Applying Levelized Cost of Storage Methodology to Utility-Scale Second-Life Lithium-Ion Battery Energy Storage Systems

July 2021

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PRE-PRINT
Published in: *Applied Energy*, Vol. 300, 2021, https://doi.org/10.1016/j.apenergy.2021.117309

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. NCST-UCD-RR-21-29	**2. Government Accession No.** N/A	**3. Recipient's Catalog No.** N/A

4. Title and Subtitle Applying Levelized Cost of Storage Methodology to Utility-Scale Second-Life Lithium-Ion Battery Energy Storage Systems	**5. Report Date** July 2021
	6. Performing Organization Code N/A
7. Author(s) Tobiah Steckel, PhD, https://orcid.org/0000-0002-5318-8735 Alissa Kendall, PhD, https://orcid.org/0000-0003-1964-9080 Hanjiro Ambrose, PhD, https://orcid.org/0000-0002-6502-5191	**8. Performing Organization Report No.** UCD-ITS-RP-21-72
9. Performing Organization Name and Address University of California, Davis Institute of Transportation Studies 1605 Tilia Street, Suite 100 Davis, CA 95616	**10. Work Unit No.** N/A
	11. Contract or Grant No. USDOT Grant 69A3551747114
12. Sponsoring Agency Name and Address U.S. Department of Transportation Office of the Assistant Secretary for Research and Technology 1200 New Jersey Avenue, SE, Washington, DC 20590	**13. Type of Report and Period Covered** Pre-Print (October 2019 – June 2021
	14. Sponsoring Agency Code USDOT OST-R

15. Supplementary Notes

Published in: *Applied Energy*, Vol. 300, 2021, https://doi.org/10.1016/j.apenergy.2021.117309

16. Abstract

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17. Key Words Second-Life batteries; lithium-ion batteries; energy storage, grid integration, LCOS; battery end-of-life	**18. Distribution Statement** No restrictions.

19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 26	**22. Price** N/A

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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Acknowledgments

This study was funded, partially or entirely, by a grant from the National Center for Sustainable Transportation (NCST), supported by the U.S. Department of Transportation (USDOT) through the University Transportation Centers program. The authors would like to thank the NCST and the USDOT for their support of university-based research in transportation, and especially for the funding provided in support of this project.

Preprint of:
T. Steckel, A. Kendall, and H. Ambrose, “Applying levelized cost of storage methodology to utility-scale second-life lithium-ion battery energy storage systems,” *Appl. Energy*, vol. 300, p. 117309, 2021, doi: https://doi.org/10.1016/j.apenergy.2021.117309.

Applying Levelized Cost of Storage Methodology to Utility-Scale Second-Life Lithium-Ion Battery Energy Storage Systems

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Abstract

The dramatic increase in electric vehicle (EV) sales has led to a rapid increase in deployed lithium-ion battery (LIB) capacity over the last decade. As EV batteries age and are retired from use in vehicles, they will require management. Second-life applications are often proposed as an environmentally and economically preferable management strategy to direct recycling or disposal. In particular, the repurposing of EV LIBs in stationary applications is expected to provide cost-effective solutions for utility-scale energy storage applications. However, the adoption of second-life battery energy storage systems (BESS) has been slow. One barrier to adoption is the lack of meaningful cost estimates of second-life BESS. Thus, this study develops a model for estimating the Levelized Cost of Storage (LCOS) for second-life BESS and develops a harmonized approach to compare second-life BESS and new BESS. This harmonized LCOS methodology predicts second-life BESS costs at 234-278 ($/MWh) for a 15-year project period, costlier than the harmonized results for a new BESS at 211 ($/MWh). Despite having a higher LCOS, the upfront costs for second-life BESS are 64.3-78.9% of new systems' costs. Results for second-life BESS are highly sensitive to assumptions of discount rate, depth of discharge, and module repurposing costs. If deemed environmentally or societally beneficial, policies should stimulate the use of second-life LIBs, such as providing incentives equal to or greater than those available for first life BESS. Further work can explore comparative economics at smaller scales and quantify non-economic benefits of second-life BESS.

Keywords

Second-Life batteries; lithium-ion batteries; energy storage, grid integration, LCOS; battery end-of-life

Nomenclature

a_{deg}	Annual battery capacity degradation
aod	Annual operating days
BESS	Battery energy storage system
cap_e	Energy capacity
cap_p	Power capacity
DoD	Depth of discharge
EPR	Energy to power ratio
EV	Electric vehicle
ITC	Investment Tax Credit
LCOE	Levelized Cost of Energy
LCOS	Levelized Cost of Storage
LIB	Lithium-ion battery
nmc_e	New battery module market cost
NREL	National Renewable Energy Laboratory
$O\&M_p$	Fixed O&M cost (power)
P_{el}	Charging cost
P_{esc}	Charging cost escalator
r	Discount rate
rc_e	Battery module repurposing cost
rl_e	Battery module replacement labor cost
SGIP	Self-Generation Incentive Program
SLBESS	second-life battery energy storage system
SOH_i	Initial state of health
T	Project years
t_c	Construction time
TCC	Total capital cost
tcc_e	Total capital cost (energy)
TDC	Total Discounted Cost
TDE	Total Discounted Energy
t_r	Replacement interval
η_{rt}	Roundtrip efficiency

1. Introduction

Approximately 5 million electric vehicles (EVs) have been deployed globally over the last decade, and with them, approximately 400 GWh of lithium-ion traction batteries [1]. The rapidly growing market for light, medium, and heavy-duty EVs will eventually result in large flows of used or retired batteries. While battery packs from these vehicles will be retired for several reasons, the typical degradation pattern for lithium ion batteries (LIBs) indicates that many will retain upwards of 80% of their rated storage potential when retired from a vehicle [2–5] after about 8–10-years of useful life [6,7]. Given this in-use lifetime estimate and remaining storage potential, the capacity of traction batteries at the end of automotive life is expected to increase ten-fold over the next decade, from 26 GWh in 2025 to as much as 227 GWh in 2030 [8,9].

Retired LIBs from EVs could be given a second-life in applications requiring lower power or lower specific energy. As early as 1998, researchers began to consider the technical feasibility of second-life traction batteries in stationary energy storage applications [10,11]. With the shift towards LIBs, second life applications have been identified as a potential strategy for reducing the up-front costs of new EVs [12]. A growing body of research has examined the potential environmental and economic benefits of second life applications [13–21]. Second-life strategies for EV batteries, especially in stationary, grid-connected, storage applications are increasingly viewed as a key part of sustainable end-of-life management for LIBs.

The majority of studies of second-life systems are limited by the system size they consider, while the few studies that focus on large-scale systems report inconsistent results. Cready et al. provided early technoeconomic research and developed a process-based model for battery repurposing costs that was subsequently applied in further studies [22–24]. Studies of smaller-scale residential and commercial applications have explored increased renewable self-consumption, time of use arbitrage, demand charge alleviation, and local balancing [25–32]. A smaller set of papers explore larger, utility-scale systems. Song et al. [33] finds that second-life batteries generally have higher costs compared with new batteries and suggests that, given the generation uncertainty, the most beneficial economic coupling for second-life batteries is wind power production. Gur et al. [34] finds a positive net present value for utility-scale second-life battery storage under favorable conditions. Mathews et al. [35] builds upon early techno-economic studies to derive the necessary capital costs for second-life batteries to be equivalent to new batteries in utility-scale operations. Overall, more research may be required to ascertain whether utility-scale second-life battery energy storage systems (BESS) are genuinely a sustainable economic strategy.

Utility-scale demonstrations of second-life BESS are essential because a larger capacity system is necessary for grid applications [36]. At least nine pilot and demonstration projects have been undertaken to explore second-life BESS in utility-scale systems (see section S1 of the supplementary material associated with this article for information on these projects). While it may seem inevitable that second-life batteries would be cost-effective in stationary storage applications, there are significant costs for collecting, transporting, and repurposing. In addition, the cost of new LIBs have fallen dramatically [37–39], which continues to present a challenge to the cost-competitiveness of second-life LIBs.

A consistent and comparable cost estimate for second life and new BESS is a critical step for determining the market competitiveness and potential adoption, yet a standardized methodology for comparing these alternatives is largely absent from prior studies [8,40–42]. One reason for a lack of standardization is that the cost of energy technologies can be examined through several lenses. Among them, the Levelized Cost of Energy (LCOE) has gained wide acceptance, especially in comparative assessments. LCOE calculations consider the life cycle costs of a system, scaled by the quantity of energy delivered, and report a break-even price for a given generation asset over its lifetime. Because of these features, LCOE is particularly useful in determining the potential profitability or comparative performance of energy generation technologies [43].

The levelized cost of storage (LCOS), similar to LCOE, quantifies the storage system's costs in relation to energy or service delivered [44,45]. Some key differences between LCOE and LCOS include the inclusion of electricity charging costs, physical constraints of the storage system during charge/discharge, and differentiation of power-related and energy-related applications [46]. Equation 1 shows a simplified LCOS equation adapted from Schmidt et al. [47], with abridged investment, operations, and financing parameters.

$$LCOS\left[\frac{\$}{MWh}\right] = \frac{TCC + \sum_{n}^{N}\frac{O\&M}{(1+r)^{n}} + \sum_{n}^{N}\frac{Charging}{(1+r)^{n}} + \frac{EOL}{(1+r)^{N+1}}}{\sum_{n}^{N}\frac{Elec_{D}}{(1+r)^{n}}} \quad (1)$$

Where: n is the project year, N is the project lifetime, r is the discount rate, O&M is the annual operation and maintenance cost in given year n, Charging is annual charging costs in a given year n, EOL is the end-of-life cost, and $Elec_D$ *is the annual electricity discharged.*

Previous research has used the LCOS method to evaluate new BESS (e.g., [48,49]). A review of these applications of the LCOS method shows variability in addressing key performance characteristics important for comparing LCOS of BESS. These performance indicators, their definitions, and the values they have been assigned in previous LCOS estimates are described in the list below, and more information on each is included in section S2 of the supplemental material:

- **Capacity fade** refers to the decreased ability of a battery to hold energy as a function of time. This decrease can accelerate as a function of cycling and exposure to ambient temperature variations and reduces the capacity of stored energy available. Various chemical and mechanical degradation mechanisms drive capacity fade (e.g., [50–52]). Capacity fade is predominantly represented through a degradation rate or within the O&M costs but is not explicitly included in some LCOS studies. When it is included, the capacity fade of new BESS is typically assigned a value between 1.3-2.6% (e.g., [37,53]).
  Relative to new BESS, studies have represented second-life systems as having both a higher [14,27]and lower capacity fade rate [54,55]or presenting a broader range of values. Integrating capacity fade within the O&M costs results in significant variability, with cost estimates ranging from 1-37 ($/kW, see section S3 for additional details).
- **Depth of Discharge (DoD)** refers to the amount of capacity discharged in a given cycle. Some studies neglect to include DoD in the LCOS model. When included, DoD ranges from 45-90% across studies (S2). DoD has a significant bearing on the revenue from discharging over the project lifetime and, thus, the LCOS. Concerning the comparison between technologies, the DoD can have a marked impact on the battery life within a storage system, which means that a higher DoD may lead to more battery module replacements over the project lifetime.
- **Energy to Power Ratio (EPR)** refers to the quantity of electricity that can be discharged instantaneously (power) as compared to how long that rate of discharge can be sustained (energy; analogous to flow rate and overall volume). All studies acknowledge this ratio within the scope of the LCOS model. However, the EPR value chosen varies widely across existing studies, from 0.25-10 (see section S2 of the supplementary material for additional details). Different EPR across studies has a trivial effect on the resulting LCOS because the answer is scaled by the energy provided. Thus, a study that opts for a smaller parameterization of EPR will likely report a higher LCOS.
- **Project Life** refers to the project's financial timeline, where costs are being paid or energy is generated. Like EPR, project life is included in the LCOS scope of all the reviewed studies. In existing studies reviewed, project life ranges from 7-30 years (Supporting Information S2). This

range might arise from differences in scope, where some models represent the life of the battery as the project life as opposed to allowing for module replacement. Because of the LCOS's financing portion, comparing results accrued over 7-30 years can be misleading [56].

A review of previous research on LCOS applied to BESS reveals that both the scope (i.e., the inclusion or exclusion of particular performance characteristics) and the assumed values of performance characteristics affect the consistency and comparability of results. Section S2 of the supplementary material provides an in-depth review of previous studies' scopes and assumptions. Variability in treating these characteristics makes comparison across studies impossible, highlighting the need for a standardized approach to LCOS applied to new or second-life BESS.

To address the problem of variability across LCOS methods, this study proposes a novel harmonized LCOS approach that defines an appropriate scope for LCOS calculation for BESS and recommends harmonized parameter values for second-life and new BESS. A robust comparative economic assessment of these two systems is absent from the existing literature. Thus, the intended outcomes of this harmonized LCOS model include:

- Adoption of LCOS as a common approach for cost assessment of second-life BESS
- Improved comparability across LCOS estimates for second-life and new BESS, which will also facilitate a meaningful comparison between them.
- Estimation of the LCOS for a utility-scale second-life BESS based on current data.
- Estimation of LCOS and repurposing costs for the purpose of informing policy around second-life batteries.

2. Methodology

This study refines the LCOS model to compare the economics of second-life EV LIBs in utility-scale BESS to new batteries in the same application. A probabilistic LCOS model is developed and used to compare prior studies through Monte Carlo analysis based on a harmonization of parameters. A critical contribution of this work is the inclusion of parameters specific to second-life applications: the initial state of health, replacements, repurposing costs, and new module costs. This section describes the LCOS model form, the parameter harmonization, and key second-life parameter estimation methods.

2.1 LCOS model for second-life and new BESS

LCOS can be described as the summation of discounted costs over discounted discharged energy (eq. 2).

$$LCOS\left[\frac{\$}{MWh}\right] = \frac{Total\ Discounted\ Cost}{Total\ Discounted\ Electricity} \quad (2)$$

The EPR defines the relationship between the system's energy capacity and power capacity (eq. 3).

$$cap_e = \text{EPR} \cdot cap_p \quad (3)$$

Total discounted costs for a new system are represented as a piecewise function (eq. 4), wherein for the initial time step (t=0), total costs are represented as the total capital costs. After construction, the costs are comprised of O&M costs and charging costs. Discounting for the O&M costs is a function of the discount rate and construction time. Charging is discounted similarly, apart from including the charging efficiency.

$$TDC_{newBESS} = \begin{cases} t = 0 & tcc_e \cdot cap_e \\ t \geq t_c & \sum_{t=t_c}^{T} \frac{O\&M_p \cdot cap_p}{(1+r)^{t_c+t}} + \frac{t \cdot (1+P_{esc}) \cdot P_{el} \cdot cap_e \cdot SOH_i \cdot DoD \cdot aod \cdot (1-a_{deg})^{t-t_c}}{\eta_{rt}{}^{.5}(1+r)^{t_c+t}} \end{cases} \quad (4)$$

Total discounted costs for the second-life BESS are defined similarly in (eq. 5). Here, repurposing costs and the new battery module's cost have been included to represent the offset of total capital costs for second-life BESS. Second, given the shorter assumed lifespan of second-life battery modules, replacement costs and a different degradation term are implemented. An offset represents the state of degradation based on years of service since the module was installed or replaced.

$$TDC_{secondlifeBESS} = \begin{cases} t = 0 & (tcc_e + rc_e - nmc) \cdot cap_e \\ t \geq t_c & \sum_{t=t_c}^{T} \frac{O\&M_p \cdot cap_p}{(1+r)^{t_c+t}} + \frac{t \cdot (1+P_{esc}) \cdot P_{el} \cdot cap_e \cdot SOH_i \cdot DoD \cdot aod \cdot \left(1-a_{deg}\right)^{t-o_{deg}-t_c}}{\eta_{rt}{}^{.5}(1+r)^{t_c+t}} \\ t = t_r & \frac{(rc_e + rl_e) \cdot cap_e}{(1+r)^{t_c+t}} \\ t < t_r & o_{deg} = 0 \\ t \geq t_r & o_{deg} = t_r \end{cases} \quad (5)$$

The total discounted energy delivered by a new storage system can also be represented as a piecewise function (eq. 6). No electricity is generated until the end of the construction period, and thus at t = 0, the discharged energy is 0. After the construction period has elapsed, the total energy is a summation identical to the total costs' charging cost component.

$$TDE_{newBESS} = \begin{cases} t = 0 & 0 \\ t \geq t_c & \sum_{t=t_c}^{T} \frac{cap_e \cdot SOH_i \cdot DoD \cdot aod \cdot (1-a_{deg})^{t-t_c}}{\eta_{rt}{}^{.5}(1+r)^{t_c+t}} \end{cases} \quad (6)$$

An additional parameter (o_{deg}) is integrated into eq. 5 when estimating the discounted energy to account for a battery replacement in the second second-life system (eq. 7).

$$TDE_{secondlifeBESS} = \begin{cases} t=0 & 0 \\ t \geq t_c & \sum_{t=t_c}^{T} \frac{cap_e \cdot SOH_i \cdot DoD \cdot aod \cdot \left(1-a_{deg}\right)^{t-o_{deg}-t_c}}{\eta_{rt}{}^{.5}(1+r)^{t_c+t}} \\ t<t_r & o_{deg}=0 \\ t \geq t_r & o_{deg}=t_r \end{cases} \quad (7)$$

This LCOS calculation is detached from explicit revenue streams and financing terms to harmonize other LCOS studies and provide a level comparison between second-life and new systems. In addition to extending to other technologies, this framework can evaluate different use cases (e.g., customer type and applications) and is in part based on the work of Schmidt et al. [47].

The harmonized parameters across technologies are provided in Table 1. Harmonizing this set of parameters in the model allows for analysis of remaining parameters to give a more realistic view of LCOS variance. The remaining parameterization of second-life BESS is an aggregation of literature values and some original modeling. Stochastic methods are applied to generate a distribution of LCOS values for second-life BESS. As for the new BESS, the remaining parameterization is drawn directly from literature values. These values are input into the LCOS model deterministically; however, because there are multiple outputs (n=8), LCOS distribution is generated, similar to second-life BESS.

Table 1 - Harmonized parameters for LCOS model.

parameter	**symbol**	**units**	**second-life BESS**	**new BESS**
Initial state of health	SOH_i	%	80.0	100
Depth of discharge	DoD	%	60.0	80.0
Replacement interval	t_r	yrs	8.00	15.00
Charging cost	P_{el}	$/MWh	32.0	
Charging cost escalator	P_{esc}	%	1.87	
Project years	T	yrs	15.0	
Roundtrip efficiency	η_{rt}	%	85.0	
Annual operating days	aod	days	365	
Construction time	t_c	yrs	1.00	
Energy to power ratio	EPR	hrs	4.00	
Discount rate	r	%	8.00	
Capacity	Cap_P	MW	1.00	

2.2 Parameterization for second-life BESS

Harmonized parameters for second-life BESS are a blend of existing literature values and some novel analysis. Previous literature for second-life battery lifetime assumes an initial state of health (SOH) of 80% (e.g., [17,19,24,35,51]) and an operational lifetime in second use around seven to eight years. This simplification also reflects the considerable uncertainty surrounding fault diagnosis in EV battery systems[57]. New storage assets are assumed to have a 15-year operating life, meaning second-life systems require one replacement over a project lifetime. DoD assumptions are based on previous literature that suggests DoD should be 60% to reduce the effect of cyclic aging (e.g., [17,24,58,59]). Martinez-Laserna et al. [8] point out the lingering uncertainty in the degradation rate of second-life batteries as well as real-world variability in degradation rates. Thus, the LCOS is calculated over a range of possible degradation rates 1-3 (%/yr.) that will dictate the second-life BESS capacity fade. The remaining parameters that are not harmonized within second-life BESS are highly dependent on two separate scenarios driven by potential business models. The first scenario, the market scenario, assumes that a retired battery is bought off an open market and incurs the costs of purchasing a retired battery and repurposing [12]. The second scenario, the owner scenario, assumes an owner leases out the battery in its first life and thus only incurs repurposing costs [60–62]. A range of LCOS is provided for both business models.

The remaining parameters, comprised of TCC, O&M, and repurposing costs are represented stochastically, based on the results of a Monte Carlo simulation. TCC and O&M costs are assumed to be identical for new and second-life BESS, except for the cost of the battery modules in the system (e.g., [35]). In effect, the balance of system (BOS) is a range of values informed by new lithium-ion battery capital costs subtracted by a new battery module cost. O&M cost is similarly presented as a range of values. In the market scenario, the battery purchase cost is simply a range of current market prices. In the owner scenario, the battery module cost is just the repurposing cost, again represented as a range of values. As in Neubauer et al. [63], the replacement cost is represented as the replacement battery module price and installation labor costs.

2.2.1 Repurposing costs

Repurposing costs are a function of the business model (owner versus market scenarios). While values for the market scenario are derived from literature [17,24,64–66], the owner scenario values are derived from an amended version of the National Renewable Energy Laboratory (NREL) repurposing calculator [24]. The changes to the NREL repurposing calculator include:

- Omitting the procurement cost of retired batteries since the owner scenario assumes the repurposer already owns the batteries.
- Shipping and collection of the batteries are still included in the repurposing cost. Since the batteries now arrive as packs and not modules, however, an increase of 5-10% (depending on the high and low scenario) to the repurposing cost is allotted to unpacking the battery [61].
- Likewise, a much higher cell fault rate is assumed than in the NREL calculator, based on personal communication with a repurposer.

The NREL calculator default values are also changed to represent technological updates. Reflective of the second-generation Nissan Leaf module, the battery module capacity shrinks from 5 kWh (in the original model) to 0.8 kWh. Shrinking the module justifies faster handling assumption while standardizing the battery source (e.g., the make and model of the EV) justifies faster sorting/testing [67–69]. Specifically, a collaboration between Ametek and the University of Warwick claims to reduce the grading time of a single module (visual inspection and electricity testing) from four hours to less than five minutes [70]. California company, Repurpose Energy, claims a similar decrease in testing time.

Given significant uncertainty in repurposing costs and how cost reductions may evolve, a low and high-cost scenario for the current day and eight years in the future are modeled (see section S3 of the supplementary material). There is an incentive for automation due to the high labor to capital costs in this process-based model. Full automation or hybridization of battery-related processes such as repurposing and recycling has recently received more attention in the literature (e.g., [69–71]). As pointed out by Harper et al. [69], these processes demand precise and standardized directions, so optimizing this process to a single battery source may prove much more feasible (as is assumed in this research).

Suppose the repurposing industry can decrease the manual labor required through automation. In that case, we assume that with the same throughput, the number of technicians could be cut in half relative to the NREL calculator default assumptions. Concurrently, positions scaled by the number of technicians are decreased by 50% (e.g., technician supervisors, human resources personnel, and administrative assistants). This rationale for halving the labor requirements reflects the assumption that repurposing activities can be divided equally between predictable physical work and non-predictable physical work. Chui et al. [72] estimate that automation can replace 78% of predictable physical work and 25% non-predictable physical work.

The parameter names, descriptive statistics, and distributions used in the Monte Carlo simulation for second-life BESS are summarized in Table 2.

Table 2 - LCOS parameters for second-life BESS.

parameter	**symbol**	**units**	**mean value**	**standard deviation**	**value range**	**distribution**	**source**
Total capital cost	tcc_e	$/kWh	319	66.0	188-350	normal	[53,73–75]
Fixed O&M cost	$O\&M_p$	$/kW	7.78	1.75	4.88-10.0	normal	[36,53,76,77]
New battery module market cost	nmc_e	$/kWh	150.9	19.0	134-180	uniform	[53,78,79]
Battery module repurposing cost	rc_e	$/kWh	37.0	15.0	18.0-64.0	normal	[6,24,63,80,81]
Second life battery module market cost	rc_e	$/kWh	80.0	21.0	50.0-108	normal	[17,24,63]
Battery module replacement labor cost	rl_e	$/kWh	11.0	9.19	4.00-17.0	uniform	[63]
Future battery module repurposing cost	rc_e	$/kWh	25.0	10.0	18.0-36.0	uniform	[66]
Future second life battery module market cost	rc_e	$/kWh	42.0	1.84	40.0-43.0	discrete	[64,66]
Annual battery capacity degradation	a_{deg}	%/yr			1.00-3.00	discrete	

2.2 Parameterization for new BESS

The remaining parameters for characterizing new systems are derived from previous LCOS studies. These include TCC, O&M cost, and annual degradation rate (where applicable). The capital costs from previous LCOS studies are based on price surveys conducted within each study, and the variability across studies is reflected in Table 3. Studies also treat capacity fade differently, with some explicitly including it, others embedding it within other parameters such a O&M (as in the studies included in Table 3), making harmonization of capacity fade impossible. As a result, all the parameters listed in Table 3 must be included, even while they cannot be harmonized across all studies. Table 3 contains five different studies released in 2019 or later. Older studies are omitted due to the rapid decline in battery prices. The modeling of new BESS results is undertaken using eight scenarios based on the values reported in Table 3. The parameter names and values for BESS are summarized in Table 3.

Table 3 - Parameterization of new BESS.

parameter	**symbol**	**units**	**BNEF, 2019**	**Cole et al., 2019 (low)**	**Cole et al., 2019 (high)**	**Lazard, 2019 (low)**	**Lazard, 2019 (high)**	**EIA, 2020**	**Lazard, 2020 (low)**	**Lazard, 2020 (high)**
Total capital cost	tcc_e	$/kWh	328	331	371	189	429	346	188	350
Fixed O&M cost	$O\&M_p$	$/kW	0	33.0	37.1	1.00	20.0	24.7	7.20	8.80
Annual battery capacity degradation	a_{deg}	%/yr	1.30	0	0	0	0	0	2.59	2.59
Capacity	cap_p	MW	N/A	60.0	60.0	100	100	N/A	100	100

3. Results and Discussion

3.1 Cost and performance results for new and second-life BESS

As reported in Table 4, the LCOS model for second-life BESS predicts mean values to be 234 ($/MWh) for the owner scenario and 278 ($/MWh) for the market scenario, with the first and third interquartile range (IQR) of 194-269 and 243-315 ($/MWh) for the owner and market scenarios respectively. This LCOS compares with second-life BESS TCC range from 222-274 ($/kWh) depending on the business model. The nominal capacity factor for SBESS ranges from 6.80-7.18 %/yr, reflecting the low initial state of health and conservative DoD. Likewise, the equivalent O&M costs are 3.15-7.78 ($/kW-yr).

The harmonized LCOS for new BESS predicts a mean value of 211 ($/MWh). The mean TCC across the new BESS is 312 ($/kWh). The capacity factor is based on the nominal capacity and is a function of calendar degradation rates and DoD. The range of degradation rates results in a nominal capacity factor of 10.0-11.5 %. The capacity fade from this range of degradation rates can also be represented as a range of O&M costs, which is found to be 7.78-17.4 ($/kW-yr).

A comparison of LCOS results shows second life BESSs are on average 11-32% more expensive than new BESS, despite having lower TCC than a new BESS. Specifically, the TCC of second-life BESS is 64.3-78.9% of the TCC of a new BESS. While TCC is an important measure of cost on its own, it is insufficient for comparison. A Welch's t-test was performed between the owner model results and a resampled population (to standardize the sample size) to quantify the significance of this difference between first and second-life BESS LCOS. Results suggest a significant difference; a 95% confidence that second-life BESS has an LCOS 22-34 ($/MWh) higher than new BESS.

Another vital component to comparing these systems is the uncertainty of costs. The difference between the first and third IQR of LCOS is 72-75 ($/MWh) in second-life BESS compared to 45 ($/MWh) for BESS. The standard deviations for the two populations are 56.8 and 47.3 for second-life and new BESS, respectively, though the new BESS sample size is significantly smaller. The uncertainty of these values is shown graphically in Figure 1.

Table 4 -Technoeconomic results for second-life and new BESS.

technology	**mean LCOS ($/MWh)**	**LCOS standard deviation**	**1Q LCOS ($/MWh)**	**3Q LCOS ($/MWh)**	**capacity factor low**	**capacity factor high**	**mean TCC ($/kWh)**	**mean TCC as % of New**	**effective fixed O&M low**	**effective fixed O&M high**
New BESS	211	47.3	193	238	10.0%	11.5%	312	100	5.62	17.4
SLBESS owner scenario	234	56.8	194	269	6.80%	7.18%	201	64.3	3.15	7.78
SLBESS market scenario	278	56.1	243	315	6.80%	7.18%	246	78.9	3.15	7.78

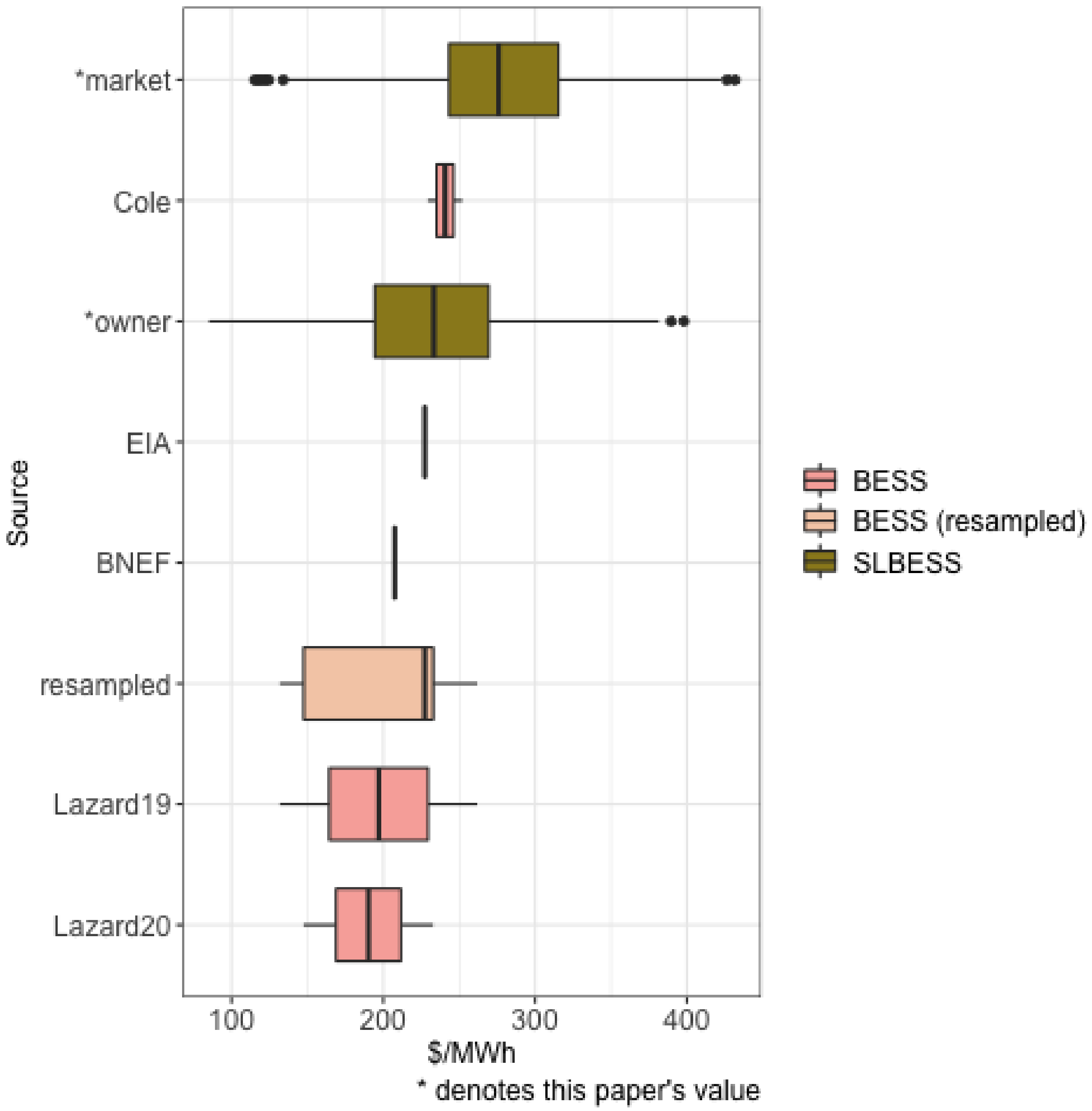

Figure 1 - Harmonized LCOS results for second-life and new BESS across sources.

While the LCOS revealed significant differences in cost, other performance measures could also shape the preference for a new BESS over a second-life BESS. Unsurprisingly, second-life BESSs have nominal capacity factors lower than that of new BESSs, but the magnitude of this performance gap has not been widely discussed. The drop in capacity factor from 10.0-11.5% to 6.80-7.18% is sizable and has potential ramifications for adopting second-life systems. For example, in an application where space is limited, the lower capacity factor may be unacceptable as the second life BESS's energy density is essentially one-third less than a new BESS. Because of energy density and other performance differences among second-life and new BESS, the inclusion of capacity fade and DoD in the nominal capacity factor is required to reflect actual performance better. For example, given the EPR assumed in this paper (4), daily operation, and a DoD of 100%, the capacity factor would be 16.7 %, when realistically, the capacity factor is much lower. Wankmuller et al. [82], one of few studies to explicitly quantify the performance of

BESS, indicate revenue reduction of 12-46% when comparing an arbitraging battery system with no degradation [. Similarly, the life-cycle performance is important between second-life BESS and new BESS and may lead to similar revenue reductions.

3.2 Business models affecting the LCOS of second-life BESS

The costs of second-life BESS are more uncertain and potentially more variable than new BESS. The choice of business model substantially affects the LCOS, and there is a clear economic advantage to the owner model. Both business model scenarios result in a wide distribution of possible LCOS, but there is little overlap (Fig. 2). By mean, the two models differ by about 44 ($/MWh). The breakdown of parameters inherent to the LCOS model is also shown for owner and market scenarios (Fig. 3). The major cost drivers for the second-life BESS systems are TCC, charging costs, and repurposing costs at the beginning of the project. TCC and charging cost account for about 180 ($/MWh), but perhaps the most exciting aspect of this disaggregation is the difference in repurposing cost. The costs are 28.6 and 10.9 ($/MWh) at the onset and the overhaul in the owner scenario. If the battery is bought off the market, the cost is 62.8 and 17.0 ($/MWh).

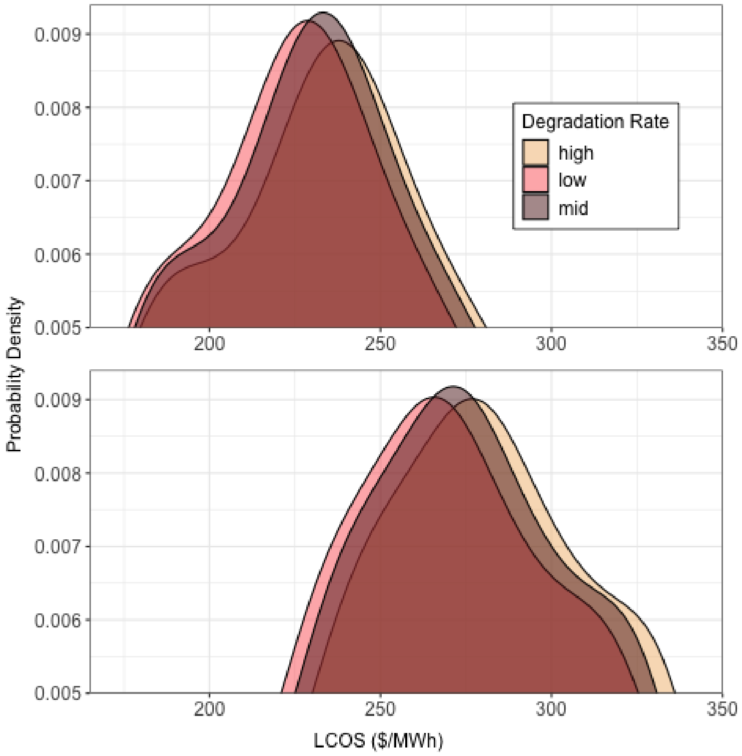

Figure 2 - Second-Life LCOS distribution by degradation rate. Probability density function (pdf) for LCOS of second-life BESS as a function of degradation rate for the owner scenario (a) and market scenario (b).

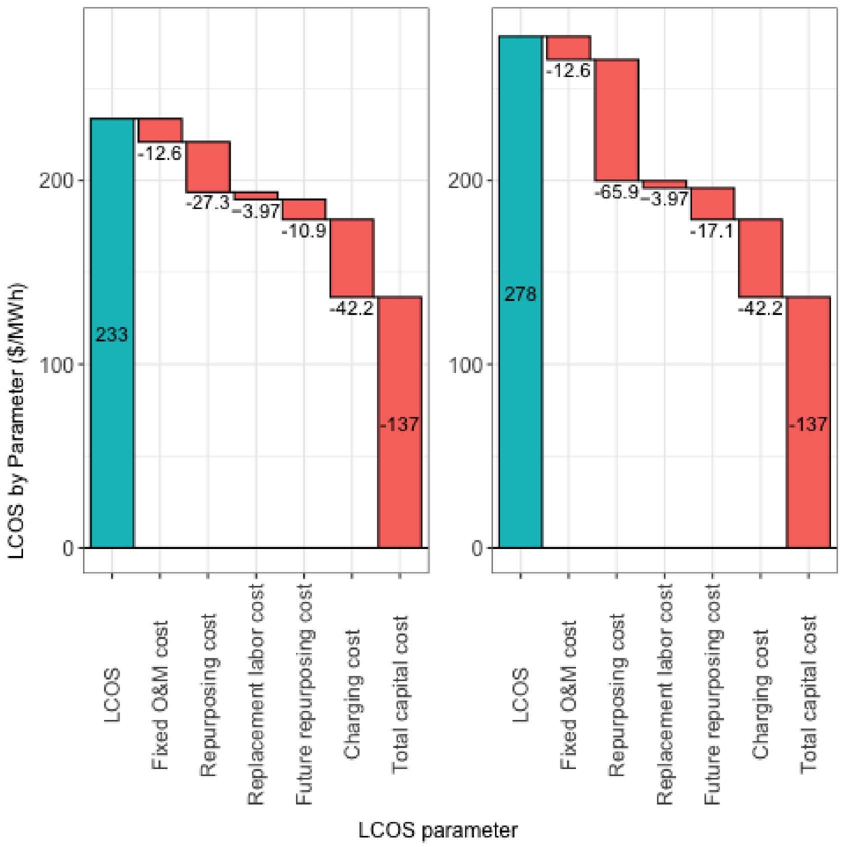

Figure 3 - Breakdown of costs within the LCOS equation for a two percent degradation rate per year. The total amount is shown in blue, and disaggregated costs in red for owner scenario (3a) and market scenario (3b).

The finding that an owner scenario outperforms a market scenario corroborates previous findings in the literature (e.g., [24,61]) and may be feasible given how some first-use batteries may be deployed. For example, an operator of a fleet of electric vehicles could use the batteries within the facility at the end of their automotive life [83]

The market scenario suggests a large fiscal barrier to utility-scale energy storage systems, and some of the perceived benefits could result in additional barriers. For example, a market-type model would be capable of accepting a wide range of products from a large pool of sellers. However, in second-life modules, heterogeneity among the products and a lack of information on first-life operating conditions will reduce efficiencies and increase costs.

3.3 Parameters affecting the LCOS of second-life BESS

Sensitivity analysis of the LCOS is performed concerning three specific parameters: DoD, discount rate, and repurposing cost. A range of DoD is plotted against the range of possible repurposing cost values in this paper's LCOS model. Within the analysis bounds, the LCOS of a second-life BESS can reach under 200 to over 300 ($/MWh; Fig. 4a). Sensitivity of the LCOS to the discount rate is also performed, revealing a similar distribution of values (Fig. 4b).

The effect of DoD on the resulting LCOS is important. Beyond just cost, the performance and duration of second-life BESS are dramatically reduced by this technical parameter. To justify the battery life assumption in this study, this relatively conservative DoD is necessary. A more aggressive DoD would accelerate the effect of cyclic battery degradation that is neglected in this analysis. Accelerated degradation would then result in additional overhauls, which comprised a considerable portion of the LCOS of second-life BESS. With the continual development of battery technologies, chemistries, and management techniques, this constraining parameter may ease.

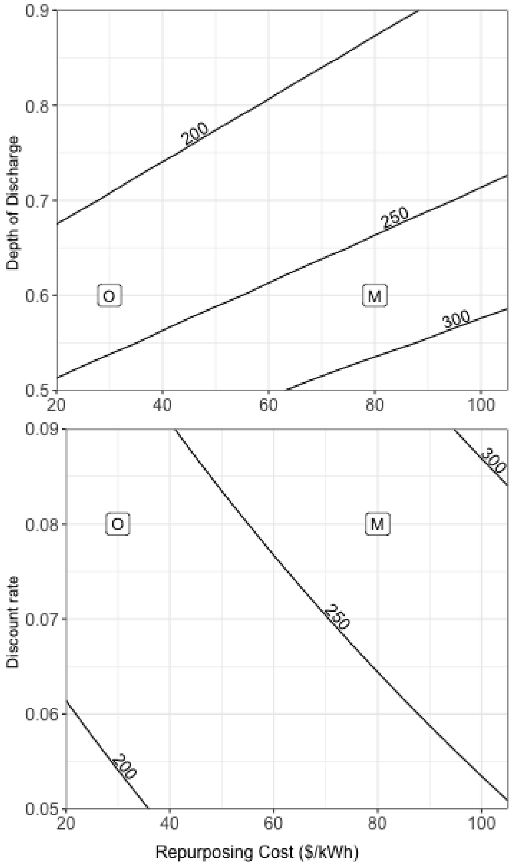

Figure 4 - Isopleths of LCOS for second-life BESS under changing parameters. For reference, the parameters from this paper are represented by O&M, owner, and market scenarios. 4a. The effect of LCOS as a function of repurposing cost and depth of discharge. 4b. The effect of LCOS as a function of repurposing cost and discount rate.

3.4 Factors affecting repurposing costs

Results from low and high-cost scenarios in the repurposing model suggest a current module repurposing cost of 28-36 ($/kWh-nominal; S3). The low-cost scenario reflects a throughput of 1500 MWh and requires about 3 million Nissan Leaf modules in a year to account for cell failure. The size of the facility is around 34,000 square feet to accommodate the operation. Conversely, the high-cost scenario represents a smaller yearly throughput of 500 MWh that requires about 1.12 million modules. The required facility size is only 8000 square feet, given the decreased throughput. Under the quasi-automated scenario, the future cost of repurposing modules drops below 18 ($/kWh). The sensitivity of module repurposing cost and the cell failure rate is shown, a sensitivity we believe was not explored in the original NREL analysis [24]. These two factors are inherently linked to the evolution of battery technologies. Under the paper's assumption of not paying an upfront procurement cost per module, it is unsurprising that the increase of cell fault rate from 0-10% only increases the repurposing cost by about 7 ($/kWh; Fig. 5a). This parameter may become crucial if the supply of spent batteries is limited, as the higher the fault rate, the more batteries are needed to sustain the operation. In this paper's model, the more interesting sensitivity is the repurposing cost to the module's energy capacity. The repurposing costs nearly halves as the module's energy capacity doubles (Fig. 5b).

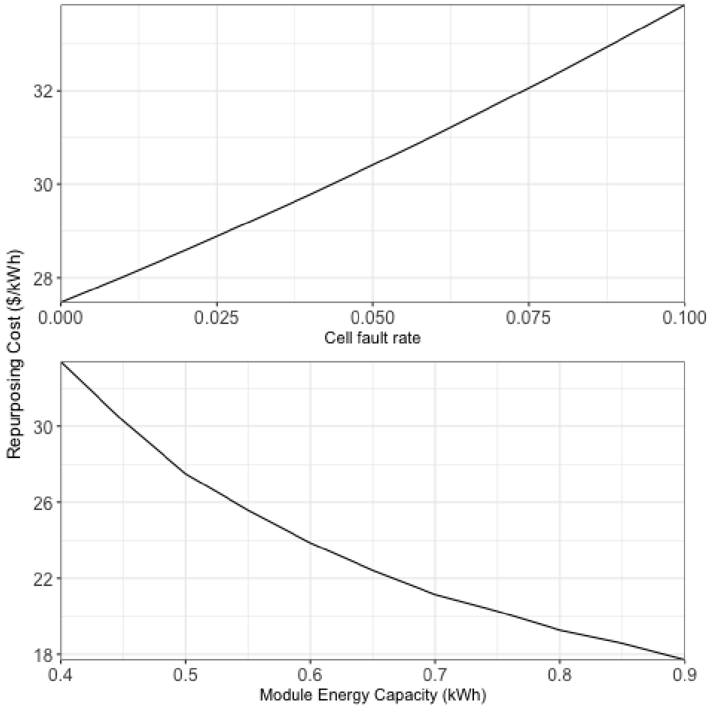

Figure 5 - Effects of different parameters on repurposing cost. 5a. The effect of cell fault rate on repurposing cost. 5b. The effect of module density on repurposing cost.

Repurposing costs are likely to drop as production scales up. Williams et al. [6], which includes repurposing costs with a much smaller throughput, reports twice as high of a repurposing cost. The low-cost scenario demands a yearly procurement of 3 million modules and a facility size of 34,000 square feet, neither of which is unrealistic. New Spiers Technology, a company that repurposes automotive batteries, recently opened a facility in Europe that is 35,000 square feet [84]. Beyond the feasibility, this analysis suggests two primary factors that could substantially lower the repurposing cost: semi-automating the repurposing process and increasing module density.

3.5 LCOS and repurposing costs of second-life systems informing policy

The LCOS of a utility-scale second-life BESS and the repurposing costs of a spent EV battery could be used to inform circular economy strategies. While the LCOS of second-life BESS is estimated to be higher than that of new BESS, second-life BESS may deliver additional value to society not reflected in the LCOS.

There are two implied benefits to using second-life BESS that the LCOS model does not consider: environmental benefit and accessibility of second-life batteries to smaller-scale customers. A breadth of literature exists for quantifying the environmental benefits, primarily due to avoiding the production of new BESS, which in turn reduces demand for virgin materials and manufacturing and their attendant impacts. A less obvious benefit of second-life systems may be the accessibility to a smaller-scale consumer. For example, a customer installing a residential system should expect to pay a higher amount than the TCC suggests in this paper for utility-scale systems because TCC refers to volume-weighted averages that bulk consumers pay. Thus, for small-scale consumers, current market prices for second-life battery modules may be cheaper and more accessible than sourcing a new module from an original equipment manufacturer [85]. Thus, if both environmental and social benefits result from the use of second-life BESS, the cost difference between new and second-life systems can inform policymakers in their design of policy to support second-life BESS. One potential mechanism, the investment tax credit (ITC) that applies to solar photovoltaic systems, could be replicated for second-life BESS [86]. Based on the LCOS estimate for the owner scenario, an ITC of 14.1% applied to a system's TCC in the first year would lead to price parity with new BESS. Likewise, in California, the Self Generation Incentive Program (SGIP) provides incentives towards distributed energy storage technologies that provide emissions and grid benefits ranging from 200-1000 ($/kWh) [87]. Second-life BESSs do not currently qualify for SGIP, but this program could be amended to do so.

The derived repurposing costs and resulting sensitivities are equally significant for policymakers, mainly compared to direct recycling or disposal costs. The LCOS model's results suggest a repurposing cost of 28-36 ($/kWh), well above recycling costs at 9-17 ($/kWh) [80,88]. If repurposing costs drop to $17, as projected in the low-cost scenario, the second-life pathway may become cost-competitive with disposal options like recycling. Also, the shift away from cobalt-intensive chemistries in new lithium-ion batteries reduces batteries' inherent value and thus decreases the economic benefits from recycling [89], potentially making repurposing more attractive (and recycling more expensive). Both pathways are integral to a circular economy. Thus, a dynamic understanding of repurposing and recycling costs will help inform realistic collection targets, infrastructure planning, and a framework for potentially subsidizing either venture. As an example mechanism, the recently drafted European Union battery legislation explicitly targets LIB recycling efficiency and collection rates [90]. Realistic repurposing targets should be likewise established and could be supported using the methods and cost estimates in this paper. Ideally, future legislation would allow producers to combine repurposing and recycling targets to accommodate a more diverse supply chain.

4. Conclusion

Despite lower upfront TCC, the LCOS of a utility-scale second-life BESS is most likely higher than a new BESS. Moreover, second-life BESS economics depend heavily upon future business models for battery ownership, with lower costs for a model where ownership is constant over first and second life uses. Approaching price parity between second-life and new BESS will likely require changes in either technological, operational, or policy parameters, including but not limited to reduced repurposing costs (e.g., through advances in automation technologies), increased DoD (operational changes), and policy-derived fiscal instruments like an ITC or SGIP incentive.

Given that second-life BESS are likely more costly than new BESS at utility-scale, the motivation for repurposing batteries should be interrogated. Second-life uses are intended to extract additional useful life from batteries and avert final disposal, but if economic, environmental, or social benefits do not materialize, second-life applications might prove undesirable. An analysis of the environmental tradeoffs between directing retired first life batteries to second-life applications instead of immediate recycling should be conducted. The scope of the analysis should include the generation of secondary material content for new batteries from recycling and the use of these materials in higher performance new BESS. Future analysis should pursue the comparative economics of second-life BESSs and new BESSs at the residential scale and the societal or non-monetary benefits of second-life strategies for grid-tied systems.

Acknowledgements

Funding: This study was funded, partially or entirely, by a grant from the National Center for Sustainable Transportation (NCST) (Grant number UCD-DOT-605), supported by U.S. Department of Transportation's University Transportation Centers Program. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated in the interest of information exchange. The U.S. Government and the

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