life. Studies estimate these costs are 32 $/kWh (Neubauer et al., 2012), 25-50 €/kWh (Reid & Julve, 2016), 65 $/kWh (Cready et al., 2003)[11], 230 €/kWh (Casals et al., 2016). Neubauer et al. (2015) estimated repurposing cost for second-life batteries can be as low as 20 $/kWh. Our model assumes a repurposing cost of 25 $/kWh. Steckel et al. (2021) show that repurposing costs have a high sensitivity for the levelized costs of second-life battery storage systems. Consistent with Steckel et al. (2021), we also find that any shift in repurposing costs results in a linear change in fair market values for reusing the battery. McKinsey & Company (2019) predicts that over the coming decades, the cost of manufacturing new batteries is assumed to fall faster than remanufacturing costs, which could impact the relative fair market value of batteries entering their second life. Our results support this prediction.

Limitations

A potential limitation of our study is uncertainty regarding the volume of a second-life market for used lithium-ion car batteries. Börner et al. (2022) elaborate challenges in multi-life battery systems affecting the economic viability of reusing batteries from electric vehicles. They argue that some EV batteries are not particularly suitable for daily cycles in stationary storage solutions. This concern is valid for nickel-cobalt-based chemistries. Whereas it is less relevant for LFP batteries with high cycle life and superior thermal stability.

Furthermore, Börner et al. (2022) argue that an EV might be used for more than 20 years, potentially impacting the economic feasibility of further usage after that. Arguably, such a long life may be difficult because of other car components breaking down, such as suspension or rust on the car's body. However, our model does not assume that all batteries will be employed in a second life. We rather think that many used batteries will be available as cars

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

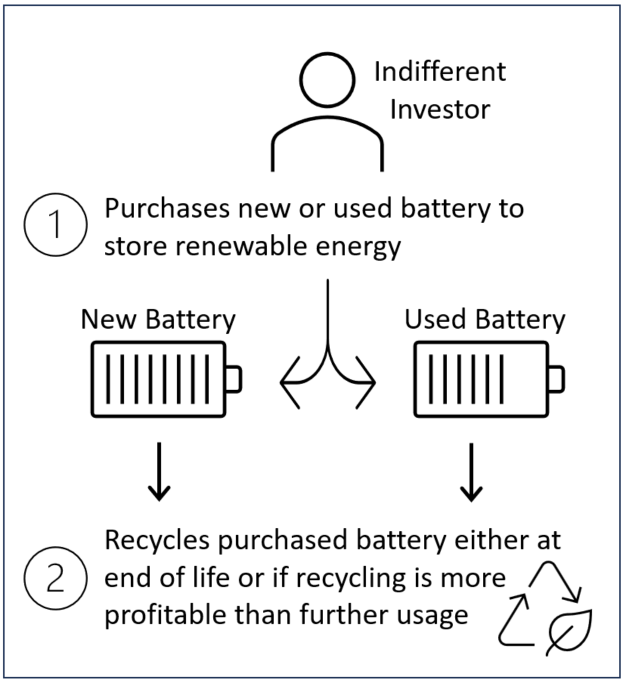
will reach their end of life due to other components breaking down or external factors such as minor car crashes. In contrast, if the volume of used batteries exceeds demand for used batteries in grid storage solutions, some used batteries, likely NCX, must be recycled after the first life. This in turn has implications for new vehicle designs, as new vehicles could be built without optimizing for low repurposing costs (e.g., a cell to pack design).

Lastly, Börner et al. (2022) argue that used batteries for a second life must compete with used car markets and new batteries. Our study helps to economically assess this concern raised by Börner et al. (2022) with a valuation model capturing heterogeneity, such as battery chemistries or new battery prices, to determine a fair market price of a used battery for a second-life application.

A further constraint of our model is its exclusion of recently developed storage technologies from the comparative analysis. However, we anticipate that lithium-ion batteries will remain among the most cost-effective options for short duration storage cycles. Nevertheless, it would be beneficial to broaden the model's scope by incorporating sodium-ion batteries, as leading battery manufacturers BYD and CATL are beginning to mass-produce these batteries for automotive applications (Zhang, 2023). Currently, data is not available for those batteries to develop our estimates.

4. Methods

The model framework developed in this section estimates fair market values of electric car batteries after their first mobile application. Our model is a standardized general-purpose methodology for assessing the cost competitiveness of new vs. second-life battery systems based on a range of operational specifications. In more detail, the fair market value of a battery entering its second life will depend on its battery size, energy capacity state of health (SoH), expected cash flows, degradation and aging knee expectations, depth of discharge (DoD), repurposing costs, interest rate, recycling profits and the alternative economics of new purpose-built lithium-ion batteries. Our model is based on a second-life storage application with solar power and daily use cycles without seasonality. After the second life, the battery will be recycled.



In a viable and functioning market, the value of used battery packs will emerge such that buyers seeking a particular expected energy storage capability should be indifferent between different options. Therefore, an investing party seeking a particular energy storage capability should be indifferent between a used battery pack and acquiring a new one in the marketplace. The notion of indifference here is that both systems' net present values of cash flows are identical. Effectively, this criterion amounts to a "no arbitrage condition" for the market value of the second-life battery pack, given its original market price. Furthermore, the operative usage of the battery will end once the owner is indifferent between further use and recycling or disposal. Hence, the second life will last until the present value of usage equals the recycling value or zero.

The net present value for the new battery is as follows:

$$NPV_{New} = \sum_{i=1}^{T} \frac{N \cdot e \cdot p_0 \cdot \eta \cdot DoD \cdot SoH_i}{(1+r)^i} + \frac{R}{(1+r)^{T*}} - e \cdot V_{e\,new} - k \cdot V_{k\,new} \qquad (1)$$

The net present value for the used battery is as follows:

$$NPV_{Used} = \sum_{i=1}^{T} \frac{N \cdot e \cdot p_0 \cdot \eta \cdot DoD \cdot SoH_i}{(1+r)^i} + \frac{R}{(1+r)^{T*}} - e \cdot (V_{e\,used} + C) \qquad (2)$$

In contrast to the NPV_{New}, the NPV_{Used} does not include the cost of the power component[12] for a used battery, as the power component from EV batteries substantially exceeds the requirements of stationary storage power components. Hence, the buyer focuses on the energy component for pricing decisions.

We set the NPV of (1) and (2) equal to calculate the variable of interest $V_{e\,used}$, the fair market value per kWh of the used battery pack after repurposing the battery. The seller of the used battery receives the fair market value. The battery buyer pays the fair market value and incurs the repurposing costs.

The state of health energy capacity is modeled as follows:

$$SoH_i = 1 - \left(N \cdot \frac{DoD}{EFC_{Theoretical}}\right)^{i-1} \qquad (3)$$

The end of the second life T* is reached once the present value of future cash flows is below the recycling profit (T*<T) or the battery SoH drops below the energy capacity aging knee (T*=T). Appendix 1 lists all variables and their respective values.

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[12] Indicates how much power can flow into or out of the battery in any given instant.

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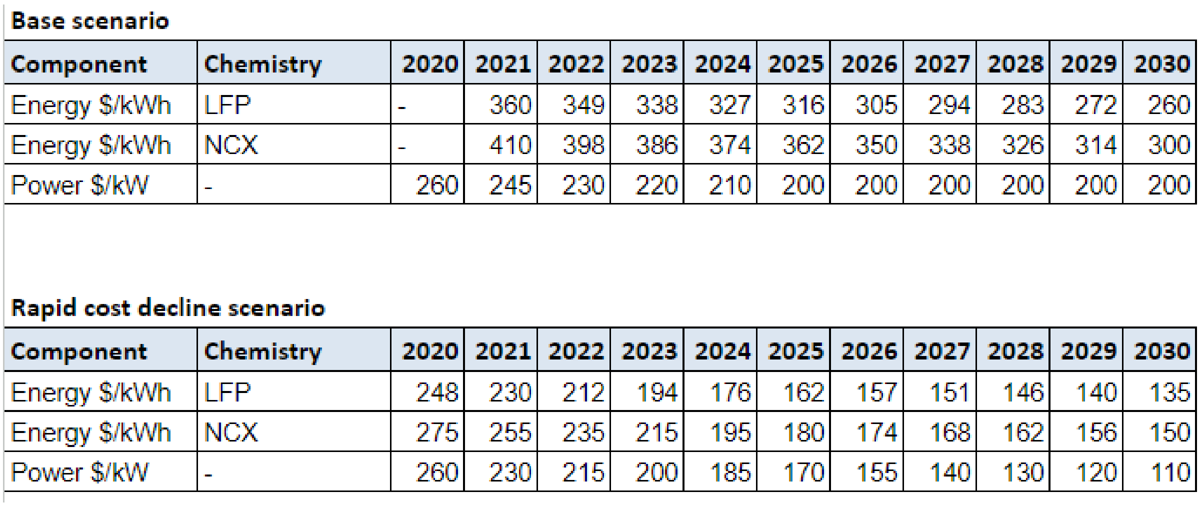
Appendix 1: Variables

Variable	Explanation	Value
i	Time period in years	-
Ve_new	System price of energy component; new battery (in $ per kWh)	See next table
Vk_new	System price of power component; new battery (in $ per kW)	See next table
V_used	System price all components; used battery (in $ per kWh)	endogenous
R	Recycling profit (in $ per kWh) (LFP/NCX	0 / 20
C	Repurposing costs for used battery (in $ per kWh)	25
r	Discount rate	8%
e	Energy - Storage capacity of new battery (in kWh)	13,5
k	Power of new battery (in kW) (charge)	3,68
N	Number of charge and discharge cycles per year (scalar)	365
p_0	The unit revenue (possibly the price premium) per kWh stored	0,16
η	Round-trip efficiency factor LFP storage system (scalar) (LFP/NCX)	0,97 / 0,95
DoD	Depth of discharge (Battery stage of charge operating range)	0,8
SoH_i	Battery State of Health Capacity in period i	endogenous
END	End of life reached at SoH level (LFP/NCX)	0,5 / 0,6
EFC_i	Equivalent Full Cycles	$\sum_{i=1}^{T} N \cdot DoD \cdot SoH_i$
EFC_Theoretical	Theoretical EFC (high degradation scenario) to 0% SoH (LFP/NCX)	10000 / 2500
	Theoretical EFC (medium degradation scenario) to 0% SoH (LFP/NCX)	20000 / 5000
	Theoretical EFC (low degradation scenario) to 0% SoH (LFP/NCX)	30000 / 7500
EFC_Usable	Total usable EFC (Battery reaches aging knee: End of life)	END*EFC_Theoretical
T	Point in time in which the battery reaches the aging knee	T(EFC_i=EFC_Usable)
T*	Point in time in which the battery gets replaced due to reaching the aging knee (T*=T) or due to financial consideration (if PV(CF)<R, hence T*<T)	endogenous

Appendix 1: Variables (continued)



Base scenario

Component	Chemistry	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Energy $/kWh	LFP	-	360	349	338	327	316	305	294	283	272	260
Energy $/kWh	NCX	-	410	398	386	374	362	350	338	326	314	300
Power $/kW	-	260	245	230	220	210	200	200	200	200	200	200

Rapid cost decline scenario

Component	Chemistry	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Energy $/kWh	LFP	248	230	212	194	176	162	157	151	146	140	135
Energy $/kWh	NCX	275	255	235	215	195	180	174	168	162	156	150
Power $/kW	-	260	230	215	200	185	170	155	140	130	120	110

Appendix 2: Literature on used battery prices

A wide variety of prices for used batteries exists in prior academic literature and industry reports. This variety stems from different SoH assumptions at the beginning and end of the second-life, different chemistries and multiple estimation approaches. Prices for second-life batteries are either reported, calculated, predicted or assumed. An industry report by Capgemini (2019) reported a price of 50 $/kWh for repurposed lithium-ion batteries in 2019. In Q4 2022, Hans Eric Melin (2022) published verified transaction prices for 5.3 kWh Tesla Model S/X nickel-cobalt-based module with second-life prices between 800-1,000 $ per module (150-189 $/kWh).

In 2016, a study by Reid & Julve (2016) reported market prices for second-life batteries of 150 €/kWh. Early academic papers assumed prices for used batteries based on their relative usability. For example, Neubauer and Pesaran (2011) estimate that the maximum cost of a used battery is considered to be the cost of a new battery multiplied by a health factor depending on the remaining capacity and subtracting the refurbishment cost. Related to this study, Gur et al. (2018) assume used battery prices to be between 30-75% of new battery prices. Neubauer et al. (2012) estimate market prices of 20-100 $/kWh after a 15-year usage in an EV based on a 75% discount factor to new batteries. Lih et al. (2012) define the residual value of a lithium-ion battery pack as the price of a new battery pack times the ratio of residual life to nominal life measured in time and capacity. Song et al. (2019) rely on a McKinsey study and assume 154 $/kWh of investment costs for a second-life battery after 10 years of usage.

Mathews et al. (2020) developed a model for stationary storage applications comparing new with used NMC batteries that have faded to 80% of their original capacity. They show in this scenario that a system with second-life batteries reaches break-even and profitability with costs (including repurposing) for the second-life battery lower than 60% of the new battery. Furthermore, second-life batteries are economically favorable compared to new batteries if they cost <80% less. They assume that a second-life battery is used until a capacity of 60-70% is reached which translates depending on the charge cycle to 5-16 years of secondary usage. Han et al. (2018) employ a model with a second-life usage of LFP batteries in China for an energy storage system. They start the second life with 80% remaining capacity and find a required capacity unit price of the second-use battery energy storage system of 204 $/kWh. Madlener and Kirmas (2017) estimated prices of 73-107 €/kWh for a second-life lithium-ion battery storage applications for rooftop PV in Germany based on an 80% remaining capacity at the beginning of the second life. Sun et al. (2018) estimate with supply and demand curves equilibrium prices for second-life batteries with 75% remaining capacity from 2010 to 2050. In all the scenarios analyzed, the price falls until about 2025 and then plateaus around 50 $/kWh in different ways depending on the penetration rate of EVs. The price is found to be insensitive to new battery costs, refurbishment costs, recycling credit, and the elasticity of supply and demand.

Steckel et al. (2021) estimate LCOS for new and used batteries. In their study, they include battery market prices for new batteries between 134-180 $/kWh and for used batteries between 50-108 $/kWh. Furthermore, they assume an operating second life of 7-8 years with a starting 80% SoH and repurposing costs between 18-64 $/kWh. LCOS calculations are for a

15-year project horizon which requires one replacement in the case of second-life batteries. The resulting LCOS for a second-life battery storage application is between 234-278 \$/MWh (56 \$/MWh standard deviation) compared to 211 \$/MWh (47 \$/MWh standard deviation) for a new lithium-ion battery storage solution. These estimates are highly sensitive to assumed discount rates, depth of discharge and repurposing costs. Overall, Steckel et al. (2021) use market prices provided by prior literature to calculate LCOS for new and second-life battery energy storage solutions. In contrast to Steckel et al. (2021), we derive the market price for second-life batteries based on the notion of identical LCOS between new and used batteries.

Appendix 3: Data degradation

The laboratory data as well as crowd-sourced online data have their specific advantages and disadvantages. The battery lab data (Zhuang et al., 2023) is unbiased, determined with high accuracy, calculated on a battery pack level and a simulation model for a higher cycle amount. The laboratory test does not include active battery cell cooling. The absence of battery cooling likely overestimates the degradation level for real-world applications with a thermal management system. The crowd-sourced internet data (see, e.g., Lambert, 2018) complements the lab's data, allowing us to observe real-life degradation levels for electric vehicle batteries. However, selection bias in self-reporting and a mixture of different cell chemistries between car models and within car models over time introduces biases into this data set.

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 capacity is left after 300,000 km. In general, data on real-life automotive usage is scarce. Therefore, most prior academic publications rely on laboratory tests or selected data from the field. In a recent academic publication, Wassiliadis et al. (2022) performed an accelerated aging test of lithium-ion battery cells based on the battery (NMC) of a Volkswagen

ID.3 Pro Performance. The test is close to real-world conditions even so no active cooling system was used. They show a reduced aging rate compared to figures reported in the literature as their projected cycle life seems to be larger than 600-1,000 equivalent full cycles with an EOL definition of 70-80% capacity. The graphs rather point towards a SoH around 85-95% after 8 years or 160,000 km (around 700 equivalent full cycles). Preger et al. (2020) perform a multi-year cycling study of commercial LFP, NMC and NCA with varying discharge rates, depth of discharges, and environment temperatures. They show that the time to reach 80% capacity strongly varies by a large magnitude of equivalent full cycles among cells of different chemistries. In figures 1 and 2, they visualize varying degradation levels due to differences in the chemistry, charge cycles and temperatures. Based on both visualizations, the approximate amount of equivalent full cycles until an EOL 80% capacity is reached is on average around 4,000 for LFP, 1,000 for NMC and 600 for NCA.