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Driving to the future of energy storage: Techno-economic analysis of a novel method to recondition second life electric vehicle batteries

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HIGHLIGHTS

- Reconditioning method is economically competitive with traditional repurposing.
- Reconditioned 2nd life ESS are marginally promising.
- 2nd life battery ESS are economically viable in three grid applications.
- Battery performance has the greatest impact on HUB reconditioning economics.

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ABSTRACT

The transportation sector is trending towards electrification which means a dramatic change to the availability of used Lithium-ion (Li-ion) batteries which can be reused for grid energy storage systems (ESS). However, second life battery modules can have an imbalanced state of health (SOH) between cells which can reduce battery safety, life, and depth of discharge. This work evaluates the economics of a novel Heterogeneous Unifying Battery (HUB) reconditioning system that cycles battery modules to unify cells' SOH to improve their second life battery performance. The HUB reconditioning cycles can be performed in one of two ways: recondition with grid services or recondition through energy shuffle. The results from this work demonstrate that a simple repurposing process will likely have a lower second life resale price (56 $/kWh) than the HUB system (62 $/kWh) in our baseline scenario; however, in our target scenario the HUB system (34 $/kWh) has a lower resale price than the repurposing system (38 $/kWh). This work also includes an economic analysis for using reconditioned batteries in a grid ESS that was compared to an ESS that is assembled with new Li-ion batteries. Results show that HUB reconditioned ESS require less grid revenue (194 $/kW-year) than new Li-ion ESS (253 $/kW-year). Finally, the HUB reconditioned ESS is shown to be economically feasible in 63% of frequency regulation, 18% of transmission congestion relief, and 16% of demand charge reduction markets but not economically feasible in spin/non-spin reserve, voltage support, and energy arbitrage markets.

1. Introduction

In 2019 there were 2.8 million electric vehicles (EVs) produced globally, and EVs are expected to be a quarter of market sales by 2030 [1]. Most EVs currently use Lithium-ion (Li-ion) batteries due to their favorable design characteristics: lightweight, high specific energy, low self-discharge rate, and good life cycle performance [2]. Li-ion batteries are anticipated to continue being the preferred battery chemistry for EVs in the near-future and current research and development (R&D) efforts are focused on improving Li-ion battery chemistries to develop the next generation of EV battery technologies [3,4,5]. However, current estimates predict that world reserves of lithium can only produce approximately one billion EVs worth of 40 kWh batteries, therefore, recycling or reusing EV batteries will be required to sustainably meet future estimates of EV demand [6]. The increasing demand and limited supply will have significant impacts on various Li-ion supply chains including the

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management of EV batteries at the end of 1st life.

The end of 1st life for EV batteries occurs when the battery State of Health (SOH) is approximately 80%. At this SOH, the batteries can no longer reliably meet the high performance criteria required for use in EVs, however, these batteries could either be reused by less demanding applications or recycled. Although Li-ion recycling will likely be necessary, Olsson et al. determined that reuse and then recycle are complementary processes that slow down the resource cycle more than just recycling [7], and recycling Li-ion has been shown to be uneconomical [8]. Therefore, Original Equipment Manufacturers (OEMs) have launched 2nd life businesses and sold batteries to 2nd life businesses such as Spiers News Technology to repurpose batteries for Energy Storage Systems (ESSs).

While OEMs have begun developing 2nd life battery applications, minimal work has been done to evaluate the economic viability of using 2nd life EV batteries in grid applications. Mathews et al. determined a utility scale solar-plus-storage system would be profitable if 2nd life batteries are sold for $<$ 60% of the price of a new battery [9]. Neubauer et al. determined area regulation to be profitable while electric service power quality, wind generation grid integration, short duration transmission and distribution upgrade deferral, and voltage support will likely be profitable [10]. Song et al. found 2nd life batteries used in wind farms is currently not economical [11]. Other studies determined residential demand management coupled with photovoltaics would be profitable [12,13]. Heymans et al. found that load leveling would only be profitable under favorable conditions [14]. While these studies have investigated the market potential for 2nd life ESS, these studies simply leveraged prior estimates for battery acquisition costs and performance. This is a major assumption and does not accurately capture the market price and performance of 2nd life batteries considering technology advancements focused on reconditioning of batteries.

Cready et al. quantified the battery resale price and repurposing costs for used Nickel Metal Hydride EV battery modules, and the results show that labor dominates the cost of repurposing [15]. A study by Neubauer et al. estimated the costs to repurpose EV Li-ion battery modules, however, the resale price was simply calculated by multiplying the price of a new battery by the health factor of the 2nd life battery [16]. While various studies have estimated the cost of a repurposed 2nd life battery systems, to our knowledge none have evaluated the cost of using reconditioning techniques to improve the performance of a 2nd life ESS.

Second life battery reconditioning represents an exciting opportunity to improve the performance and thus the value of 2nd life batteries. This study evaluates the economics to recondition batteries using a novel reconditioning process that uses a Heterogeneous Unifying Battery (HUB) system to improve SOH uniformity of the cells in each battery module without the need to deconstruct the battery module. The HUB reconditioning process economics were modeled using two different scenarios: reconditioning with grid services (RGS) and reconditioning through energy shuffle (RES). The economics of the HUB reconditioning methods are directly compared to the traditional repurposing process which sorts battery modules to produce battery packs with similar SOHs. This work determines the resale price after HUB reconditioning or repurposing batteries and then expands the system boundary of the economic analysis to include energy or power services that leverage the 2nd life batteries. The economics of the 2nd life batteries are compared to new Li-ion batteries used for power and energy services. Specifically, the cost and performance of the 2nd life and new Li-ion batteries for multiple power and energy applications are considered. The work includes a sensitivity analysis to support strategic investment in R&D to drive the technology towards commercialization. The novelty of the work includes the economic evaluation of 2nd life battery reconditioning that enables improved performance as compared to repurposing with an extended system boundary used to evaluate the viability of grid ESS.

2. Methods

This work includes a battery performance model coupled with techno-economic analysis (TEA) methodology to evaluate the economic viability of two novel HUB reconditioning pathways (RGS and RES) as well as a direct comparison to traditional repurposing. The RGS scenario performs grid services at certain times in the day to charge and discharge the battery modules which is required for reconditioning. The RES scenario constantly shuffles energy between two battery banks reducing the time for reconditioning.

Two system boundaries were used to evaluate the technology; the first determined the minimum battery selling price for a 2nd life battery and the second expanded the system boundary to determine the minimum required revenue from a grid ESS that uses 2nd life batteries. All scenarios and methods assumed relevant expenses and revenue streams to operate a facility in California. California was chosen since it has an expanding battery storage market and the most EV sales in the United States since 2011 [17,18].

2.1. TEA overview

2.1.1. System boundary and scenarios

The framework and description of the scenarios, economics, sensitivity analysis, and market potential developed is presented in Fig. 1. The economic analysis included two system boundaries: 2nd Life Resale and Grid ESS. The resale system boundary was limited to the scenarios of reconditioning or repurposing of batteries to define the required resale price of 2nd life batteries. The grid ESS system boundary included all aspects of the resale system boundary and extended the economic assessment to also include the use of 2nd life batteries in an ESS to provide either power or energy grid services. Repurposing was used for comparison in both the 2nd life resale and grid ESS system boundary scenarios while a new Li-ion battery scenario was used as a comparison to the reconditioned batteries in the grid ESS system boundary. A sensitivity analysis was performed for the energy market ESS to identify high impact inputs of each battery type. Also, the market potential of the ESS with different battery types was determined based on the revenues and market sizes of energy and power applications.

As shown in Fig. 1, three 2nd life battery processing scenarios were modeled: RGS, RES, and repurpose. The economics of these methods are presented in the subsequent sections of 2.2 Recondition with Grid Services (RGS), 2.3 Recondition through Energy Shuffle (RES), and 2.4 Repurpose. Each of these methods had specific operational parameters that characterized the key performance of the process with a summary presented in Table 1.

All methods evaluated both a baseline and target scenario. The baseline scenario represented the best estimates for a system built in 2019. The target scenario represented potential improvements to the system based on preliminary findings from R&D efforts. The assumptions in Table 1 were for the baseline scenarios and the assumptions for the target scenario for each method are shown in Table S1. The target scenarios include potential reductions in the reconditioning cycles, labor task times, warranty, transportation distance, hardware costs, and acquisition price.

The annual battery yield (Table 1) of each method was used to compute the variable operational costs and annual revenue from battery sales. The annual battery yield of the two HUB reconditioning methods varied depending on the number of reconditioning cycles that could be achieved each day due to the system operation. The annual battery yield (Y) was calculated (Eq. (1)) based on the facility reconditioning capacity (C_{rec}), number of reconditioning cycles needed (N), and average number of reconditioning cycles per day (n).

$$Y = C_{rec}365n/N \tag{1}$$

The annual battery yield of the repurposing method (Y) was set equal to the annual battery yield of the RES method for comparison.

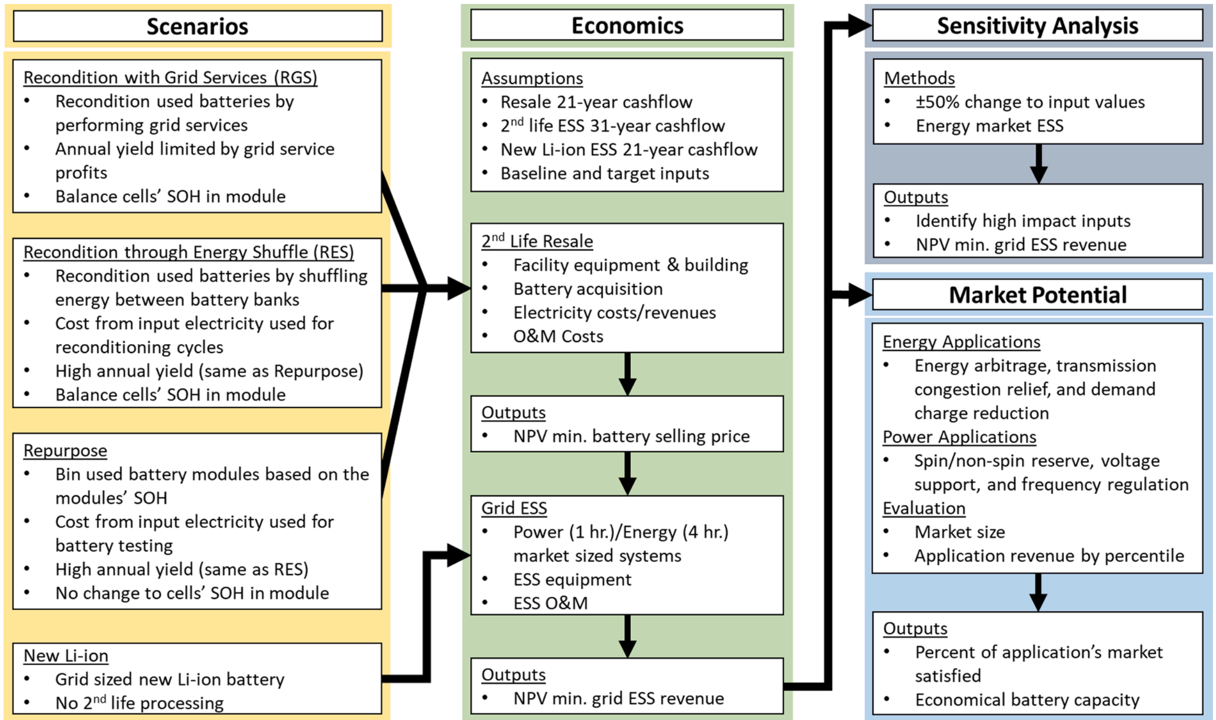

Fig. 1. Flow diagram of the scenarios used to evaluate the economics of 2nd life battery resale and grid ESS. The resale scenario was for 2nd life batteries that use the processing methods of RGS, RES, and repurpose. The grid ESS scenario was for new and 2nd life batteries that were used in either power markets or energy markets. The sensitivity analysis was for grid ESS based on an energy market application that have new Li-ion, RGS, RES, or repurposed batteries. The economic outputs from the ESS were used to determine the market potential of each of the battery types.

Table 1
Key performance parameters for 2nd life battery processing scenarios RGS, RES, and repurpose.

Assumption	RGS	RES	Repurpose	Units
Annual Battery Yield	122 (Eq. (1))	219 (Eq. (1))	219 (Eq. (2))	MWh
Battery Acquisition Price	35 [16]	35 [16]	35 [16]	$/kWh
C-rate	0.5 (a)	0.5 (a)	0.5 (a)	1/h
Viable Product	99% [16]	99% [16]	99% [16]	%
Reconditioning/ Repurposing Cycles	300 (a)	300 (a)	2 (a)	Cycles
Cycles per Day	3.35 (b)	6 (c)	–	Cycles/ day
Roundtrip Efficiency	90% [9]	90% [9]	90% [9]	%
DC-DC Converter/ BMS Cost	500 (a)	500 (a)	–	$/kW
Electricity Purchase Price	0.16 [19]	0.14 [20]	0.16 [19]	$/kWh
Warranty	5% [16]	5% [16]	5% [16]	%
Adapter Tub Price	100 (a)	100 (a)	–	$/kWh
Facility Size	2,463 (T. S2)	2,463 (T. S2)	1,620 (T. S2)	m^2

(a) Developer input (b) Based on CAISO RTM energy arbitrage from 2018 [21] (c) 4-hour cycles and 24-hour operation.

Repurposing was assumed to take three days (t). The facility repurposing capacity (C_{rep}) was calculated using Eq. (2).

$$C_{rep} = Yt/365 \quad (2)$$

2.1.2. TEA methodology

Capital costs, operational costs, grid revenue, and annual battery yields from the facility were used as inputs into a yearly discounted cash flow rate of return (DCFROR) analysis. This methodology is consistent with previous repurposing studies that quantified the cost of repurposing [15,16]. The DCFROR used n^{th} plant assumptions which most notably assumed an internal-rate-of-return (IRR) of 10%, a 35% tax rate, and debt financing at 50%. The capital costs included all of the expenses incurred in year zero of the cashflow during the 1-year build period which included the facility building, grid connection equipment, and facility equipment expenses. The operational costs consisted of the expenses incurred after year zero while the facility was in operation for years 1 through 20. The operational costs did not account for changes to market prices over time. The DCFROR analysis calculated the minimum battery selling price by adjusting the required revenue from the 2nd life battery resale such that a Net Present Value (NPV) of zero was achieved in the 21-year cashflow. The minimum battery reselling price was computed for the HUB reconditioned and repurposed batteries. The economic analysis for the grid ESS determined the required revenue in a 31-year cashflow for the ESSs instead of a selling price for the batteries. For both system boundaries, the reconditioning and repurposing facilities were assumed to operate for 20-years. Thus, a 31-year cashflow was used for the grid ESS to account for the batteries processed in the final year of the facility that were then used in ESSs; the batteries processed in the final year of the facility were retired from the grid ESS 10 years later (Table 2). The new Li-ion battery scenario used a 21-year cashflow that also computed the required revenue from the ESS. Each grid ESS was assumed to operate for 20 years for both 2nd life and new Li-ion ESSs. All expenses were converted to 2019 values using producer price indexes.

2.2. Recondition with grid services (RGS)

We assumed that OEMs disassemble battery packs and extract modules prior to acquisition. Once the modules were acquired and transported to the reconditioning facility, the modules underwent the reconditioning process to balance the SOH of the cells within the modules without deconstruction. The HUB system used a modular DC-DC power converter matrix with isolated series output connections to achieve fully independent control of energy flow to each of the battery cells [22]. This provided model-based control that drove each battery's SOH towards uniformity. The energy flow required for reconditioning was

Table 2
Major assumptions of ESS with scenarios of RGS, RES, repurpose, and new Li-ion.

Assumption	RGS	RES	Repurpose	New Li-ion		Units
				Today	2030	
Battery Module Price	NA	NA	NA	209 [27]	110 [40]	$/kWh
Battery Life	10 [16]	10 [16]	10 [16]	10 [41]	10 [41]	Years
Power Applications ESS Cost	449 [27]	449 [27]	449 [27]	449 [27]		$/kW
Energy Applications ESS Cost	743 [27]	743 [27]	743 [27]	743 [27]		$/kW
ESS Life	20 [42]	20 [42]	20 [42]	20 [42]		Years
C-rate Power Applications	1 [43]	1 [43]	1 [43]	1 [43]	1 [43]	1/h
C-rate Energy Applications	0.25 [43]	0.25 [43]	0.25 [43]	0.25 [43]	0.25 [43]	1/h
Individual System Size	4 [43]	4 [43]	4 [43]	4 [43]	4 [43]	MW
Initial SOH/ Usable Capacity	80% [44]	80% [44]	80% [44]	100%	100%	%
Depth of Discharge	50% [16]	50% [16]	50% [16]	80% [41]	80% [41]	%
Annual Operating Cost	10 [41]	10 [41]	10 [41]	10 [41]	10 [41]	$/kW

used to perform grid services in the energy arbitrage market.

2.2.1. Capital costs

The capital costs of the reconditioning facility consisted of the facility building ($2.4 million (M) [23,24,25,26]), grid equipment ($3.1 M [27,28]), and facility equipment ($9.2 M [25,29,30,31]). To determine these costs, a commercial sized facility with a reconditioning capacity of 30 MWh-nameplate was assumed. The electronics power rating (P) was computed (Eq. (3)) based on the reconditioning capacity (C), average usable battery capacity (U), and C-rate (R) (Table 1).

$$P = CUR \tag{3}$$

A detailed breakdown of the analysis for the facility size (Table S2), facility building (Table S3), grid equipment (Table S4), and facility equipment (Table S5) is presented in the supplementary material.

2.2.2. Operational costs

2.2.2.1. Electricity. The aim of using grid services to complete reconditioning cycles was to gain a net profit from charging and discharging the batteries. Energy arbitrage was chosen as the grid service since it had the appropriate C-rate and load profile for reconditioning batteries. The grid profits were estimated to be 0.02 $/kWh per cycle or $820 K annually for energy arbitrage in the California Independent System Operator (CAISO) Real-Time Market (RTM) using 2018 historical pricing data; details of our study are provided in the supplementary material [21]. This estimate accounted for the grid participation fees and efficiency losses for a ½ C-rate system. The auxiliary electricity used for lighting and HVAC (heating, ventilation, and air conditioning) was assumed to be supplied by Pacific Gas and Electric rather than from CAISO and the A-10 Tariff (0.16 $/kWh) was used and thus resulted in an annual cost of $82 K [19].

2.2.2.2. All other costs. The remainder of the operational costs were transportation (90 thousand (K) $/year [32,33]), battery acquisition (35 $/kWh-nameplate [16]), variable labor (6.31 $/kWh-nameplate or 772 K $/year [34,35]), fixed labor (457 K $/year [35,36,37,38]), insurance (80 K $/year), and warranty (5% of resale price [16]). The supplementary material includes details on the costs of transportation (Table S6), labor (Table S7), and facility operations.

2.3. Recondition through energy shuffle (RES)

The RES scenario used the same process as in 2.2 Recondition with Grid Services to cycle the batteries to get a unified SOH. The primary difference was that the energy used for reconditioning was supplied by the utility and discharged to another battery bank rather than back to the grid. The energy taken from the utility resupplied the energy that was lost due to charging and discharging losses from shuffling energy between battery banks.

2.3.1. Capital costs

The same building costs ($2.4 M) and facility equipment costs ($9.2 M) were used as in the Recondition with Grid Services scenario (section 2.2). The grid equipment ratings were reduced relative to the Recondition with Grid Services scenario since the only power drawn from the grid for reconditioning was to replenish the energy lost due to charging and discharging efficiencies. With lower ratings, the grid equipment costs were $574 K.

2.3.2. Operational costs

2.3.2.1. Electricity. The electricity used for reconditioning to charge the batteries from the grid was an expense since the energy was not discharged back to the grid like in 2.2 Recondition with Grid Services. The levelized cost of electricity for a continuous load was estimated to be 0.14 $/kWh with the Pacific Gas and Electric E-20 tariff (higher load) and the annual electricity cost was estimated to be $808 K annually [20]. The electricity cost included the electricity used for both auxiliary and reconditioning loads. The auxiliary load (72 K $/year) was the same as in the Recondition with Grid Services scenario (section 2.2) but this scenario used a less expensive E-20 tariff for electricity charges. The annual reconditioning load (L) was calculated using Eq. (4) based on the reconditioning capacity (C), average usable battery capacity (U), roundtrip efficiency (E), and average number of reconditioning cycles per day (n) (Table 1 and Table 2).

$$L = CU(1 - E)n365 \tag{4}$$

2.3.2.2. All other costs. The other operational costs were similar to that of the Recondition with Grid Services scenario (section 2.2) since the same battery acquisition (35 $/kWh-nameplate), fixed labor (457 K $/year), insurance (80 K $/year), and warranty costs (5% of resale price) were assumed. The energy shuffle method had a higher battery yield (Table 1) which increased the total variable costs. The average discounted transportation costs were estimated to be $107 K per year, and the variable labor costs were estimated to be 6.31 $/kWh-nameplate or $1.4 M annually.

2.4. Repurpose

The repurposing method did not change the SOH of individual cells in modules. Rather, the repurposing method sorted modules by their SOHs and then the similar SOH modules were combined to make a "new" 2nd life battery pack. The repurposing method required the battery module to be inspected, tested, and then binned by SOH. The battery modules were inspected to check the integrity of the module prior to charging and discharging. The modules that passed the initial inspection were then characterized by charging and then discharging the modules at a ½ C-rate. The modules were subsequently binned by sorting and then placing them in a battery pack. The pack was then packaged by connecting the contacts and inspecting the pack. The battery pack was tested for quality assurance with a full charge and discharge cycle at a ½ C-rate.

2.4.1. Capital costs

For comparison purposes, the facility processing capacity was calculated to be 1.8 MWh (Eq. (2)) in order to have the same annual yield as the RES scenario (Table 1). The capital costs included the facility building ($1.7 M) and facility equipment ($3.9 M). It was assumed that grid equipment was not needed since the repurposing facility drew low power and did not perform grid services.

2.4.2. Operational costs

2.4.2.1. Labor. The operational costs were similar to the reconditioning methods (Sections 2.2 and 2.3) with minor changes presented in the supplementary material. The variable labor cost was estimated to be 10.17 $/kWh-nameplate or $2.2 M annually [34,35]. The fixed labor was estimated to be $470 K annually [36,37,38,39].

2.4.2.2. All other costs. The same costs as section 2.3 were used for transportation (107 K $/year), battery acquisition (35 $/kWh-nameplate), insurance (80 K $/year), and warranty (5% of resale price). The same A-10 electricity rate (0.16 $/kWh) that was used for section 2.2 auxiliary loads was used based on the total electricity load [19]. The electricity costs were from the lights, battery testing, and HVAC, and the total electricity costs were $100 K annually.

2.5. Energy storage system (ESS) revenue

An alternative to computing the selling price of the battery module was to compute the required revenue from the battery in a 2nd life grid ESS. The scenarios considered were RGS, RES, repurpose, and new Li-ion. The ESSs with 2nd life batteries were compared to a new Li-ion battery ESS used for grid applications to determine the competitiveness of each technology. The high impact assumptions for each scenario's estimates are in Table 2.

The assumptions in Table 2 are for the baseline scenario. The target scenario assumptions for the ESS are shown in Table S8. The ESS target scenario included all inputs from the resale target scenario (Table S1). The target scenario was based on improvements from R&D and projections for ESSs in 2025. Specifically, the target scenario reduced the ESS capital cost, ESS operating cost, battery acquisition prices, and increased the depth of discharge (DOD).

2.5.1. Energy storage system costs

2.5.1.1. Capital costs. The ESS costs (Table 2) were determined for power and energy applications estimated by Fu et al. [27]. The ESS costs were defined as all ESS costs except for the battery. For power applications, the ESS was sized for a 1-hour discharge duration or 4-MW (4-MWh) [43,45], and the ESS was estimated to cost 449 $/kW or $1.8 M per ESS [27]. The power applications considered were spin/non-spin reserve, voltage support, and frequency regulation. A description of each power application can be found in Balducci et al. [45]. For energy applications, the ESS was sized for a 4-hour discharge duration or 4-MW (16-MWh) [43,45], and the ESS was estimated to cost 743 $/kW or $3.0 M per ESS [27]. The energy applications considered were energy arbitrage, transmission congestion relief, and demand charge reduction. A detailed breakdown of costs for the power and energy ESSs are shown in Table S9.

2.5.1.2. Operational costs. Each ESS was assumed to have a yearly operating cost of 10 $/kW [41]. The ESS operational costs also included a disposal cost of 5 $/kWh-nameplate for the batteries removed from the ESS. Upon disposal, the batteries were recycled by a separate business.

2.5.2. 2nd life batteries

The grid ESS cashflow expanded upon the resale cashflows from RGS, RES, and repurpose. The cashflows from the resale scenario were expanded upon by adding the costs to build and operate the ESSs. A new 2nd life ESS was assumed to be built while the batteries continued to be processed. Each ESS was assumed to have debt financing as described in 2.1.2 TEA Methodology. Once the batteries were processed, they were transported to the ESS site. The batteries were then installed in the ESS and connected to the grid to perform grid services; the ESS grid services were different than the grid services performed for RGS. The reconditioned batteries were expected to have a longer life than repurposed batteries; however, since there was limited aging data for reconditioned batteries, the reconditioned batteries and repurposed batteries were assumed to have the same aging behavior. The batteries were projected to last for 10 years in a moderate climate such as Los Angeles [16]. Each ESS was assumed to last for 20 years of service with the first set of batteries replaced by recently processed batteries after 10 years of service [42]. ESSs were built until the first set of 2nd life batteries needed to be replaced. Thus, new ESSs were built from years 1 through 10. Then in years 11 through 20, the initial batteries were swapped with batteries that were recently processed. The ESSs and second set of batteries were then decommissioned in years 21 through 30. The total ESS capacity from years 0 through 30 was determined as the sum of the capacities multiplied by the DOD (Table 2) of the ESSs at each respective time. The maximum capacity of all the ESSs was 1.6 GWh which occurred from years 11 to 20. The ESS capacity over time is shown in Figure S1.

2.5.3. New Li-ion battery

A yearly DCFROR analysis was used for a new Li-ion battery. The ESS cost and assumptions from 2.5.1 Energy Storage System Costs were used. The new Li-ion batteries were assumed to cost 209 $/kWh in year zero of the cashflow [27]. The batteries were assumed to last 10 years with an 80% DOD before needing replacement [41]. A new Li-ion battery was then be swapped in for a projected cost of 110 $/kWh in 2030 [40]. The required revenue for power and energy applications was then calculated based on this cashflow.

2.5.4. Market potential

The required revenue for the 2nd life ESSs from grid applications were compared to the current market revenue from power and energy applications to assess the economic viability. The potential capacity (P_{cap}) from each application that could satisfy the minimum revenue of an ESS at a given revenue value was calculated by Eq. (5) using the market capacity (M) and percentile of revenue (R_{per}).

$$P_{cap} = M(1 - R_{per}) \quad (5)$$

For each application, the potential capacity represents the portion of the market capacity with a revenue value equal to or greater than the revenue value at the given percentile. Balducci et al. provided a range of revenues from numerous energy storage valuation studies in terms of the minimum (0th percentile), 25th percentile, mean, 75th percentile, and maximum (100th percentile) [45]. The mean was assumed to be a reasonable approximation of the median. The percentiles of revenue that were not specified in Balducci et al. were linearly interpolated between the given percentiles.

2.6. Sensitivity analysis

A sensitivity analysis was performed to identify high impact inputs in the TEA model and demonstrate how changes to these high impact inputs impacts the economics of the battery storage systems evaluated. Specifically, a sensitivity analysis of all baseline inputs of the ESS scenarios for RGS (105 inputs), RES (105 inputs), repurpose (96 inputs), and new Li-ion (24 inputs) were completed for energy applications. The 2nd life ESS scenarios included inputs from both the resale and expanded system boundaries. The sensitivity analysis varied each input independently by ± 50% and then recorded the respective result. A ± 50% variation to the inputs was deemed appropriate to encapsulate the uncertainty of the high impact inputs such as battery life which has been estimated to be between 5 [44] and 16 years [9].

3. Results and discussion

The results from this work are presented in three sections: 2nd Life Battery Resale Price for RGS, RES, and repurpose processing methods; Grid ESS where 2nd life batteries processed and integrated into an ESS for grid applications; and Sensitivity Analysis to support future research direction.

3.1. 2nd life battery resale price

The minimum viable resale price based on the DCFROR analysis for 2nd life batteries (excluding battery performance) is shown in Fig. 2 for the RGS, RES, and repurpose processing methods. A baseline and target scenario are evaluated for each of the three processing methods and the red diamonds denote the minimum viable resale price. Repurposing and RGS are found to be the most economical pathway for 2nd life battery processing under the baseline and target scenarios respectively. However, the repurpose scenario only provides a 10% advantage in the baseline scenario and assumes that the repurposed batteries would have equal lifetime performance as the HUB reconditioned batteries. The baseline and target results for 2nd life battery resale are further discussed in 3.1.1 and 3.1.2.

3.1.1. Baseline scenario

The baseline resale prices for RGS, RES, and repurposing are 62.21, 61.89, and 55.65 $/kWh-nameplate respectively. The RES method has a higher annual yield (219 MWh) than RGS (122 MWh). The higher throughput for RES is due to the ability to continually recondition the batteries (charge and discharge) without the need to wait for optimal times to participate in the energy arbitrage market to maximize grid profits (Table 1). While the systems are assumed to be continually cycled, proper charging levels are maintained to protect the system electronics from overheating. The repurposing method was modeled to have the same annual yield as the RES method of 219 MWh (Table 1). With a higher battery yield due to reduced time in the facility, the RES and repurposing processes distribute the fixed capital and operational costs across the resale price of more batteries due to a higher annual yield thus reducing these impacts.

The baseline resale price of RES is lower than RGS, however, the repurposing method has the lowest baseline resale price of all the scenarios (55.65 $/kWh-nameplate). The resale price does not account for the potential battery life improvement and reliability from reconditioning. Repurposing has high labor costs while the HUB reconditioning processes also have high capital costs due to the facility equipment, facility building, and grid equipment. The high labor cost of the repurposing method is due to the labor intensity of the repurposing process. The impact of the high labor cost for the repurposing method is approximately equal to the impact of the high capital cost in the RES method. In the DCFROR analysis, an annual operational cost of $1M from years 1 to 20 is equivalent to a capital cost of $9M in year 0. Thus, there is a trade-off between increasing capital costs to reduce operational costs and vice versa which is demonstrated by the reconditioning and repurposing scenarios.

One major operational difference between reconditioning and repurposing is that reconditioning is an energy intensive process and repurposing is not. The RGS method eliminates electrical operational costs required for battery reconditioning cycles by participating in the energy arbitrage market. Using historical CAISO data, the simulated grid service revenues from energy arbitrage are 6.40 $/kWh-nameplate of battery or 0.02 $/kWh of profit per cycle for RGS. Since the RES method does not participate in grid services, our model assumes a 10% energy loss during each reconditioning cycle that must be resupplied at a cost of 0.14 $/kWh (Table 1) to maintain system functionality. The total cost of electricity used for reconditioning cycles for the RES method is 3.36 $/kWh-nameplate. Thus, the difference between the RGS profits and RES costs for reconditioning cycles is a substantial 9.76 $/kWh-nameplate. The RGS method does not generate enough revenue from grid services to offset the opportunity cost of waiting to perform reconditioning cycles. The opportunity cost is defined as the time the batteries are idle when they could be actively reconditioned through energy cycling. This opportunity cost results in a lower annual yield and therefore fewer battery sales. As a result, the RGS method has the highest resale price for the baseline scenario.

Under the baseline scenario, the RGS method could be competitive with the RES method if the revenue from grid services increases. The baseline resale price of RES is 61.89 $/kWh-nameplate. For the baseline RGS to have the same resale price as the baseline RES, the grid services

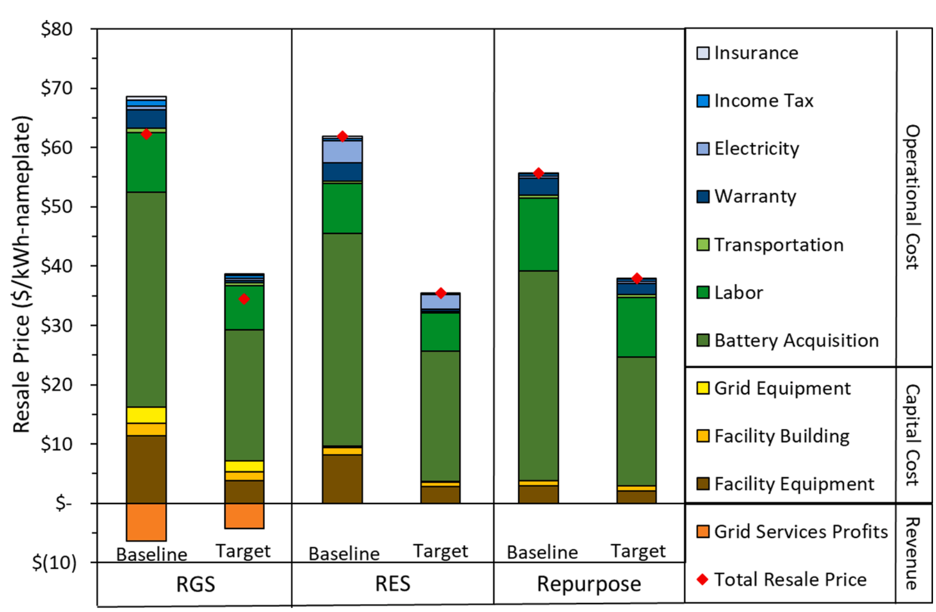

Fig. 2. Baseline and target resale prices per kWh-nameplate for the recondition with grid services, recondition through energy shuffle, and repurpose scenarios.

would need to profit $857 K annually which is a mere 4% increase to the baseline revenue assumption. This value could be surpassed by stacking the grid services of frequency regulation and energy arbitrage [46]. This is not included in the primary analysis of the RGS method due to uncertainties on the compatibility of frequency regulation with the SOH balancing process and participating in these two markets simultaneously.

The estimated resale prices of each of these methods can be compared to the resale prices of prior EV battery repurposing studies [15,16]. Repurposing batteries consists of testing and repackaging modules without balancing the cell SOH in modules [16]. Based on 2nd life battery health factors, Neubauer et al. calculated the resale price of repurposed batteries to have equivalent values to new EV Li-ion batteries [16]. Neubauer et al. estimated the resale price of batteries after repurposing to be between 44 $/kWh and 180 $/kWh [16]. Cready et al. estimated the resale price of repurposed batteries to be 145 $/kWh [15]. Cready et al. used a bottom up approach to determine the resale price which consisted of a repurposing cost of 64 $/kWh and an acquisition price of 81 $/kWh. These studies, like ours, show battery acquisition and labor to be the largest contributors to the resale price. These studies also show capital costs to be a minor contributor to resale price like ours. Our analysis determines the repurposing battery resale price to be 55 $/kWh under the baseline scenario. Thus, all the methods analyzed in our study are shown to be on the lower-end of estimated repurposing costs primarily due to a lower acquisition price associated with recent reductions to new Li-ion EV battery prices. The target scenario is shown to have lower repurposing costs than all the previous studies considered above.

3.1.2. Target scenario and future reductions

The target scenario improves the battery economics by reducing the reconditioning cycles, labor task times, warranty, transportation distance, hardware costs, and acquisition price based on expected improvements to the process through research and commercialization. The majority of reductions for all methods is due to the acquisition price decreasing from 35 $/kWh-nameplate (Table 1) in the baseline scenario to 21.50 $/kWh-nameplate in the target scenario (Table S1). The target RGS scenario (34.41 $/kWh-nameplate) and target RES scenario (35.51 $/kWh-nameplate) are less than the target resale price of repurposing (37.93 $/kWh-nameplate), primarily due to fewer reconditioning cycles needed for SOH balancing. With fewer reconditioning cycles, the battery yield (Eq. (1)) is increased, consequently reducing the impact of fixed capital and operational costs through a higher annual yield. As a result, RGS has a lower resale price than RES.

There are several improvements that could be made to the reconditioning process to further decrease the price in the future. Decreasing the number of cycles required to balance battery module SOH by improving balancing schemes would lower the price substantially for the RGS and RES methods. Reducing the number of cycles to 50% of the assumed values in the target scenario results in a battery resale price of 31 and 30 $/kWh-nameplate for RGS and RES. The capital costs could be reduced by decreasing hardware costs from manufacturing. Little reduction to the transportation cost would be achievable as this analysis already assumes a class 8 freight truck could be filled to its full capacity with batteries. Each method would increase in price if the current transportation regulation is used which has a maximum battery weight of 333 kg per truck [32]. The increase in resale price due to transportation for the baseline RGS, RES, and repurpose methods would be 6.67, 6.87, and 7.33 $/kWh-nameplate, respectively [47,48,49]. This assumes that cargo vans are used as the transportation vehicle instead of a class 8 freight truck. Lastly, as mentioned in the previous paragraph, a reduction in battery acquisition cost ultimately has the largest impact (Figure S2).

New EV Li-ion batteries are estimated to cost 195 $/kWh in 2020 so the 2nd life batteries (RGS 62 $/kWh) would have a resale price less than a new Li-ion battery today [5]. However, new EV Li-ion batteries could optimistically cost as little as 50 $/kWh in 2030 [5]. Therefore, there is uncertainty on the competitiveness of 2nd life batteries in the future. With a lower new Li-ion battery price in the future, the acquisition price of the 2nd life batteries would likely decrease [16]. Assuming the acquisition price of 2nd life batteries decreases linearly as a fraction of the price of new Li-ion batteries, the resale price of the 2nd life batteries would decrease as shown in Figure S2. In 2030, the new Li-ion baseline price is estimated to be 75 $/kWh so the 2nd life acquisition price would be 13.50 $/kWh-nameplate representing a 21.50 $/kWh-nameplate reduction compared to the baseline. Each of the baseline 2nd life scenarios with the 2030 acquisition price would continue to have a lower price per usable capacity (Table 2) than a new Li-ion battery in 2030 (Figure S2). With an adjusted acquisition price, a new Li-ion battery would become less expensive than the baseline resale prices of RGS, RES, and repurpose scenarios at a price of 43, 43, and 33 $/kWh of usable capacity, respectively.

Assuming 2nd life batteries to be economical in the future, 2nd life batteries could be used in a variety of applications. If a 2nd life battery is of high enough quality it could go back into an EV [50]. Alternatively, 2nd life batteries could be used for stationary residential, commercial, and utility applications; specifically, 2nd life batteries could be integrated with renewable energy for energy storage in residential and utility settings [9,51]. Finally, 2nd life batteries could also be used to perform various grid services such as spin/non-spin reserve, voltage support, frequency regulation, energy arbitrage, transmission congestion relief, and demand charge reduction [51].

3.2. Grid energy storage system (ESS)

The system boundary of the analysis is expanded to evaluate the economic feasibility and competitiveness of using 2nd life batteries in grid energy storage markets. Baseline and target scenarios are completed for the processing methods of RGS, RES, and repurpose. A baseline and target scenario for a new Li-ion battery ESS is used to create a comparison to the 2nd life battery scenarios. The grid applications analyzed for two different ESS systems are power applications and energy applications. The power applications are sized for applications that require high power and a fast discharge rate (1-hour) while the energy applications are sized for applications that require bulk energy and a slow discharge rate (4-hour). The minimum required revenue of each scenario is shown in Fig. 3 and discussed in 3.2.1 ESS Minimum Revenue. The minimum required revenue of the baseline RES and target RGS scenarios are compared in 3.2.2 Market Potential to the revenue potentials of power applications (spin/non-spin reserve, voltage support, and frequency regulation) and energy applications (energy arbitrage, transmission congestion relief, and demand charge reduction). Baseline RES and target RGS are the least expensive reconditioning scenarios. The economically viable applications for the baseline RES scenario include frequency regulation, transmission congestion relief, and demand charge reduction. With improved economics, the target RGS scenario is viable for two additional applications: energy arbitrage and spin/non-spin reserve.

3.2.1. ESS minimum revenue

The baseline RGS, RES, and repurpose scenarios are shown to require less revenue for both power (P) and energy (E) applications (P: 87–89 $/kW-y; E: 184–194 $/kW-y) than the baseline new Li-ion scenario (P: 103 $/kW-y; E: 253 $/kW-y) (Fig. 3). This is due to the lower combined costs of 2nd life battery acquisition and processing (P: 18–20 $/kW-y; E: 72–80 $/kW-y) relative to the battery acquisition cost of a new Li-ion battery (P: 36 $/kW-y; E: 146 $/kW-y). The target new Li-ion battery is shown to have a lower grid revenue requirement (P: 76 $/kW-y; E: 182 $/kW-y) than all the baseline 2nd life battery scenarios (P: 87–89 $/kW-y; E: 184–194 $/kW-y) and a higher grid revenue requirement than all the target 2nd life battery scenarios (P: 62–63 $/kW-y; E: 122–126 $/kW-y). Overall, the 2nd life batteries are preferable to new Li-ion batteries. However, as new Li-ion battery prices are reduced, as shown

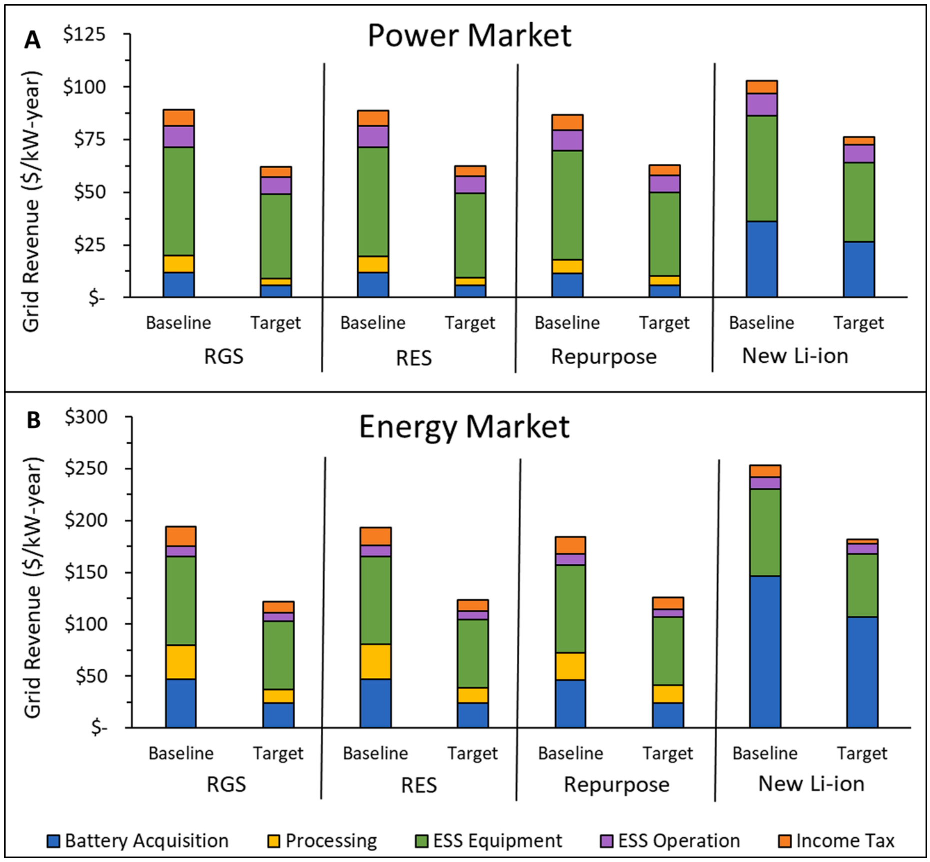

Fig. 3. The required revenue for 2nd life batteries as compared to new Li-ion batteries in (A) power markets (B) energy markets with baseline and target scenarios.

by the target scenario, the answer from this analysis could change. As discussed in 3.1 2nd Life Battery Resale, the reduction in 2nd life battery price is smaller than the reduction in new Li-ion battery price implying a reduction in new Li-ion acquisition costs would be greater.

The target scenario for new Li-ion batteries in an energy application (Fig. 3B) has the largest cost reduction from the battery acquisition cost. However, all other power and energy market target scenarios see the largest reduction from the ESS equipment costs; the ESS equipment costs are assumed to be reduced by 23% in the target scenario [41]. The ESS equipment cost is the largest cost component for the majority of scenarios with the exceptions being for the baseline and target new Li-ion energy market scenarios. The energy market ESS scenarios are dominated by costs assessed on a per unit energy basis such as battery acquisition and processing. Alternatively, the costs assessed on a per unit power basis are more prevalent for the power market ESS as shown by ESS operation.

These results can be compared to benchmarked annual costs found in literature. New Li-ion ESSs deployed in 2018 and 2025 are estimated to have annual costs of 294 $/kW and 241 $/kW for 4-hour systems (energy applications) [41]. Our estimate for the new Li-ion baseline scenario (253 $/kW) is lower than the 2018 benchmark and higher than the 2025 benchmark since we used a longer lifetime of the ESS (20 years) and the same 10 year lifetime of the batteries. This is mainly driven by the assumed longer lifetime in this study (20 years). The new Li-ion target scenario estimate (182 $/kW) is lower than both the 2018 and 2025 benchmarks.

The results from our study do not account for the value of performance differences among new, reconditioned, and repurposed batteries. A new battery is expected to have the best performance since the cells have a uniform 100% SOH upon deployment of the ESS. EV battery aging has been shown to vary by manufacturer, generating a wide-range of battery performance characteristics [52]. HUB reconditioning aims to balance the SOH of cells and continuously monitor the battery's performance over hundreds of cycles. As a result, HUB reconditioning can produce battery modules with an improved SOH and also a more accurate understanding of the performance characteristics of the battery modules than traditional repurposing can achieve. The performance characteristics of the battery dictate the suitability of the ESS to be used for certain power and energy market applications [44]. The minimum revenue for both power and energy market ESSs are compared to their respective market application revenues in the following section.

3.2.2. *Market potential*

The ESS minimum revenue for power market ESSs (Fig. 3A) is compared to the range of market revenues from the applications of spin/non-spin reserve, voltage support, and frequency regulation. The potential market size of the applications in the United States is also considered for spin/non-spin reserve, voltage support, and frequency regulation are 6.0-GW, 9.2-GW, and 1.0-GW [43]. The energy applications include energy arbitrage, transmission congestion relief, and demand charge reduction which have market capacities of 18.4-GW, 36.8-GW, and 32.1-GW in the United States [45].

The potential capacity of the power and energy applications that could satisfy the minimum required revenue of the ESSs (Fig. 3) are shown in Fig. 4. Market size data from Eyer & Corey and revenue data from Balducci et al. are combined using Eq. (5) [43,45] and shown in Fig. 4. The minimum required revenue from the baseline and target RES method (Fig. 3) is plotted by the vertical lines in Fig. 4. The market size to the right of the vertical line represents the size of the application's market that could satisfy the revenue requirement of the ESS.

3.2.2.1. *Power markets.*

As shown in Fig. 4A, frequency regulation is the only power application necessary to satisfy the minimum revenue of the baseline RES ESS. However, at the baseline minimum ESS revenue the

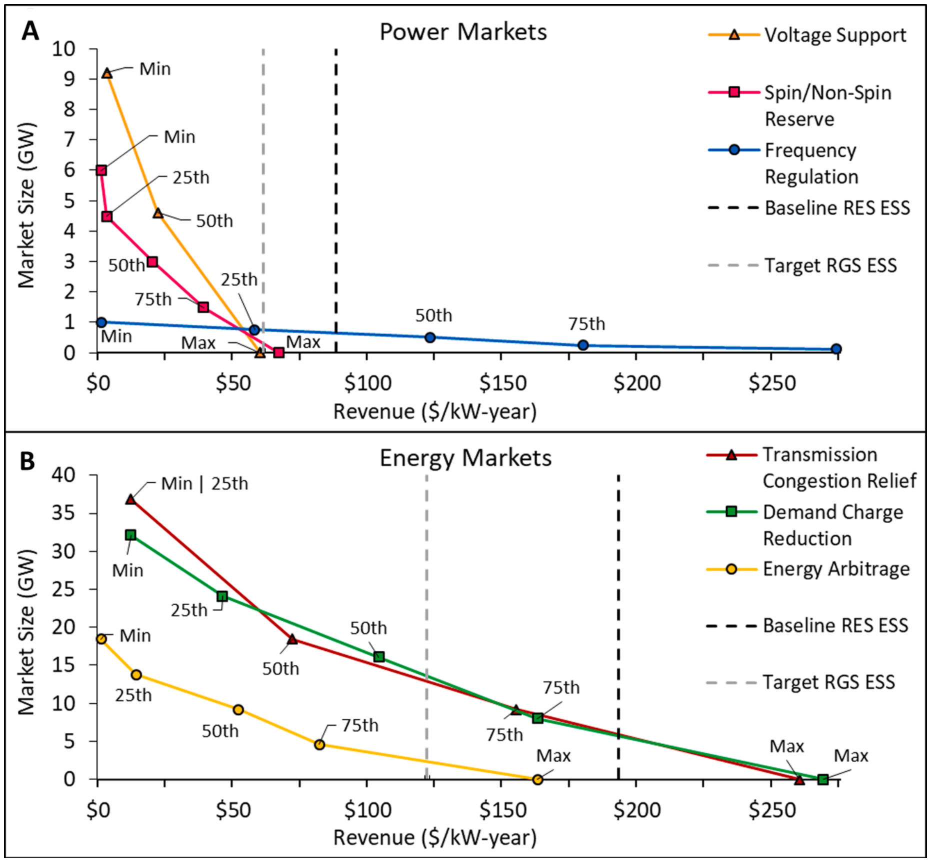

Fig. 4. Market size for applications based on the total market size [43] and percentile of revenue from estimates in literature for energy storage in (A) Power Markets and (B) Energy Markets [45].

capacity of the frequency regulation market (63%) to meet that revenue is only 0.64-GW (0.64-GWh). This analysis modeled the maximum ESS capacity online for the baseline RES method to be 1.6 GWh so the 2nd life batteries could not exclusively be used for frequency regulation or power applications. For the power applications ESS target revenue value (Fig. 4A), the 2nd life batteries could be used for spin/non-spin reserve and frequency regulation which have potential capacities of 0.27-GW and 0.74-GW. The target ESS scenario has a maximum capacity online of 2.0-GW, therefore the power applications could not satisfy the revenue requirement of the target ESS scenario. The 2nd life capacity of the target scenario could satisfy up to 73% of the frequency regulation market size, 5% of the spin/non-spin reserve market size, and none of the voltage support market size. The 2nd life batteries could also be used for energy applications.

3.2.2.2. Energy markets. The energy applications of transmission congestion relief, demand charge reduction, and energy arbitrage each have a higher market capacity than all the power applications combined. As shown in Fig. 4B, the minimum revenue for the baseline scenario is 194 $/kW-year which could be satisfied by the energy applications of demand charge reduction (5.7-GW or 22.8-GWh) and transmission congestion relief (5.8-GW or 23.2-GWh). The minimum revenue from the target scenario is 123 $/kW-year which could be satisfied by each of the energy applications. Energy arbitrage, transmission congestion relief, and demand charge reduction have potential market capacities of 2.2-GW (8.8-GWh), 12.8-GW (51.2-GWh), and 13.5-GW (54.0-GWh) at the target scenario's minimum revenue value. The target scenario 2nd life capacity (0.5-GW or 2-GWh) could satisfy up to 0.6% of the total market size (87.3-GW or 349-GWh) for the considered energy applications. The results indicate that the reconditioned batteries in this analysis could have their revenues satisfied by power and energy applications. However, it is also important to consider the total size of the 2nd life EV battery market in the United States.

3.2.2.3. Overall 2nd life market. The size of the total 2nd life EV market can be approximated based on the cumulative capacity of EVs sold in the United States. The cumulative capacity of EV batteries sold from 2010 to 2019 is 61.5-GWh in the United States [53]. A fraction of the total capacity of EVs is expected to have a 2nd life. Bloomberg New Energy Finance assumed that about 27% of the EV batteries available in 2025 could be used for 2nd life applications based on their end of 1st life performance [54]. The reconditioning process has the potential to enable a larger portion of available batteries to be used for 2nd life applications due to performance improvement. The size of the 2nd life market will ultimately be dictated by the demand from economical applications.

This analysis assumes that only 2nd life batteries will satisfy the markets for the power and energy applications considered. The total potential capacity of 2nd life batteries that could have their baseline revenue satisfied by the three economical grid applications considered is 46.6-GWh. For the target scenario, the total 2nd life capacity that could be satisfied is 115-GWh from the five economical applications considered. If only 27% of the EV batteries sold from 2010 to 2019 have a 2nd life (16.6-GWh), the baseline and target ESS scenario would have their revenues satisfied by participating in the power and energy markets. If all of the EV batteries sold from 2010 to 2019 have a 2nd life (61.5-GWh), then the target scenario would be able to satisfy all of the batteries' minimum revenues however the baseline scenario would only be able to satisfy 76% of 2nd life batteries' minimum revenues.

The range of application revenues represent the distribution of revenue values determined in literature. The study by Balducci et al. looked at studies that examined multiple electricity markets such as CAISO, New York Independent System Operator (NYISO), and Midcontinent Independent System Operator (MISO) [45]. Each of these electricity markets have different generation sources, transmission networks, and loads which impact the value of an ESS for certain applications. The potential ESS market size for the applications is also dependent on the generation sources and loads. The revenue differences between electricity markets indicates that 2nd life batteries could be economical in certain markets and not economical in others.

3.3. Sensitivity analysis

Sensitivity analyses of the baseline inputs for RGS, RES, repurpose, and new Li-ion are completed for 3.2 Energy Storage System energy applications. The sensitivity analyses of the TEA inputs are shown in Fig. 5 for the 10 most sensitive inputs from each scenario.

As shown in Fig. 5, the DOD is the most sensitive variable for all scenarios. For 2nd life batteries, the DOD is typically operated between 15% and 65% state of charge which is considered best practice [9]. The aging of reconditioned 2nd life batteries is an area of uncertainty so the DOD may have a different optimal operating range than repurposed batteries. The battery life is one of the top four most sensitive variables for each scenario. The lifetime of 2nd life batteries is an area of uncertainty since there is limited aging data on 2nd life batteries. A 50% increase to the battery lifetime is shown to have a much lower impact than a 50% decrease due to the time value of money in the DCFROR analysis. The battery acquisition price is a sensitive variable for every scenario in Fig. 5 since it is a high cost in the cashflows. The battery acquisition price also makes the viable product for the repurposing and reconditioning scenarios very sensitive, as shown in Fig. 5A, B, and C. A lower viable product results in more batteries acquired which are disposed rather than used in the ESS. In Fig. 5A and B, the reconditioning time is sensitive since it determines the battery yield. The roundtrip efficiency of the RES scenario (Fig. 5B) is shown to be sensitive due to its impact on the reconditioning electricity cost from charging and discharging cycles. The sensitivity analysis also shows that decreasing the cost of the ESS installation and electrical balance of system will lower the minimum revenue required. The TEA assumptions, including the internal rate of return, loan term, income tax rate, and loan interest rate, are shown to be sensitive in Fig. 5. Therefore, the TEA results would change substantially with different economic assumptions, but the comparisons of the technologies should remain consistent.

4. Conclusion

The cost to process batteries for a 2nd life was determined for the methods of RGS, RES, and repurposing with a comprehensive high-fidelity model. The results indicated the RES is likely the most cost-effective reconditioning method. The traditional repurposing approach was shown to be less expensive than reconditioning for the baseline scenario but more expensive for the target scenario. The resale price of reconditioned batteries was determined to be between 34 $/kWh and 62 $/kWh. This range of resale prices was less than the price of a new Li-ion battery today and most estimates for 2030. The 2nd life battery ESSs were shown to be more economical compared to new Li-ion ESSs for both power and energy applications. The 2nd life ESSs were determined to be economically feasible for both power and energy applications with

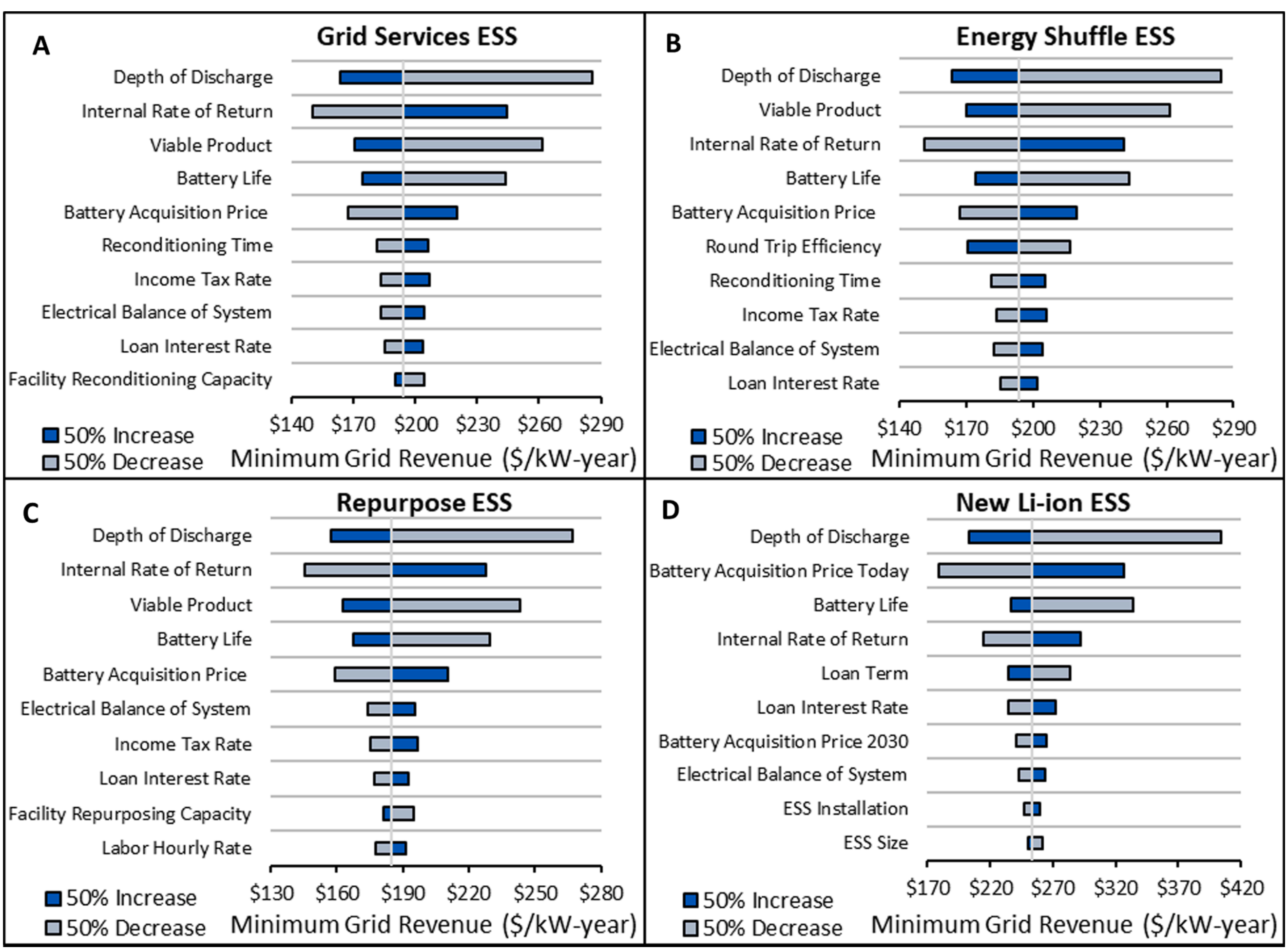

Fig. 5. Sensitivity analysis of the 10 most sensitive model inputs for (A) RGS ESS (B) RES ESS C) repurpose ESS D) new Li-ion ESS.

the latter having a much larger potential market size. The combined market size of power and energy applications is expected to be able to satisfy the market size and minimum revenue of 2nd life battery ESSs in the United States. R&D should be focused on reducing battery prices, ESS costs, and 2nd life processing costs as well as reducing the uncertainty of 2nd life battery performance.

CRediT authorship contribution statement

Noah Horesh: Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization. **Casey Quinn:** Methodology, Validation, Investigation, Writing - original draft, Visualization. **Hongjie Wang:** Resources, Investigation, Writing - original draft. **Regan Zane:** Resources, Investigation, Writing - original draft. **Mike Ferry:** Resources, Investigation. **Shijie Tong:** Conceptualization, Methodology, Investigation. **Jason C. Quinn:** Conceptualization, Methodology, Validation, Investigation, Writing - original draft, Visualization, Supervision.

Declaration of Competing Interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2021.117007.

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