Fair Market Value of Used Capacity Assets: Forecasts for Repurposed Electric Vehicle Batteries*

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July 2025

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*We thank Marie-Louise Arlt (discussant), Stephen Comello, Bruis van Vlijmen, seminar participants at the Stanford StorageX Group meeting, University of Mannheim, VfS AURÖ Workshop 2024, and 12th Mannheim Conference on Energy and the Environment for helpful comments and suggestions. Financial support for this study was provided by the German Research Foundation (DFG Project-ID 403041268, TRR 266). Authors are listed in alphabetical order. Correspondence should be addressed to Amadeus Bach (email: ambach@uni-mannheim.de).

Abstract

Responding to economic and environmental pressures, a growing number of companies seek to repurpose products (assets) that retain functional capacity beyond their initial first life. This paper examines a generic valuation model for used capacity assets that can either be recycled immediately or repurposed for a second life application. We apply our model framework to lithium-ion batteries retired from electric vehicles, as these assets typically retain substantial energy storage capacity at the end of their first life. Our analysis focuses on two battery chemistries: lithium-iron-phosphate (LFP) and nickel-cobalt-based (NCX). We project their future fair market values in the United States and China. Our findings indicate that repurposing LFP batteries will be economically viable in both countries for the coming decade. In contrast, for most NCX batteries immediate recycling will soon be preferable due to their more valuable raw material content and shorter usable lives.

Keywords: Capacity Assets, Second Life Application, Fair Market Valuation, Used EV Batteries, Repurposing, Recycling

I INTRODUCTION

The scarcity of many natural resources and the attendant drive towards a circular economy have prompted companies to design and manufacture new generations of products in a manner that extends their useful life and makes them easier to recycle (Adidas, 2019; Apple, 2022; Fairphone, 2025; Philips, 2025). For certain product categories, the useful life of the entire product, or possibly major product components, can be extended by repurposing the product or its major components for a second-life application. Such repurposing will be particularly attractive when the second life application is less demanding in terms of performance requirements.

A primary motivation for the model developed in this paper and its empirical calibration is the emergence of a sizable market for lithium-ion batteries originally deployed in electric vehicles (EVs). Once the vehicle reaches the end of its operational life, its battery can be either recycled or repurposed for a less demanding second life application, such as stationary energy storage in businesses or households. The rapid growth in new EV registrations ensures that there will be an ample supply of batteries coming out of their mobile first life application in the foreseeable future. Yet it remains a challenge to forecast the fair market value of these used assets, as this value depends on multiple parameters, including the future rate of technological progress for new batteries.

Our generic model for assessing the fair market value of repurposed assets builds on the familiar *replacement value* concept of assets in use, as developed in earlier studies in economics, accounting and finance.[1] Accordingly, the replacement value of an asset in use can be conceptualized as the sum of the future discounted cash flows that can be obtained from this asset. In contrast to a general equity valuation problem, this conceptualization is relatively straightforward in contexts where operating assets provide productive capacity for delivering goods and services (e.g., energy storage services) over a finite time horizon. Assuming the capacity of assets degrades over time, the fair market value of a used asset is then given by the discounted future cash flows that derive from the asset's remaining capacity in future periods valued at the so-called *user cost of capital* (Arrow, 1964). Provided there is a competitive and frictionless market for both new and used assets, the user cost of capital will be equal to the equilibrium market price of *one unit of capacity made available for one period of time.*

Prior accounting literature that has relied on the concept of the user cost of capital has mostly assumed that new assets are acquired at a constant market price (Pfeiffer and Schneider, 2007; Rajan and Reichelstein, 2009; Nezlobin et al., 2012). For certain types of assets, including batteries, market participants will anticipate that the market price of new assets will decline over time due to ongoing technological progress. For such settings, Rogerson (2008) developed an infinite horizon model wherein the user cost of capital properly

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[1] One prominent application of the replacement value of assets is Tobin's q, defined as the ratio between a firm's equity market value and the replacement value of its assets (Lindenberg and Ross, 1981). McNichols et al. (2014) derive a "conservatism correction factor" that yields Tobin's q as a function of a firm's market-to-book ratio (Penman, 2013).

reflects the anticipated rate of decline in the market price of new assets.[2]

Our model framework extends earlier accounting and economic studies on the fair market values of used assets by incorporating two new elements. First, depending on the nature of the asset, a significant terminal cash flow may be associated with the recycling of its constituent materials. Second, the redeployment of a used asset into a second-life application often requires a repurposing cost. As a result, the effective fair market value of the asset at the end of its first life is determined by the better of two alternatives: immediate recycling or costly repurposing followed by second-life deployment and delayed recycling.

Aside from repurposed EV batteries, our valuation model is applicable to a range of other products that have a potential second-life application. Examples include refurbished consumer electronics such as smartphones and laptops (Apple, 2022), redeployed cloud computing hardware for data centers (Microsoft, 2025), and refurbished manufacturing equipment such as semiconductor fabrication tools (ASML, 2023). In the transportation sector, passenger aircraft are converted for cargo use (Reuters, 2020) and shipping containers are repurposed for modular storage or shelter (Tighe, 2018). Finally, repurposing of used assets is also emerging for renewable energy systems, particularly for solar photovoltaic panels and wind turbine components (BBC, 2023; Ørsted, 2023).

EV batteries represent a particularly prominent application for our model framework,

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[2] Several branches of the accounting literature have pointed to the advantages of adopting depreciation schedules for operating assets such that the book value of assets coincides with their replacement values at all points in time. The corresponding depreciation schedule has been referred to as the *relative practical capacity rule*. Specifically, in the model of Nezlobin (2012), investors can correctly value a firm's equity value based on current accounting information, provided that operating assets are depreciated in accordance with the relative practical capacity rule. Rajan et al. (2007) obtain a corresponding result ensuring that the accounting rate of return reflects the internal rate of return of a firm's investment projects; see also Feltham and Ohlson (1996). Finally, Dutta (2003); Pfeiffer and Schneider (2007); Rogerson (2008); Dutta and Reichelstein (2021) demonstrate goal congruence between a firm's owners and its management, provided managerial performance is assessed on the basis of accounting information such that acquired operating assets are depreciated according to the relative practical capacity rule.

in part because batteries typically retain substantial capacity at the end of their initial life (Redwood Materials, 2025). Furthermore, recent growth rates in the deployment of EVs worldwide indicate that the global market for used EV batteries could soon reach several hundred billion dollars annually.[3] Industry estimates suggest that repurposed EV batteries could supply over half of the entire energy storage market. This outlook is supported by the 2025 completion of the largest second-life battery deployment worldwide to date, a 63 MWh installation in the U.S., demonstrating both the scalability and operational efficiency of repurposed systems (Redwood Materials, 2025).

Our model framework allows for different technologies to compete in the market for capacity services. Specifically, our application in connection with lithium-ion batteries considers two competing chemistries: Lithium-iron-phosphate (LFP) and Nickel-cobalt (NCX).[4] LFP batteries have recently gained traction due to lower costs compared to NCX batteries (IEA, 2022). NCX batteries have shorter lifespans and require more expensive raw materials, thus providing significant recycling value. We estimate fair market values for LFP and NCX batteries in the U.S. and China. The substantial price differential for new batteries in these two markets (BloombergNEF, 2023) is shown to have a significant impact on the decision to repurpose used batteries rather than recycle them immediately.

Our estimates indicate robust fair market values for used LFP battery packs in both the U.S. and China, making a clear business case for repurposing these batteries. For the U.S., value retention shares range from approximately 13–59%, depending on battery health and

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[3] For 2024, global EV and plug-in hybrid registrations were projected to increase from 14.2 to 16.6 million (IEA, 2023; King, 2024). With a growing electric share of the roughly 90 million new passenger vehicles sold annually worldwide (S&P Global, 2025), the long-term market for used batteries could reach several hundred billion dollars per year, based on the fair market value estimates projected in our study.

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

degradation rates. For China, due to lower new-battery prices, we project somewhat lower retention shares, ranging from 1–50%. Nevertheless, repurposing of LFP batteries remains preferable to immediate recycling in both markets.

For NCX batteries, conclusions are more nuanced due to significant recycling values and shorter battery lifespans. In the U.S., NCX retention shares range between 5–17%, with immediate recycling generally preferred when the state of health is below 80%. By around 2031, immediate recycling will also become preferable even at a 90% state of health unless degradation rates are slow. This outcome is partly driven by the cost advantages of LFP batteries, as the user cost of capital for NCX batteries is determined by the more competitive rates set by LFP batteries. We find that in China, owners of NCX batteries generally achieve higher payoffs from immediate recycling than from repurposing.

The fair market valuation methodology employed in this paper complements earlier studies that have derived value estimates based on supply and demand curves for second-life batteries (Sun et al., 2018), or based on life-cycle cost calculations for new batteries (Steckel et al., 2021). The relatively wide range of fair market value estimates obtained in prior studies reflects the different timing of these studies, different battery health assumptions, and different cathode chemistries being analyzed.[5]

The remainder of this paper is organized as follows. Section II develops the model. Estimates for the fair market value of used LFP batteries are presented in Section III, while Section IV presents the findings for used NCX batteries. Section V discusses our findings and presents some sensitivity tests. We conclude in Section VI.

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[5] Actual transaction prices for second-life batteries have been reported 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).

II Model Framework

To assess the fair market value of repurposed capacity assets, we develop a model that builds on earlier models for the replacement value of operating assets (Arrow, 1964; Rogerson, 2008; Rajan and Reichelstein, 2009; Rogerson, 2011). A basic assumption in these models is that both new and used assets can be traded in frictionless competitive markets. As a consequence, market participants are indifferent between old and new assets trading at their respective fair market values. They are also indifferent between owning and renting assets.

For such market settings, the central concept underlying the replacement value of used assets is the so-called user cost of capital. It refers to the revenue that an investor would need to obtain for one unit of capacity that is rented out to another market participant for one period of time. Specifically, the trajectory of user costs of capital is determined 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, an investor will exactly break even on all investments in new assets.

The model framework in earlier studies presumes an infinite horizon in which all market participants discount future expected payoffs at the common discount rate, r. Dates and time periods are indexed by t, with period t beginning at date $t-1$ and ending at date t. Due to technological progress, the market prices of new assets are assumed to decline over time. Further, the capacity of assets is assumed to degrade as a function of usage or calendar time. For a new asset acquired at date 0, the percentage of capacity that is still operational in period t is 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 at date T.

Rogerson (2008) assumed that the market prices of new assets decline geometrically over time, that is, $MV_t = \eta^t \cdot v$. It then follows that the user cost of capital in period t is given by:

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

This expression for the user cost of capital can be validated by checking that if an investor acquires new assets in each period and rents out new and used assets at the current user cost of capital, c_t, for a $t = 1, 2...$, then the investor 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. Critically, this equality holds independently of the pathway in new capacity investments.[6]

In order to model the possibility of repurposed used assets being deployed in a second-life application, we extend the above framework in three directions. First, we allow for a more flexible trajectory regarding the declining market value of new assets, i.e., $MV_t = \eta^t \cdot v + w$. The stationary component, w, includes the cost of materials, while the time-dependent component, $\eta^t \cdot v$, reflects that some manufacturing costs are subject to technological progress, possibly due to learning-by-doing. Second, our model extension includes the possibility of a recycling value that investors receive when assets reach the end of their useful lives. This recycling value is assumed to be a time-invariant value, represented by the parameter u. Thus, one unit of the asset acquired at date t still has a recycling value of u at date $t + T$. Finally, before deploying a "cross-over" asset (which thus far has served in its original first

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[6] Earlier accounting literature has shown that if assets are depreciated according to the relative practical capacity rule, then in each period the per unit of capacity charge for depreciation plus the imputed interest charge on the remaining book value are exactly equal to c_t (Rogerson, 2008; Dutta and Reichelstein, 2021).

life) in its second life application, investors incur a time-invariant repurposing cost, denoted by RPC. Since the repurposing cost is immediately sunk once the asset has been repurposed, it has no impact on the equilibrium user cost of capital in the competitive market for new and used capacity assets.

Claim 1. *Suppose the acquisition value of a new asset at date t is given by $MV_t = \eta^t \cdot v + w$, and the recycling value of an asset at the end of its useful life is u. The user cost of capital in period t is then given by:*

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

Appendix A formally demonstrates the expression for the user cost of capital shown in equation (2). Here, we observe that the introduction of a fixed cost component in the market value of new assets, i.e., the parameter w, and the presence of a recycling value, i.e., the parameter u effectively adds the constant $\frac{w-u\cdot(1+r)^{-T}}{\sum_{i=1}^{T} x_i\cdot(1+r)^{-i}}$ to the user cost of capital shown in equation (1).

If new assets experience faster technological progress, i.e, η assumes a lower value, the user cost of capital, c_t^*, will, ceteris paribus, decline faster over time. While one might intuitively expect faster technological progress to also lower the user cost of capital uniformly over all periods, this is generally not true, simply because lower values of η decrease both the numerator and the denominator in the first term on the right-hand side of equation (2). At the same time, faster degradation, that is, uniformly lower remaining capacity values, x_t, implies higher user costs of capital, provided $w \geq u$.

To derive the fair market value of the used capacity asset, suppose now that at the beginning of period t, i.e., at date $t-1$, the remaining capacity of the asset is x_i, for $1 \leq i \leq T$. An investor will then be able to obtain the rental payment of

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

at date t, while the attainable rental fee at date $t+1$ becomes $RP_{t+1}(x_i) = x_{i+1} \cdot c_{t+1}^*$, and so forth. At the beginning of period t, the future rental fees for a used asset with remaining capacity equal to x_i thus amount 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 a used asset with remaining capacity equal to x_i is given by:

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

We note that the term $FRV_t(x_i)$ depends on x_i because this parameter determines how many years into the future the used asset will reach its terminal age.

If an asset is transferred from its original first-life application to its second-life use, the investor will incur time-invariant repurposing costs of RPC. Hence, the fair market value of a repurposed asset entering its second life application is:

$$FMV_t^o(x_i) = \max\{FRP_t(x_i) + FRV_t(x_i) - RPC, 0\}. \tag{5}$$

Assuming the recycling value u could also be earned immediately, 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 cost and opt for immediate recycling. In period t, the fair market value of a used asset with a remaining capacity equal to x_i is thus given by:

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

Depending on the underlying parameter values, it is also conceivable that investors may incur the repurposing cost but not utilize the asset to the end of its useful life in order to collect the recycling value 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 solutions, that is, it is either preferable to recycle now or at the end of the asset's useful life.

Figure 1 provides a schematic summary of our model framework in the context of lithium-ion batteries. Investors, represented here as Rental Equipment Providers (REPs), are the effective market makers. Repurposed batteries that were deployed in electric vehicles in their first life compete with new and used batteries in the market for stationary energy storage. The assumed competitive market setting implies that all parties are indifferent between owning and renting batteries.[7] Regardless of age and remaining capacity, all batteries fetch the same rental fee, c_t^*, for providing the capacity to store up to one kWh of electricity for the time period of one year. When a battery reaches the end of its useful life, its owner obtains a recycling value, u, per unit of the asset from a recycling company.

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[7] If the current model is expanded to include uncertainty and risk, ownership does, of course, entail additional risk which must then be reflected in the competitive rental rates. We note that for combined residential solar and battery systems in the U.S., developers offer households a choice between ownership and rental contracts.

The assumption of competition in the recycling industry ensures that the unit revenue u is independent of the volume transacted.

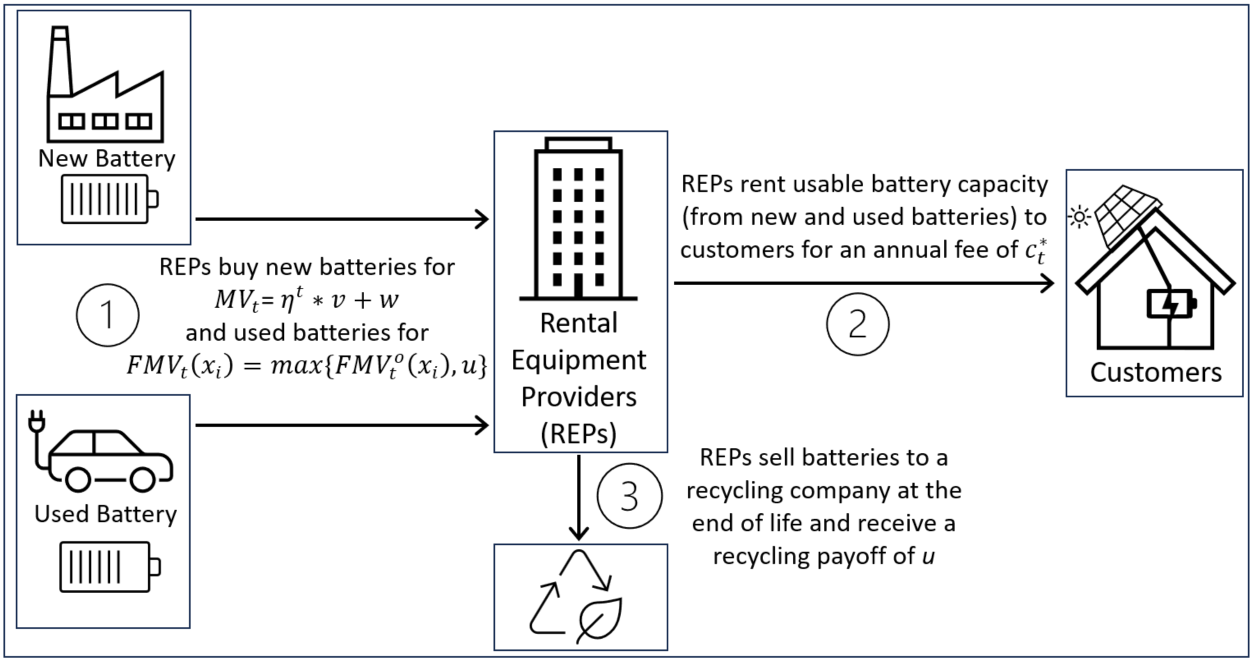

Figure 1: **Rental market for battery energy capacity** This figure provides a schematic summary of the rental market for used lithium-ion batteries.

Our model presentation has focused on one type of asset competing in the market for capacity services. If there are multiple asset types that potentially differ in their useful lives, degradation rates, or available recycling values, the respective fair market values must reflect the lowest of the corresponding user costs of capital. Since customers only pay for the storage capacity made available for one period of time, a frictionless competitive market implies that the lowest user cost of capital determines the effective market rate. Thus, the fair market value of "less efficient" capacity assets must reflect the rental fees that the most efficient type of asset can command. Our valuation of NCX batteries below reflects this feature as LFP batteries entail a substantially lower user cost of capital in comparison to NCX batteries.

In our analysis of the value of used batteries from electric vehicles, we refer to the battery's remaining energy storage capacity at the end of its first life, x_i as the battery's "State of Health (SOH)" (Zhuang et al., 2025). Further, the SOH is assumed to decline geometrically, so that $x_i = x^i$, with $x < 1$, up to some critical value, referred to as the battery's "aging knee". Thus, our calculations assume that $x_i = 0$ once x^i drops below this critical value.

In further extending the model developed here, we note that the fair market value characterization in equation (6) requires modification if REPs face significant uncertainty at the time of the repurposing decision. This is because in the presence of uncertainty about future rental payments and recycling values, the decision to repurpose does not imply a commitment to operate the used asset to the end of its second-life application. Instead, there will be an abandonment option in each of the remaining periods leading up to the asset's terminal date. This real option is valuable and makes the decision to repurpose ceteris paribus more attractive (Schwartz and Trigeorgis, 2004).[8]

There are multiple plausible ways of introducing uncertainty into the above model. One variant assumes that, while at time t the immediate recycling value is known for sure and equal to u_t, the corresponding payoffs available at future dates constitute a joint random variable with a corresponding joint probability distribution. The volatility inherent in these random variables may reflect that recycling values correlate positively with commodity prices for virgin raw materials. The expected future recycling value $F\tilde{R}V_t(x_i)$ in equation (4) can then becomes:

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[8] In the accounting literature, the value of real options has been explored in multiple contexts including the option to invest in capacity sequentially (Dutta and Fan, 2009; Johnson et al., 2017), the option to wait when demand is uncertain (Baldenius et al., 2016; Livdan and Nezlobin, 2022), or the option to redeploy capacity among divisions within a firm (Dutta and Reichelstein, 2010).

$$FRV_t(x_i) = E[(1+r)^{-(T-i+1)} \cdot \tilde{u}_{T-1+i}]. \tag{7}$$

The option to abandon the second life application implies that, contrary to the characterization in (6), even if

$$u_t > FRP_t(x_i) + E[(1+r)^{-(T-i+1)} \cdot \tilde{u}_{T-1+i}] - RPC \tag{8}$$

a risk-neutral decision-maker may prefer to repurpose the asset in order to collect a potentially even higher recycling value at one of the remaining dates between $t+1$ and $t+T-i$.

When future recycling values are uncertain, the fair market value of the repurposed asset will reflect that abandonment decisions can be made in a sequentially optimal fashion. Specifically, given the realization of past recycling values, the decision-maker will update his/her beliefs regarding the distribution of future recycling values in the remaining time periods up to the terminal date, and on that basis decide whether recycling now is optimal. Importantly, the option to abandon becomes more valuable with higher volatility (variance) in the underlying joint probability distribution.

In concluding this section, we note that the closed form expression for the user cost of capital in equation (2) was enabled by assuming that the current price for a new asset evolves according to $MV_t = \eta^t \cdot v + w$ and a known recycling value u. The following result characterizes the user cost of capital for an alternative specification where recycling values are always a fixed share of the current market value of new assets.

Claim 2. *Suppose the market value of new assets at date t is given by $MV_t = \eta^t \cdot v$, and the recycling value of assets at the end of their useful life is a fixed share u (with $0 \leq u \leq 1$) of their initial market value. The user cost of capital in period t is then given by:*

$$c_t^* = \frac{\eta^t \cdot v \cdot [1 - u \cdot (1+r)^{-T}]}{\sum_{i=1}^{T} \eta^i \cdot x_i \cdot (1+r)^{-i}}. \tag{9}$$

As shown in Appendix A, the arguments demonstrating Claim 2 mirror those for Claim 1. In checking the robustness of our findings for repurposed lithium-ion batteries, Section V shows that the model specification underlying Claim 2 yields virtually identical forecasts for the fair market value of the two battery types.

III Fair Market Value of LFP Batteries

The preceding model framework enables us to forecast the fair market value (FMV) of repurposed LFP batteries based on the estimated future user costs of capital, c_t^*. Appendix B provides details on the calibration of the underlying parameters in the context of LFP battery packs. There, we argue that, in contrast to NCX batteries, LFP batteries have no distinct recycling value. Thus, owners of a dead LFP battery should not expect to receive a payment from the recycling companies. See Table 10 for a list of all parameters.

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	17.1	16.6	16.1	15.5	15.1	14.6	14.1	13.7	13.3	12.9	12.5	12.1
	Medium	14.1	13.6	13.2	12.8	12.4	12.0	11.6	11.2	10.9	10.5	10.2	9.9
	Slow	13.4	13.0	12.6	12.2	11.8	11.4	11.0	10.7	10.3	10.0	9.7	9.4

Consistent with the expression for the user cost of capital in Claim 1, the values for c_t^* in Table 1 decrease at around 3%, driven essentially by the estimated cost-decline parameter $\eta = .965\%$ for the non-material part of the battery pack. Our base calculations assume a discount rate of $r = 5\%$. Increasing r from 5% to 7% would increase the user cost of capital by 20% for LFP batteries in the medium degradation scenario.[9]

In estimating the fair market value of LFP batteries, we distinguish three alternative scenarios based on the battery's state of health, SOH, as it exits its first life mobile application. Specifically, we consider the alternatives of 70, 80, and 90% SOH. In conjunction with the three degradation scenarios, Table 2 then shows the FMVs for nine alternatives 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 II, 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%. The corresponding absolute dollar figures are shown in the second row of Table 2.

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%	150.0	145.3	140.9	136.5	132.3	128.3	124.4	120.6	117.0	113.5	110.1	106.9
	Fast Degradation Scenario	90%	56.3%	55.3%	54.3%	53.3%	52.2%	51.2%	50.0%	48.9%	47.7%	46.5%	45.3%	44.1%
		80%	41.5%	40.5%	39.5%	38.5%	37.5%	36.4%	35.3%	34.1%	32.9%	31.7%	30.5%	29.2%
		70%	25.5%	24.5%	23.5%	22.5%	21.4%	20.4%	19.2%	18.1%	16.9%	15.7%	14.5%	13.2%
	Medium Degradation Scenario	90%	58.9%	58.0%	57.0%	55.9%	54.9%	53.8%	52.7%	51.6%	50.4%	49.2%	48.0%	46.7%
		80%	47.0%	46.1%	45.1%	44.0%	43.0%	41.9%	40.8%	39.6%	38.4%	37.2%	36.0%	34.7%
		70%	33.0%	32.0%	31.0%	29.9%	28.9%	27.8%	26.6%	25.5%	24.3%	23.1%	21.8%	20.6%
	Slow Degradation Scenario	90%	58.9%	58.0%	57.0%	56.0%	54.9%	53.8%	52.7%	51.6%	50.4%	49.2%	48.0%	46.7%
		80%	49.1%	48.1%	47.1%	46.1%	45.0%	43.9%	42.8%	41.7%	40.5%	39.3%	38.1%	36.9%
		70%	37.8%	36.8%	35.8%	34.8%	33.7%	32.6%	31.5%	30.4%	29.2%	28.0%	26.8%	25.5%

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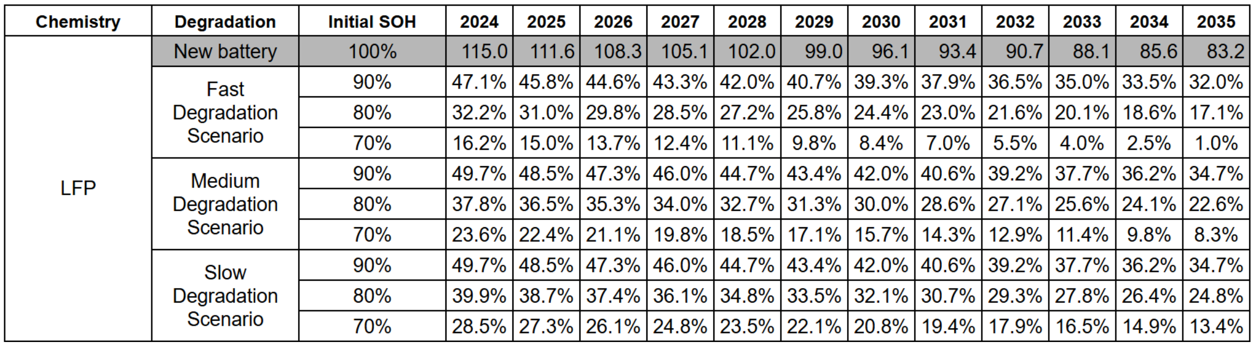
[9] See Section V for further sensitivity analysis.

Our findings indicate significant value retention shares for used LFP batteries, ranging from 13% to 59%. Higher initial SOH values and a slow degradation rate are projected to result in a remarkably high retention share of 59%, while at the opposite end of the spectrum fast degradation and a relatively low SOH=70% would still result in a retention share of only 13%. 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 75 kWh battery pack has a fair market value of around \$3,800 (approximately \$51 per kWh equal to 40.8% of \$124.4) in 2030. These surprisingly high FMV values reflect the anticipated long useful lives of LFP batteries, possibly exceeding 20 years. These valuation estimates are of obvious relevance for multiple stakeholders, including battery and automotive manufacturers, consumers and recycling companies.

The above calculations were based on U.S. battery price 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. Similar to the approach taken in connection with the U.S. market, we assume a 3.5% decline in the non-material portion of battery prices over time. Admittedly, the rate of future price declines is highly uncertain, depending on various factors, including the potential convergence of national markets versus the imposition of new trade barriers (Gopinath et al., 2024).

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	108.3	105.1	102.0	99.0	96.1	93.4	90.7	88.1	85.6	83.2
	Fast Degradation Scenario	90%	47.1%	45.8%	44.6%	43.3%	42.0%	40.7%	39.3%	37.9%	36.5%	35.0%	33.5%	32.0%
		80%	32.2%	31.0%	29.8%	28.5%	27.2%	25.8%	24.4%	23.0%	21.6%	20.1%	18.6%	17.1%
		70%	16.2%	15.0%	13.7%	12.4%	11.1%	9.8%	8.4%	7.0%	5.5%	4.0%	2.5%	1.0%
	Medium Degradation Scenario	90%	49.7%	48.5%	47.3%	46.0%	44.7%	43.4%	42.0%	40.6%	39.2%	37.7%	36.2%	34.7%
		80%	37.8%	36.5%	35.3%	34.0%	32.7%	31.3%	30.0%	28.6%	27.1%	25.6%	24.1%	22.6%
		70%	23.6%	22.4%	21.1%	19.8%	18.5%	17.1%	15.7%	14.3%	12.9%	11.4%	9.8%	8.3%
	Slow Degradation Scenario	90%	49.7%	48.5%	47.3%	46.0%	44.7%	43.4%	42.0%	40.6%	39.2%	37.7%	36.2%	34.7%
		80%	39.9%	38.7%	37.4%	36.1%	34.8%	33.5%	32.1%	30.7%	29.3%	27.8%	26.4%	24.8%
		70%	28.5%	27.3%	26.1%	24.8%	23.5%	22.1%	20.8%	19.4%	17.9%	16.5%	14.9%	13.4%

We find that even when the prices in China for new LFP batteries are 30% below U.S. prices, it is still profitable to repurpose used EV batteries for a second-life application, though the value retention shares drop significantly 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 repurposing lowers the overall value retention shares. Further, this effect will become more pronounced in the years with particularly low prices for new battery packs. 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 will be a toss-up between repurposing the used LFP battery and discarding it.

IV Fair Market Value of NCX Batteries

In contrast to LFP batteries, NCX batteries have distinctly positive recycling values; see Appendix B for details. At the same time, new NCX batteries are more expensive and degrade faster due to a smaller overall number of equivalent full charge- and recharge cycles. Table 4 shows that the latter two effects clearly dominate the former, resulting in user costs of capital that are substantially larger for NCX chemistries than those for LFP chemistries.

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	61.4	59.4	57.5	55.7	53.9	52.1	50.5	48.8	47.3	45.8	44.3	42.9
	Medium	39.3	38.1	36.8	35.6	34.5	33.4	32.3	31.3	30.3	29.3	28.4	27.5
	Slow	31.1	30.1	29.2	28.2	27.3	26.4	25.6	24.8	24.0	23.2	22.5	21.8

In calculating the fair market value of used NCX batteries, it is important to recall that the logic of our model requires future rental fees 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. Direct comparison of Tables 1 and 4 reveals that the competitive user cost of capital is determined by the LFP rather than 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%	220.0	213.2	206.6	200.2	194.0	188.1	182.4	176.8	171.5	166.4	161.4	156.6
	Fast Degradation Scenario	90%	5.0%	5.2%	5.3%	5.5%	5.7%	5.8%	6.0%	6.2%	6.4%	6.6%	6.8%	7.0%
		80%	5.0%	5.2%	5.3%	5.5%	5.7%	5.8%	6.0%	6.2%	6.4%	6.6%	6.8%	7.0%
		70%	5.0%	5.2%	5.3%	5.5%	5.7%	5.8%	6.0%	6.2%	6.4%	6.6%	6.8%	7.0%
	Medium Degradation Scenario	90%	10.4%	9.8%	9.2%	8.6%	8.0%	7.4%	6.7%	6.2%	6.4%	6.6%	6.8%	7.0%
		80%	5.0%	5.2%	5.3%	5.5%	5.7%	5.8%	6.0%	6.2%	6.4%	6.6%	6.8%	7.0%
		70%	5.0%	5.2%	5.3%	5.5%	5.7%	5.8%	6.0%	6.2%	6.4%	6.6%	6.8%	7.0%
	Slow Degradation Scenario	90%	17.2%	16.6%	16.0%	15.4%	14.8%	14.1%	13.4%	12.7%	12.0%	11.3%	10.5%	9.8%
		80%	9.0%	8.5%	7.9%	7.3%	6.6%	6.0%	6.0%	6.2%	6.4%	6.6%	6.8%	7.0%
		70%	5.0%	5.2%	5.3%	5.5%	5.7%	5.8%	6.0%	6.2%	6.4%	6.6%	6.8%	7.0%

The value retention shares shown in Table 5 are distinctly lower than those of their LFP counterpart in the context of the U.S. market. 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.

All cells marked in yellow in Table 5 indicate scenarios where instant recycling becomes the preferred alternative. The general pattern emerging from Table 5 is that immediate recycling is preferable to a second life deployment when future degradation is projected to be relatively fast and the initial SOH is low. Specifically, in the scenario of a 70% SOH, immediate recycling is always economically preferred. For 80% SOH batteries, almost all NCX batteries achieve a higher payoff from immediate recycling, except in the scenario of slow degradation before 2030. For batteries with a 90% SOH combined with a medium degradation scenario, starting in 2031, it would be preferable to collect the recycling value of the used NCX battery immediately. The value retention shares corresponding to immediate recycling increase over time, simply because new NCX battery prices are assumed to decline at a rate of about 3% while the recycling value is assumed to be time-invariant.

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.

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 repurposing 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. However,

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%	169.0	163.9	159.1	154.4	149.8	145.4	141.2	137.1	133.2	129.4	125.7	122.1
	Fast Degradation Scenario	90%	6.5%	6.7%	6.9%	7.1%	7.3%	7.6%	7.8%	8.0%	8.3%	8.5%	8.8%	9.0%
		80%	6.5%	6.7%	6.9%	7.1%	7.3%	7.6%	7.8%	8.0%	8.3%	8.5%	8.8%	9.0%
		70%	6.5%	6.7%	6.9%	7.1%	7.3%	7.6%	7.8%	8.0%	8.3%	8.5%	8.8%	9.0%
	Medium Degradation Scenario	90%	6.5%	6.7%	6.9%	7.1%	7.3%	7.6%	7.8%	8.0%	8.3%	8.5%	8.8%	9.0%
		80%	6.5%	6.7%	6.9%	7.1%	7.3%	7.6%	7.8%	8.0%	8.3%	8.5%	8.8%	9.0%
		70%	6.5%	6.7%	6.9%	7.1%	7.3%	7.6%	7.8%	8.0%	8.3%	8.5%	8.8%	9.0%
	Slow Degradation Scenario	90%	11.6%	10.8%	10.1%	9.3%	8.5%	7.7%	7.8%	8.0%	8.3%	8.5%	8.8%	9.0%
		80%	6.5%	6.7%	6.9%	7.1%	7.3%	7.6%	7.8%	8.0%	8.3%	8.5%	8.8%	9.0%
		70%	6.5%	6.7%	6.9%	7.1%	7.3%	7.6%	7.8%	8.0%	8.3%	8.5%	8.8%	9.0%

even in this optimistic scenario, immediate recycling would be preferable starting in 2030.

V Discussion

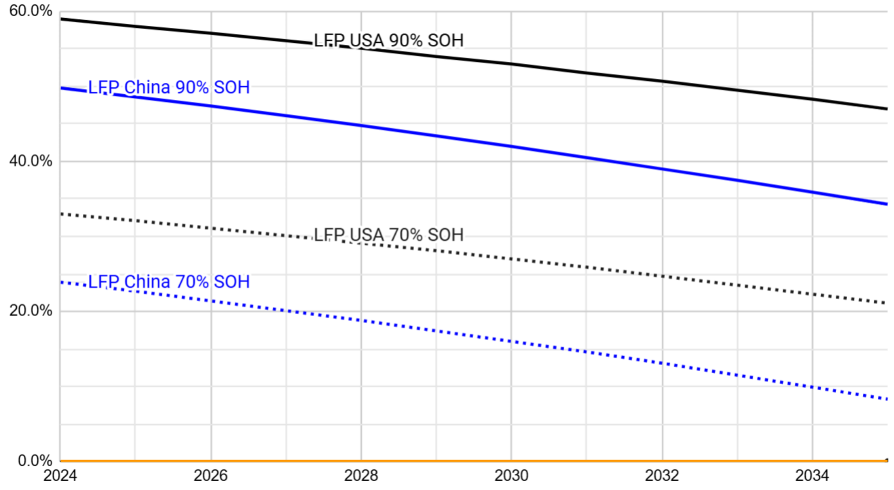
Our findings in the previous sections indicate a sizable market for repurposed LFP battery packs that have had a first-life automotive application. For used NCX batteries, in contrast, immediate recycling is becoming the preferred option for an increasing number of scenarios. To display our findings visually, Figure 2 plots the value retention shares from repurposing, defined as:

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

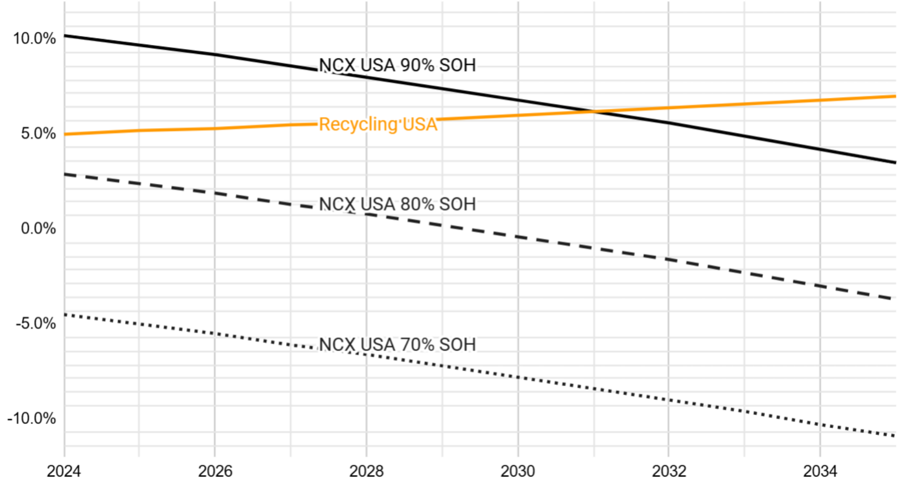
and the value retention shares from immediate recycling, defined as:

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

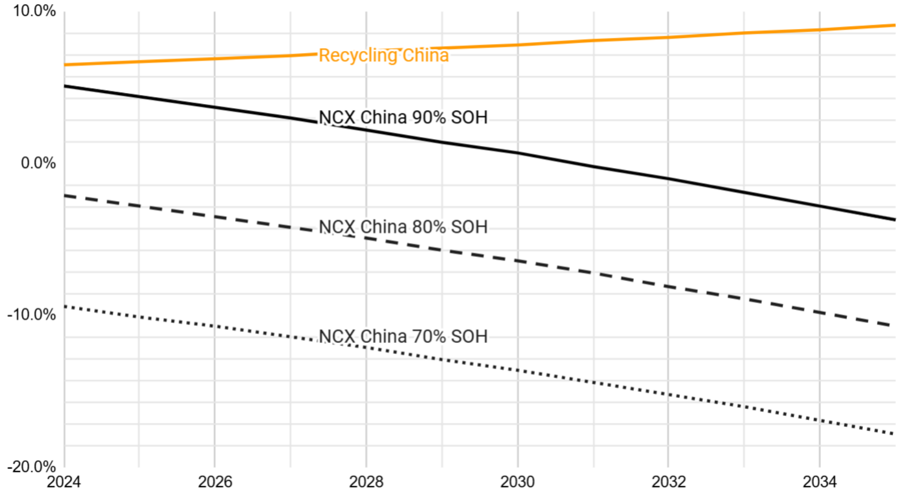
for LFP and NCX batteries in both the U.S. and China. Here, the black and blue curves represent the value retention shares from repurposing, while the orange curves represent the



(a) LFP USA and China



(b) NCX USA



(c) NCX China

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

value retention shares from immediate recycling. The value retention shares shown in Tables 2 and 3, as well as 5 and 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, $VRS_t^{rep}(x_i)$ 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 value 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 with the same SOH do not overlap in 2a. This can be attributed to the new battery price differential between the U.S. and China and an assumed identical percentage decline in the non-material portion of battery prices. 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.

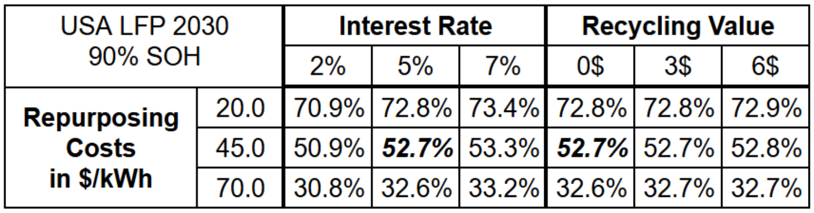
Panel 2b illustrates that for NCX batteries in the U.S., the year 2031 will be the "tipping point" at which immediate recycling becomes preferable for all NCX batteries, at least in the medium degradation scenario. Naturally, this tipping point will occur at a later point in time in a slow battery degradation 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 value immediately.

To further validate our findings, we compare our valuation estimates to available market data and subsequently conduct a series of sensitivity analyses. Our FMV estimates for 2024 suggest figures in the range of \$50–90 per kWh for used LFP batteries under a medium degradation scenario in the U.S. market. These results are in line with market data presented by Circular Energy Storage in an IRT webinar, which reported the lowest observed prices for used lithium-ion batteries in Europe and North America in the range of \$60–80 per kWh in 2024, although without specifying battery chemistries (Melin, 2025).

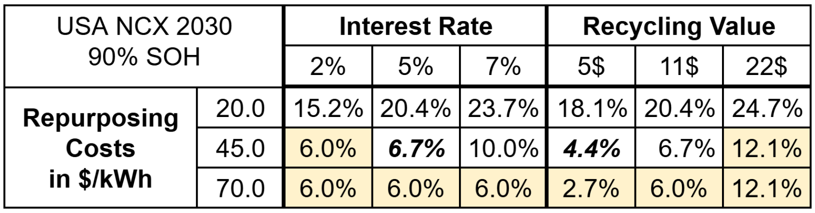
Tables 7 and 8 report select sensitivity tests regarding the impact of alternative parameter values for the interest rate r and the recycling value. Our base estimates obtained in the previous sections are highlighted in bold.[10]

Table 7: Value Retention Shares LFP, medium degradation scenario.



USA LFP 2030 90% SOH		**Interest Rate**			**Recycling Value**		
		2%	5%	7%	0$	3$	6$
Repurposing Costs in $/kWh	20.0	70.9%	72.8%	73.4%	72.8%	72.8%	72.9%
	45.0	50.9%	***52.7%***	53.3%	***52.7%***	52.7%	52.8%
	70.0	30.8%	32.6%	33.2%	32.6%	32.7%	32.7%

Table 8: Value Retention Shares NCX, medium degradation scenario.



USA NCX 2030 90% SOH		**Interest Rate**			**Recycling Value**		
		2%	5%	7%	5$	11$	22$
Repurposing Costs in $/kWh	20.0	15.2%	20.4%	23.7%	18.1%	20.4%	24.7%
	45.0	6.0%	***6.7%***	10.0%	***4.4%***	6.7%	12.1%
	70.0	6.0%	6.0%	6.0%	2.7%	6.0%	12.1%

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[10] Untabulated, we tested the impact of the model underlying Claim 2 and found only minor changes in the value retention shares.

We conduct our comparisons for the projected value retention shares in the 2030 U.S. market, assuming a 90% SOH and a medium degradation scenario. For alternative parameter values, we consider repurposing costs of $ 20, 45 and 70 per kWh for both LFP and NCX batteries, interest rates of 2%, 5% and 7% and recycling values of $ 5, 11 and 22 for NCX batteries, and $ 0, 3 and 6 for LFP batteries.

Table 9 examines the impact of alternative technological progress parameters η, ranging from 0.98 to 0.95.

Table 9: LFP and NCX, medium degradation scenario.

USA 90% SOH	η	**LFP**		**NCX**	
		c*	**VRS**	**c***	**VRS**
2025	0.980	12.1	57.9%	37.6	7.8%
	0.965	**13.6**	**58.0%**	**39.3**	**10.4%**
	0.950	15.9	59.2%	41.1	12.8%
2030	0.980	11.0	55.0%	33.7	5.8%
	0.965	**11.6**	**52.7%**	**32.3**	**6.7%**
	0.950	12.0	50.0%	31.0	7.3%
2035	0.980	10.1	51.9%	30.7	6.1%
	0.965	**9.9**	**46.7%**	**27.5**	**7.0%**
	0.950	9.5	40.5%	24.6	8.1%

Overall, our sensitivity tests indicate that for the range of variations considered here, the corresponding value retention shares vary between 0% and 20%, with changes in repurposing costs having the most significant impact. Lower interest rates, higher repurposing costs and lower recycling values decrease the value retention shares for both types of batteries.

As noted in Section II, if the decision to repurpose a battery coming out of its mobile application is made under uncertainty concerning the recycling values that can be obtained at different points in time, a risk neutral decision-maker may prefer to repurpose the asset, even though the expected future cash flows associated with holding the repurposed asset to the end of its useful life are less than the certain payoff attainable from immediate recycling. This potential shift in the decision rule reflects that repurposing does not entail a commitment to keep the asset. Instead, the cost of repurposing constitutes an "entrance ticket" to a real option for making sequentially optimal abandonment decisions in future periods. Similar reasoning applies if uncertainty and volatility in future payoffs stem from an uncertain degradation rate in the second life application or uncertainty about the future user costs of capital that can be earned. We also note that while these considerations apply to risk-neutral decision-makers, risk aversion would sway REPs towards the known immediate payoff associated with recycling.

VI Conclusion

The fair market valuation of used operating assets plays a central role in advancing circular economy goals, where economic and environmental considerations favor the redeployment of products, or significant components thereof, beyond their initial application. This paper develops and analyzes a general framework for assessing the fair market value of used capacity assets in the presence of repurposing costs and end-of-life recycling values. While our primary application focuses on lithium-ion batteries retired from electric vehicles, our framework is applicable more broadly to other second-life asset types, including consumer electronics, data center hardware, industrial equipment, and renewable power assets.

Batteries from retired electric vehicles represent a particularly compelling case for a second-life application. As the adoption of electric vehicles rises globally, more retired batteries become available, many of which still retain significant energy storage capacity.

Industry estimates suggest that the volume of repurposed electric vehicle batteries could meet a significant share of future demand for stationary energy storage. As such, electric vehicle batteries are poised to become one of the most economically significant categories of assets to be redeployed in a second-life application.

Applying our fair market valuation model to LFP and NCX batteries in the U.S. and China, we find that repurposing is economically viable for LFP batteries in both markets. In contrast, NCX batteries are typically better suited for immediate recycling. This result reflects the fact that NCX batteries are valued relative to LFP batteries, which have a substantially lower user cost of capital. Accordingly, the fair market value of NCX batteries is limited by the cost advantage of their more efficient counterparts.

Our analysis can be extended in future research to emerging battery chemistries such as sodium-ion and solid-state batteries. Notably, sodium-ion batteries are gaining traction, with Chinese car makers BYD and CATL beginning to scale up production (Zhang, 2023). A recent study suggests that cost parity with LFP may be reached within the next decade (Yao et al., 2024). In accordance with our model framework, cost-competitive battery chemistries with lower user cost of capital would then reduce the fair market value of incumbent battery types. A broader market shift toward new chemistries may also reduce demand for raw materials, such as nickel, cobalt and lithium, thereby lowering their recycling values.

Our results suggest that as new battery prices decline, used NCX batteries will be recycled more frequently. This trend may guide corporate investment toward recycling infrastructure. Without expected reuse, automakers may adopt a weight-optimized cell-to-body approach with the battery serving as a structural element. Repurposing efforts, by contrast, are more likely to focus on LFP batteries, with automakers potentially changing car designs to reduce repurposing costs. Our analysis leaves open the broader question of how vehicle owners will capture the residual value of used battery packs. One potential approach is for manufacturers to offer lower upfront vehicle prices in exchange for future ownership rights to the battery, similar to the model adopted by NIO (Zhang, 2024).

Beyond the market for batteries, our model has posited a competitive rental market for energy storage services. In practice, transaction costs or buyer preferences might favor asset ownership, potentially with warranties to offset performance risk. Our competitive valuation framework enables the quantification of the inherent trade-offs in the sale of a used battery and the terms of an accompanying warranty, providing the buyer with performance protection while allowing the seller to earn a zero economic profit in expectation.

Appendix A: Proof of Claims 1 and 2

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:

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

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:

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

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,

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

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

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

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

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

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

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

which obviously holds true.

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

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

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

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

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

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

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

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

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). □

Proof of Claim 2

The proof proceeds exactly along the same lines as the proof of Claim 1. Specifically, if

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

then the modified expressions for (6) and (7) above will coincide for any **I**. □

Appendix B: Parameter Calibration for LFP and NCX Batteries

This Appendix calibrates the model in the context of LFP and NCX batteries that transition to a stationary storage application. To that end, we begin with a discussion of different battery chemistries and then explain the estimates we rely on for the market prices of new battery packs, the degradation rates in second-life applications, repurposing costs, and recycling values.

Battery Chemistry

The vast majority of lithium-ion batteries that have been deployed up to now in electric vehicles are based either on lithium iron phosphate (LFP) or nickel-cobalt-X (NCX) chemistries (IEA, 2022). LFP batteries have a comparative advantage in terms of 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 had relied predominantly on NCX lithium-ion batteries up to that point in time (Tesla, 2022).[11]

Due to their higher energy density, NCX batteries are particularly attractive in electric

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[11] 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 terms of 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).

vehicle markets that prioritize the achievable range and acceleration capability of vehicles. In contrast, LFP batteries have gained a significant market share in countries like China, where consumers are willing to trade off range and performance for lower costs. Both battery chemistries are now suitable for mass-produced electric vehicles. For example, the standard version of the European Tesla Model 3 utilizes LFP chemistry, whereas the long-range Model 3 version employs NCX chemistry.

Prices of New Batteries

The overall market price of a battery pack includes the power component, the battery management system, and the battery cells. The battery is assumed to have a duration of 2.0 hours.[12] The power component of the battery pack will then be appropriate for both mobile automotive and stationary behind-the-meter applications.

In calibrating the trajectory of market prices for new battery packs, that is, the sequence $MV_t = w + \eta^t \cdot v$, we equate the stationary component, w, with the material related costs of the battery pack. For LFP batteries, we estimate w at \$17 per kWh based on raw material prices published in Fastmarkets (2024).[13]

For U.S. battery prices, we rely on reports from BloombergNEF (2023, 2024) and adjust the prices according to the impact of import tariffs introduced in 2024 (Murray, 2024). Specifically, we adopt an estimated market price of $v + w =$ \$150 per kWh for new LFP

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[12] 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.

[13] Our estimates are based on Tesla's Long Range and Standard Range battery packs, respectively. For LFP batteries, we included lithium (Li), iron (Fe), electrolyte, and other materials, while for NCX batteries, we considered lithium (Li), nickel (Ni), cobalt (Co), electrolyte, and other materials. The total material price of each pack was then divided by its respective energy capacity in kilowatt-hours (kWh).

battery packs in 2024.[14]

Regarding the technological progress parameter η, 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 of cumulative trade volume, the time-dependent part of MV_t would drop to 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 an annual price decline of 3.5% (η=.965). Applying this decline rate over the next decade, comparable new LFP battery packs are forecast to trade for $v \cdot \eta^{11} + w =$ \$107 per kWh in the year 2035.

For NCX batteries, we again rely on U.S. battery prices reported from BloombergNEF (2023) and incorporate the expected impact of import tariffs introduced in 2024 (Murray, 2024). Accordingly, our calculations begin with a U.S. market price of $v + w =$\$220 per kWh for new NCX battery packs in 2024. Consistent with our calculations for LFP batteries, we estimate the material cost share w of NCX batteries with data from Fastmarkets (2024) as \$24.5 per kWh. The technological progress parameter is again set at $\eta =$.965 for NCX batteries.

Degradation

The model described in Section II assumes that an asset's productive capacity declines as a function of time, represented through the declining sequence $0 = x_{T+1} < x_T \leq x_{T-1} \leq$

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[14] We rely on reported data for LFP batteries in China of \$115 per kWh BloombergNEF (2024). LFP battery prices are modeled to be 32% cheaper than NCX batteries, consistent with data from BloombergNEF (2023). Finally, we estimate U.S. battery prices to be 30% above Chinese prices, based on 11-20% higher prices before tariffs BloombergNEF (2023) and an additional tariff impact of 11-16% (Murray, 2024). Reports in the summer of 2025 suggest that U.S. prices for new LFP battery packs have reached \$130–140(Davies et al., 2025).

... $\leq x_1 = 1$. 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.[15] Specifically, the SOH, x_t, of a battery is modeled here as:

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

where $EFC_{\mathrm{Theoretical}}$ 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.

A battery's state of health (SOH), x_i, as it enters its second life, depends on the usage pattern during its 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:

$$x_t = x_i \cdot \left(1 - \frac{N \cdot \mathrm{DoD}}{EFC_{\mathrm{Theoretical}}}\right)^{t-i}, \text{ for } t \geq i. \tag{10}$$

The decline pattern in equation (10) 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 a stationary second-life deployment assume daily cycles, that is $N = 365$, and a DoD factor of 80%, a value commonly posited to avoid excessive degradation. In addition, we consider three degradation scenarios: fast, medium,

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[15] As the name suggests, depth of discharge refers to the percentage of remaining energy capacity that is left in the battery in each charge or discharge cycle.

and slow, allowing for theoretical EFCs of 10,000, 20,000, and 30,000 for LFP batteries.[16]

Finally, our calculations reflect the concept of the "aging knee" by supposing that equation (10) is applicable only up to a critical SOH value, dropping to zero thereafter. Specifically, we assume that for LFP batteries, life ends once x^i=50%.

To reflect the shorter life cycles of NCX chemistry, our analysis of NCX batteries considers fast, medium and slow degradation scenarios corresponding to 2,500, 5,000 and 7,500 Equivalent Full Cycles, respectively. In line with Zhuang et al. (2025), the aging knee for NCX batteries is assumed to occur once the SOH reaches 60%, in contrast to the 50% threshold set for LFP chemistries.

Recycling Value

The accelerated pace of EV adoption 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, and it has yet to achieve significant scale economies. Industry estimates for 2025 indicate that around 70% of used passenger car batteries are recycled, the remaining 30% end up in second-life applications, a share that is expected to increase over time (Kampker et al., 2023), with strong company activity in both sectors driving competition for a limited battery supply.[17] By 2030, recycling capacity for EV batteries in the U.S. is projected to exceed the available stock of end-of-life EV batteries and manufacturing scrap from battery cell production, raising concerns about a shortage of recyclable input materials (Morris, 2024).

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[16] 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.

[17] Recycling firms include Redwood Materials, Li-Cycle, and Umicore; second-life companies include B2U Storage Solutions, Circular Energy Storage, and Redwood Energy.

Reflecting this, our model assumes that sufficient recycling capacity is available and does not impose constraints on recycling throughput.

The model described in Section II posits that recycling values, that is, recycling revenues less applicable transportation and processing costs, result in a time-invariant payoff. In contrast to NCX batteries, there is currently insufficient data to support the suggestion that LFP batteries entail positive recycling values (Lander et al., 2021). 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.

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 payoff of $u =$ \$11 per kWh.[18] We assume this recycling value is time-invariant in light of the fact that raw material prices are not subject to the same learning curves that are characteristic of new battery packs. Clearly, our estimate is sensitive to variations in metal prices, recycling processes, as well as transportation and disassembly costs (Slattery et al., 2021; Lander et al., 2021). Section V reports some sensitivity tests regarding the recycling value.

Repurposing Costs

Prior to deployment in a stationary second-life application, the EV battery must be repurposed at a cost. Several second-life applications for EV batteries have been explored and discussed in the literature (Zhuang et al., 2025), with repurposing costs estimated at \$32 per kWh (Neubauer et al., 2012), \$21-50 per kWh (Neubauer et al., 2015),[19] €25-50 per

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[18] Our estimate of u is consistent with Elon Musk's April 2022 claim: "Even a dead battery pack is worth about a thousand dollars" (TED, 2022). A 75 kWh battery pack would have a recycling value of $75 \cdot$ \$11 $=$ \$825 in our calculations.

[19] See Figure 27 in Neubauer et al. (2015).

kWh (Reid and Julve, 2016), and \$65.3 per kWh (Cready et al., 2003).[20] In line with these literature estimates, we assess the cost of repurposing an EV battery, RPC, for deployment in a stationary second-life application at \$45 per kWh. This value is approximately the average of the above literature estimates. Lower values could be achieved with local battery sourcing and economies of scale, as elaborated in Neubauer et al. (2015). As with battery recycling, we assume that repurposing faces no capacity constraint. While large-scale repurposing of EV batteries is still in its early stages, the industry is expanding rapidly, with numerous firms investing in new capacity.[21] This emerging activity suggests that capacity is expected to grow in parallel with the availability of used batteries, reducing the likelihood of a structural bottleneck in second-life deployment.

Following our analysis for LFP batteries, our calculations also impute a \$45 per kWh charge to repurpose NCX battery packs for a stationary storage application.

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

[21] Such as Redwood Energy, B2U Storage Solutions, Circular Energy Storage and LiberTech.

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Variable	Explanation	Value
t	Time period (in years)	-
i	Age of battery (in years)	-
T	End of battery life (in years)	-
c_t	User cost of capital in t	-
x_i	Battery State of health energy capacity in i	-
r	Discount rate	5%
v	Battery non-material price ($/kWh, excl. raw materials, incl. power; Energy/Power ratio = 2.0)	varies
w	Material costs of new batteries ($/kWh) (LFP/NCX)	17 / 24.5
u	Recycling value for batteries ($/kWh) (LFP/NCX)	0 / 11
η	Price decline of non-material portion of new batteries (v) per year (scalar) (3% price decline)	0.965
RPC	Repurposing costs for used battery ($/kWh)	45
FMV	Fair market value of used battery ($/kWh)	-
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	-
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)	50% / 60%

Table 10: Summary of variables