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Item Type	Article
Authors	Fallah, Narjes;Fitzpatrick, Colin
Citation	Journal of Energy Storage 68, 107740
Publisher	Elsevier
Download date	2026-05-09 13:49:55
Item License	https://creativecommons.org/licenses/by-nc-sa/4.0/
Link to Item	https://doi.org/10.34961/researchrepository-ul.23531097

Journal of Energy Storage 68 (2023) 107740

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Research papers

Is shifting from Li-ion NMC to LFP in EVs beneficial for second-life storages in electricity markets?

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ARTICLE INFO

Keywords:
Battery repurposing
Financial feasibility
Electric vehicles
Circular economy

ABSTRACT

While electric vehicles are promising to reduce carbon emissions on the road, from a holistic life-cycle view, further environmental considerations in the production and end-of-life management of their batteries are required. Recently, circular end-of-life thinking has been promoted with strategies to increase retired batteries' lifetime through second-life as lifetime extension is typically favoured in life cycle assessment. However, standardization of these strategies toward recycling or repurposing paths is recommended for different Li-ion chemistries. This categorization mainly concerns the cobalt-containing cathode Li-ion batteries i.e., NMC which is the dominant technology for transportation, and the alternative technology i.e., LFPs with a more recent attention toward them in automobile sector due the cobalt scarcity in the supply chain. This technology shift will impact their end-of-life management at the retirement. In this arrangement, the economic priority of repurposing such battery chemistries needs quantification. This study evaluated the financial return of repurposing retired Li-ion NMC and LFP batteries for energy arbitrage applications in power systems. The feasibility of repurposing is examined in the Irish and Queensland's markets. Results show that retired Li-ion LFPs respond to price fluctuations more frequently with a higher financial return compared to NMCs; thus, they have higher potential for repurposing as such their greater integration in new vehicles is promising from a circular economy perspective. Different rates of return have been observed for various sizes of systems and battery durations. The financial benefits are more prominent for a one-hour battery in a medium system compared to half and two-hour durations and a smaller system. A sensitivity analysis shows that even spending the same capital cost as a new system for a repurposed system results in a marginal financial return in a competitive electricity market like Queensland's, whereas further incentives toward circular-enabling business models from local authorities will effectively make such investments feasible.

1. Introduction

Attempts to reduce carbon emissions in transport have recently pushed the adoption of Electric Vehicles (EVs) globally. This has been targeted, amongst other means, by placing a ban on registering internal combustion engine vehicles by 2035–2040 in several countries such as the UK, Ireland, and France, leading to future market uptake of EVs. Such policy shifts and all the encouragement and market competition in the automobile sector will result in a substantial amount of End-of-Life (EOL) EVs with a stockpile of obsolete batteries [1], whereas strategies to address the management of them are not yet well developed.

Uncertainty about the fate of retired EV batteries poses a risk to the sustainability of their supply chain. Currently, Li-ion Batteries (LIBs) are facing numerous challenges in their supply chain including the extraction of rare earth material and huge production costs. Furthermore, in the use phase, the substitution of combustion engine vehicles with EVs would create new peaks in the electricity demand which the electricity market may not always be in a position to accommodate. In the EOL phase, the staggering number of EOL LIBs in the future could create challenges regarding their disposal, reuse, and recycling. Their dismantling and removal from vehicles, collection and transportation are highly costly with a lack of trained technicians & facilities with appropriate safety measures. Further, the absence of regulations and standards, inconclusive reuse business models and unautomated & inefficient recycling facilities are barriers to their EOL management [2].

Baars et al. [3] proposed that introducing new circular strategies in every phase of the supply chain of LIB helps their sustainability. They suggest that retired batteries with above 80 % State of Health (SOH) will

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https://doi.org/10.1016/j.est.2023.107740
Received 14 November 2022; Received in revised form 4 May 2023; Accepted 15 May 2023

be suitable for reuse and repurposing, whereas the ones below this threshold are recommended to be recycled. For material recovery, recycling strategies are being developed [4] toward a full recycling concept via hydrometallurgical methods; whereas other studies [5] indicate that, where cascading the lifetime of LIBs in the first and second life is possible, it is environmentally favoured. However, there are several technical and economic challenges with battery second lives [6].

Recent studies aimed to address some of the second-life battery challenges and opportunities. For example, Noa Horesh et al. [7] argue that the reconditioning cost of retired batteries is a huge barrier to their repurposing and proposed a method to evaluate that. They found the second life reconditioning to be an opportunity for improving the potential for batteries' second life. Elisa Braco et al. [8] discovered that the ageing assessment of LIBs is fundamental for their repurposing and performance during their second life. Their analysis is focused on finding the relevant features for health estimation and the robustness of the health indicators. Cheng et al. [9] also discussed that the sustainability performance of second-life LIBs concerns their degradation profile. They mention that the initial State of Health (SOH) and degradation rate are the two factors to consider in cost models and conclude that the pricing model is challenging to create unless more data would be available on the second-life supply chain of batteries.

Although pricing is not a straightforward task for second-life batteries, some studies have worked on the feasibility of second-life applications. For instance, Lacap et al. [10] evaluated the applicability of retired EV batteries for demand control in a microgrid. They reported a satisfactory performance of the battery system for peak shaving; however, the capacity degradation of battery cells was not measured during one year of operation. Thus, the economic return of their analysis is not transparent without providing a lifetime overview. Wilson et al. [11], on the other hand, propose a critical SOH parameter indicating the quality of modules as a minimum threshold to be environmentally justifiable. They tested their analysis in the residential Australian context.

Al-Wreikat et al. [12] measured the payback period for different brands of retired EV batteries repurposed in residential storage systems. They identified the right sizing to the peak and off-peak demand, the battery price drop by EV overtaking the market, and the battery storage application to more than one household as favourable factors to reduce the payback. Xu et al. [13] evaluated the economic feasibility of repurposing retired batteries in the Danish electricity market i.e. day ahead and regulation market. Their result shows that using retired batteries in this market is not cost-effective at the moment. However, they discuss beneficial scenarios where the investment cost is reduced by 10 % or the prices in the regulation market rise by 50 %.

While the abovementioned studies were not taking different types of LIBs, comparatively, in their assessment, some studies discussed how the EOL strategies would be different for various types of LIBs. As such, Geng et al. [14] narrowed down the second life feasibility assessment of LIBs for the Lithium Iron Phosphate (LFP) chemistry only, due to the long cycle life, high safety and low cost despite lower energy density and low temperature. Whereas they categorized the lithium Nickel Manganese Cobalt oxide (NMC) and Lithium Nickel Cobalt Aluminium oxides (NCA) chemistries as favourable for recycling since they are a good source of the secondary supply of critical raw materials. The same conclusion is reported in work by Wang et al. [15] showing that the environmental advantages of recycling LFP are much lower than NMC chemistries. Moreover, Dunn et al. [16] discussed the circularity barriers of LIB materials and highlighted the required policy intervention for the lower-value materials in future EV LIBs. In a review by Xin Lai et al. [17], it has been discussed that sorting and standardization are important from an EOL policy perspective.

Considering the environmental advantages of repurposing retired LFP batteries in vehicles compared to the NMC ones, there are a few works addressing their economic priority in second life. As such a study by Casals et al. [18] in which a summary of compatibility between the battery chemistry and potential stationary second life application is provided. Although, their analysis is more focused on the environmental impact and their economic evaluation is not a quantitative analysis but rather an indicative comparison. Exploring the literature, we found out that no proper economic evaluation has been performed confirming the techno-economic advantages of LFP to Cobalt containing LIB batteries including NMC. This is specifically important to investigate with the recent attention toward using LFP batteries in the automobile sector. Currently, Li-ion LFPs are becoming very popular in China, the main producer of EVs [19]. Likewise, the American producer, Tesla [20], announced a change of its battery types to LFPs in all its standard-range vehicles. Also, industry competitors favour LFP chemistries due to the fire safety, operational cost and higher flexibility to the depth of discharges which is a considerable advantage for short-duration applications [21].

With this recognized gap, this study aims to answer this question: Is the shift from NMC to LFP batteries in the automobile sector favourable for the circular economy approach of repurposing as stationary applications? Answering this question will help to better understand and quantify the economic advantages of using LFP batteries for repurposing in stationary storage systems. This comparison has been tested for second-life applications of retired Li-ion NMC and LFP battery types for energy services in the Irish and Queensland (QLD), Australia electricity markets. While the current practice for battery use in electric grids is more focused on reserve/ancillary services, it is more insightful to consider energy trading applications which has a much higher potential global demand while reserve services will remain a more limited use case. Testing our case study, we are evaluating the economic return of this business model in an energy competitive market i.e., QLD and a simpler case of the Irish electricity market, as good and baseline scenarios.

The rest of the paper is as follows: The methodology approach is discussed in the following section: after that the results of this evaluation are represented in Section 3, followed by a conclusion to the analysis at the end of the paper.

2. Methodology

The economic evaluation of the second-life feasibility of retired EV batteries in this work is approached using a revenue-cost analysis and has been conducted for battery participation in energy trading services in the electricity market. Two initial SOH of retired batteries are assumed: 90 % and 85 %, in 4 and 8-year-old retired vehicles followed by Fallah and Fitzpatrick [26] suggesting that this is approximately the expected SOH at this age of vehicle disposal. The four and eight-year-old batteries could potentially be coming from early failure vehicles or at the end of an eight-year lease agreement.

Two types of Li-ion Batteries i.e., LFP (A123 Systems' APR18650m1 LiFePO4 cells) and NMC (type US18650V3 manufactured by Sony Energy Devices) have been selected for this evaluation. The batteries' ageing profile is modelled using the same model as applied in Fallah and Fitzpatrick [26] and fitted by the experimental data provided by Maheshwari et al. [27] and Lam and Bauer [28]. Battery modelling details and parameters are provided in the Supplementary document.

In this work, energy arbitrage trading in the power system is tested for second-life feasibility. Energy trading applications are highly sensitive to batteries cycling profile, thus a better representation of the performance of different Li-ion chemistries compared to reserve services or backup storages. Although we showed in our previous work [26] that reserve services are the most beneficial application in the Irish electricity market, these types of applications are limited in demand, whereas the demand for energy trading applications either real-time markets or demand response peak shaving is increasing globally. In principle, the revenue from arbitrage trading in the electricity market comes from price fluctuations. Taking the Irish electricity market as an example, the settlement prices are determined every half an hour. The arbitrage revenue is created when batteries buy/charge for lower prices and sell/discharge for higher prices. Therefore, those markets with the so-called duck-curve price profiles are appreciated better for arbitrage trading. In this work, we are examining batteries' contribution to two real-time energy markets i.e. Irish Imbalance (IMB) market [22] and Queensland, Australian Spot market [23]. The same compensation mechanism of these two markets made this comparison feasible. The reason for selecting these two markets is that Queensland's Spot market is one of the recognized markets for revenue-making by arbitrage trading [21], whereas the Irish IMB market is not incentivized for battery operation [26]. By comparing these two markets, we are taking the optimistic and pessimistic case studies for this evaluation. Both case studies take scenarios as listed in the table below (Table 1). More on these parameters and their impact on the project financial returns are explained in the Results and discussion section.

$$Max(Income - Expenses):$$

$$\begin{cases} Income = (P \times E_{dis}) \\ Expenses = \underbrace{(P \times E_{ch})}_{\text{Charging cost}} + \underbrace{5 \times Cost_{capital} \times (\delta_{cyc} + \delta_{cal})}_{\text{Battery Replacement Cost}} + \underbrace{Cost_{O\&M}}_{\text{O\&M cost}} \end{cases}$$

s.t:

Availability const.:

$$E_{avail}[t] = E_{avail}[t-1] + E_{ch}[t-1] \times \underbrace{eta}_{eta\text{ is the round-trip efficiency.}} - \frac{E_{dis}[t-1]}{eta} - E_{leak} \tag{1}$$

$$E_{avail}[t] \leq Capacity[t]$$

Capacity lost const.:

$$Capacity[t] = Capacity[t-1] - \delta_{cyc}[t] + \delta_{cal}[t] - \delta_{cal}[t-1]$$

SOC const.:

$$0.2 \leq SOC[t]$$

Dis const.:

$$E_{dis}[t] \leq P_{rated} \times 0.5$$
$$E_{dis}[t] \leq E_{avail}[t]$$

Depth of dis. const.:

$$DOD[t] = \frac{E_{dis}[t]}{E_{avail}[t]*eta} + \frac{Capacity[t]-E_{avail}[t]}{Capacity[t]}$$

An optimization algorithm has been designed to pick the optimum price periods to maximize revenue. The objective, as indicated in Eq. (1), is to maximize the profit, while the income is coming from the compensation for discharges. Moreover, the expenses are broken down into charging costs, battery replacement or depreciation cost, and O&M cost. The number five in the second term of *Expenses* represents that the battery capital cost is spent for the first 20 % capacity after which the EOL threshold would be surpassed. Thus, this term is divided by 0.20 or multiplied by five.

This objective is further subject to several conditions stated below. The available energy E_{avail} is updated by every charge and discharges with a round trip efficiency, *eta*, and the leakage charges. The charge availability is also limited by the capacity as the capacity degrades over time, the maximum charge will be affected accordingly. The capacity itself is affected by calendar and cycling ageing shown as δ_{cyc} and δ_{cal} and defined in the Supplementary data. The State of Charge (SOC) is bounded by a minimum of 20 % as it is recommended by manufacturers. The discharge energy, E_{dis}, is impacted by the battery output power and the dispatch duration interval, as it also needs to meet the charge availability in the battery. The Depth of Discharge (DOD) counts the amount of discharged energy to the available charge in the battery, while sequential charges or discharges are also counted by the second term in the formulae. The optimization programming codes which are developed using the Pyomo library in Python are provided in the Supplementary document.

Table 1
Scenario description for case studies.

Parameters in scenarios	Case study 1	Case study 2
Market	Queensland's Spot market	Irish IMB market
Battery type	LFP &NMC	LFP &NMC
Battery SOH	90 % & 85 %	90 %
Battery age	4- & 8-year-old	4-Year-old
System size	Small and medium size (1 and 10 MW)	Small and medium size (1 and 10 MW)
Battery duration	0.5, 1, and 2 h	1 h

The parameters for the cost components i.e., capital and O&M costs in Eq. (1) are adopted from Viswanathan et al. [29] and Mongird et al. [30] for 1 and 10 MW systems sizes. The considered values for parameters are represented in the Appendix A-1 and A-2. Although the capital investment for retired batteries is expected to be lower, thus we incorporated this financial impact by estimating the cost of battery cells themselves within a BESS. According to Mongird et al. [30], battery block cost is counted as 35 to 40 % of the system cost for durations below 2 h and with system sizes of 1–10 MW. We assumed if the retired battery

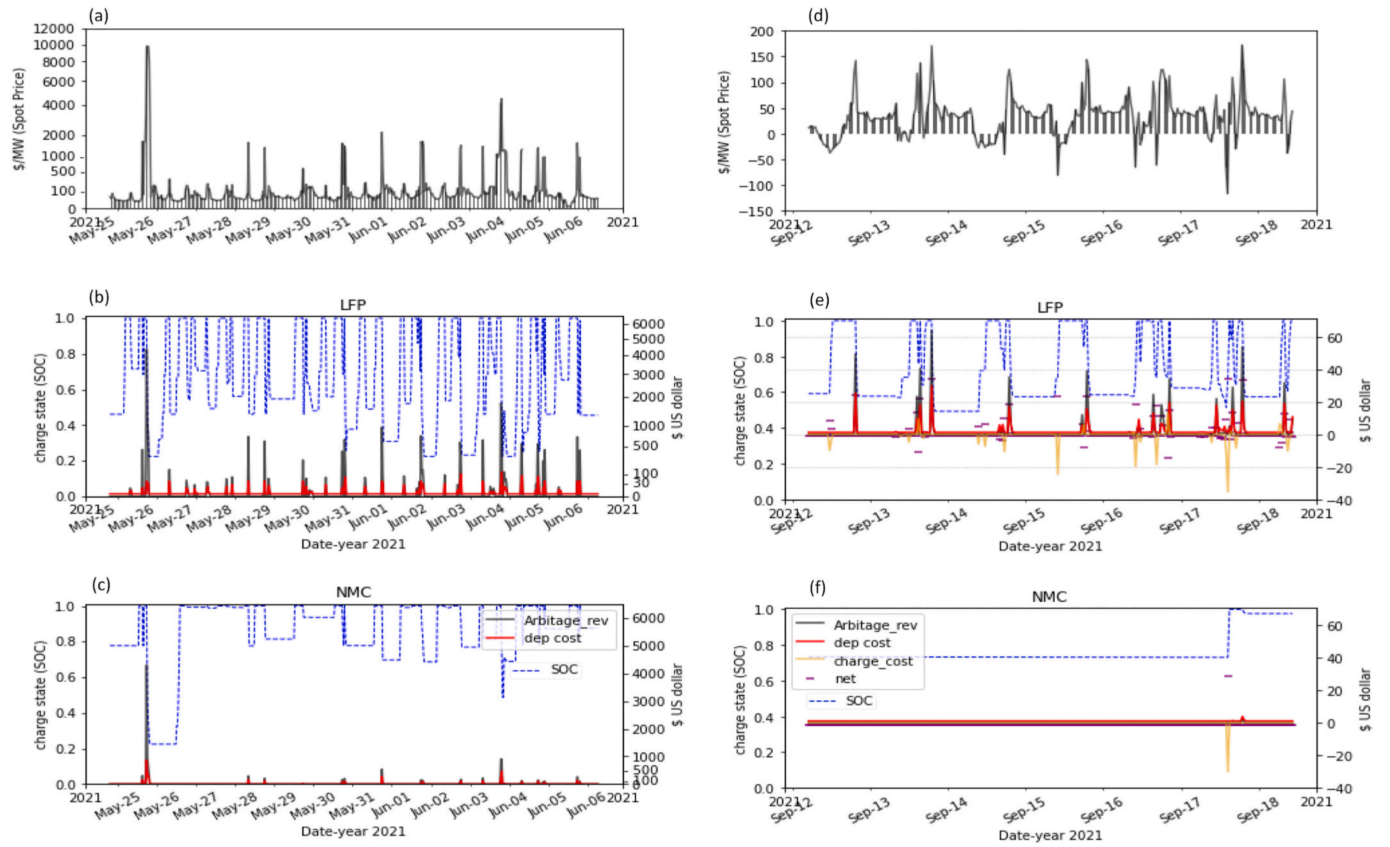


Fig. 1. (a & d) Half-hourly Spot prices in the QLD market (b & e) LFP battery operation and revenue making in the QLD market. (c & f) NMC battery operation and revenue making in the QLD market.

blocks are worth 20 % of the new ones, as is the assumption in Zhan et al. [24]. The whole BESS cost will decrease to almost 70 % of a system with new battery blocks. We acknowledge that this assumption might be not fully valid, therefore a cost sensitivity is represented in the Results and discussion section.

The calendar life is also considered to be 15 years for a brand-new battery as recommended by Cole et al. [31] in a moderate scenario, although there are studies that take a 20-year lifetime for Li-ion batteries.

And finally, the economic return of the retired battery investment is conducted using the Internal Rate of Return IRR index. The IRR is achievable by solving the below formula [25]. This index indicates the annual rate of growth that investment is anticipated to achieve. This index is ideal when analysing the over-the-lifetime financial return compared to the capital investment. The higher the IRR, the more desirable the investment.

$$\text{The } 0 = NPV = \sum_{t=1}^{T} \frac{C_t}{(1+IRR)^t} - C_0$$

where:

$C_t = Net\ cash\ inflow\ during\ the\ period\ t$
$C_0 = Total\ initial\ investment\ costs$
$IRR = The\ internal\ rate\ of\ return$
$t = The\ number\ of\ time\ periods$

The results of this methodology are discussed in the following section.

3. Results and discussion

Results of the battery scheduling for energy trading in the QLD Spot market and Irish IMB market are visualized in Figs. 1 and 2. The prices for two various date periods are selected to be visualized in these figures as samples of different price fluctuation profiles. Figs. 1(a) and 2(a) represent extremely high spike price periods in which prices rise to $10,000 and $ 4500 for QLD and IMB markets. The LFP and NMC batteries respond differently to these extreme optima though, by deeper and more frequent discharges for LFP batteries compared to NMC ones, as indicated in Figs. 1(b & c) and 2(b & c). The reason the NMC batteries do not respond as frequently as LFPs is because of their high depreciation cost with severe sensitivity to DOD, as the red graphs for both battery types show.

The other date periods represented in Figs. 1(d) and 2(d) does not contain as many spikes, while the presence of negative prices in these time slots is mainly the reason for battery charge and discharges. In this sense, battery charging is creating revenue (by buying negatively priced energy) as indicated in Figs. 1(e & f) and 2(e & f). The battery discharges in these periods are comparatively shallower than in extreme price periods. However, the LFPs pick more negative prices with more frequent charging compared to NMCs.

Although the depreciation cost happens because of discharging and not charging (The battery degradation model is sensitive to discharges and charging does not cause degradation. More on this is provided in the Supplementary document.), batteries need to discharge at some point to be able to charge at negative optima prices. Thus, the revenue from negative charging would not compensate for the discharges of NMCs. Furthermore, the annual battery revenue captured by summing up the results of the optimization represented in previous figures along with other technical and economic parameters are listed in Tables 2 and 3 for

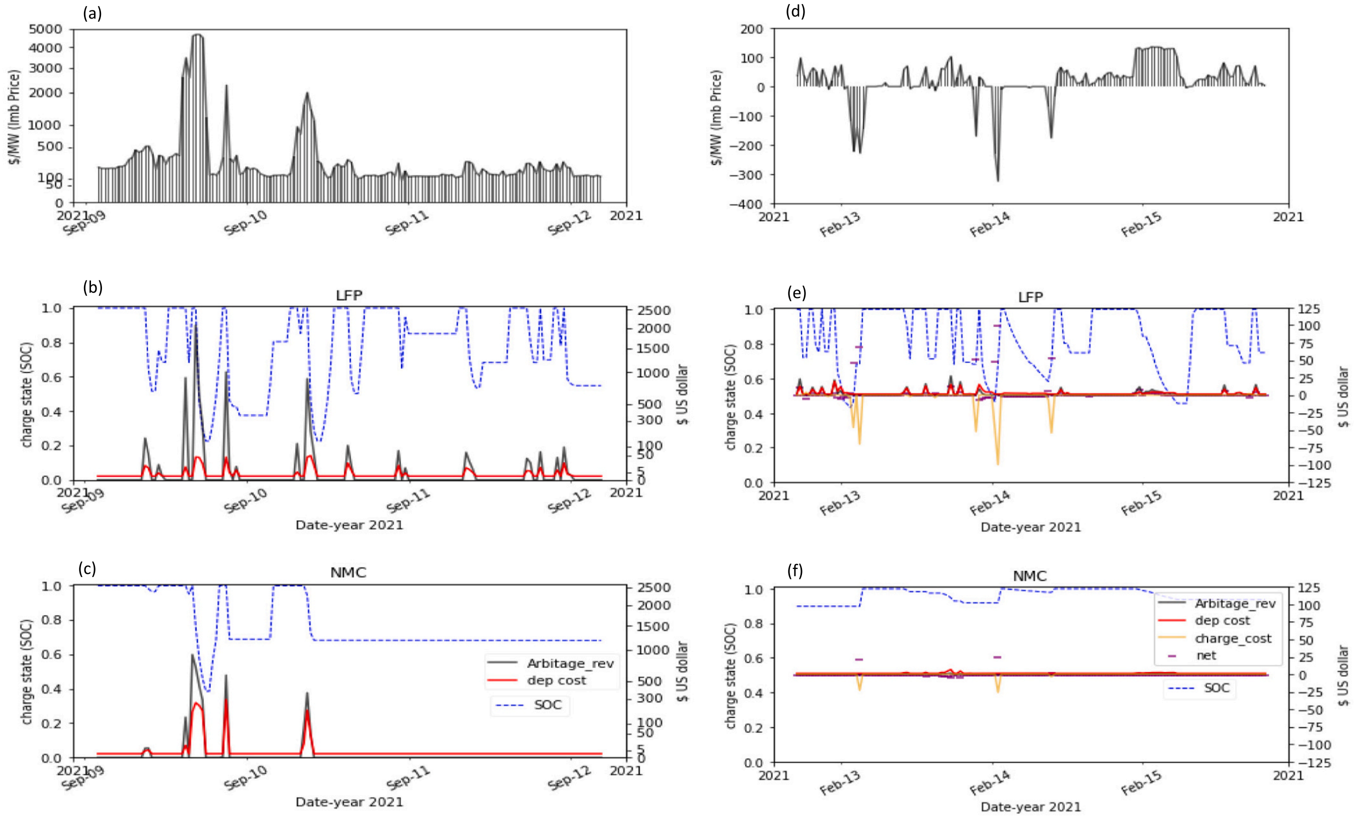
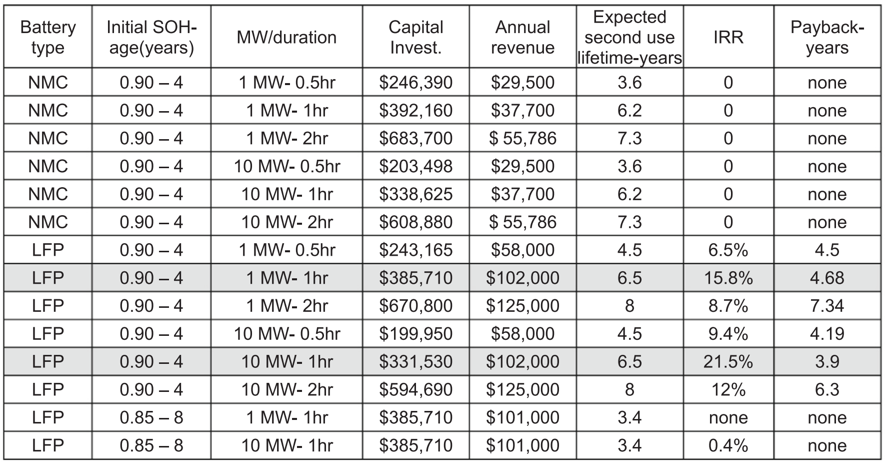


Fig. 2. (a & d) Half-hourly settlement prices in the IMB market (b & e) LFP battery operation and revenue making in the Irish IMB market. (c & f) NMC battery operation and revenue making in the Irish IMB market.

Table 2
Results of economic analysis of retired battery investment in Queensland Spot market.



Battery type	Initial SOH-age(years)	MW/duration	Capital Invest.	Annual revenue	Expected second use lifetime-years	IRR	Payback-years
NMC	0.90 – 4	1 MW- 0.5hr	$246,390	$29,500	3.6	0	none
NMC	0.90 – 4	1 MW- 1hr	$392,160	$37,700	6.2	0	none
NMC	0.90 – 4	1 MW- 2hr	$683,700	$ 55,786	7.3	0	none
NMC	0.90 – 4	10 MW- 0.5hr	$203,498	$29,500	3.6	0	none
NMC	0.90 – 4	10 MW- 1hr	$338,625	$37,700	6.2	0	none
NMC	0.90 – 4	10 MW- 2hr	$608,880	$ 55,786	7.3	0	none
LFP	0.90 – 4	1 MW- 0.5hr	$243,165	$58,000	4.5	6.5%	4.5
LFP	0.90 – 4	1 MW- 1hr	$385,710	$102,000	6.5	15.8%	4.68
LFP	0.90 – 4	1 MW- 2hr	$670,800	$125,000	8	8.7%	7.34
LFP	0.90 – 4	10 MW- 0.5hr	$199,950	$58,000	4.5	9.4%	4.19
LFP	0.90 – 4	10 MW- 1hr	$331,530	$102,000	6.5	21.5%	3.9
LFP	0.90 – 4	10 MW- 2hr	$594,690	$125,000	8	12%	6.3
LFP	0.85 – 8	1 MW- 1hr	$385,710	$101,000	3.4	none	none
LFP	0.85 – 8	10 MW- 1hr	$385,710	$101,000	3.4	0.4%	none

Table 3
Results of economic analysis of the retired battery investment in the Irish IMB market.

Battery type	Initial SOH-age (years)	MW/duration	Capital invest.	Annual revenue	Expected second use lifetime-years	IRR	Payback-years
LFP	0.90–4	10 MW- 1 h	$331,530	$68,960	5.23	0.01	5.23
LFP	0.90–4	1 MW- 1 h	$385,710	$68,960	5.23	0	None
NMC	0.90–4	1 MW- 1 h	$392,160	$6466	8.6	0	None

QLD and IMB markets, respectively. Results of the battery arbitrage trading in the QLD market in Table 2 for a 1 MW BESS size and half-hour duration, containing the retired NMC batteries from an early failure vehicle at age of four and 90 % SOH, show that the $29,000 annual revenue within the estimated 3.6 years of service will not compensate the investment of $246,000 along with other O&M costs (Appendix A-2); thus the IRR is zero with no payback period. Whereas, for the same system size and almost similar investment costs, an LFP-based BESS would return 6.5 % annually and will pay back by end of its lifetime. However, increasing the duration of such a system to 1 h will end up in a higher return and sensible payback as highlighted in Table 2. Increasing the duration further to 2 h, on the other hand, results in a lower IRR compared to the one-hour system. The reason behind the various financial profiles of different duration batteries is that the one-hour duration battery can harvest the sequential spiked prices, thus ending up with higher IRR compared to half-hour ones; whereas in a two-hour system, although this capability is given, the higher cost of investment will not be met by this extra harvesting reimbursement. The same rationalization is applicable to NMC batteries with the difference that the revenue is not high enough for this battery chemistry to compensate the investment cost even with higher duration.

Further in Table 2, the results of examining a medium system with 10 MW power capacity and different durations are listed. As highlighted, the highest return is for a one-hour battery duration with 21.5 % IRR. Comparing this scenario with the same BESS specifications but a lower size of 1 MW, it is more profitable due to the lower investment cost per MWh capacity of a medium-sized system thanks to the economy of scale.

The best scenarios with 1-hour battery and 1 and 10 MW system sizes have been picked and examined with the retired 85 % SOH batteries from eight-year-old vehicles. A 4 % rate of return is estimated for a 10 MW system and no return at all for a 1 MW system, concluding that the 85 % SOH is not financially beneficial to be repurposed for energy trading in the QLD market. Although, hybrid applications which also include ancillary services might make this investment profitable.

Moreover, looking at the arbitrage results in the IMB market in Table 3, shows that batteries contribution in this market marginally reimburses the investment costs in the best-case scenario for an hour duration, 10 MW BESS with 90 % SOH of LFP battery cells. Whereas NMCs' contribution in this market is minor with only $ 6466 of annual revenue, with more than eight years of service life showing that very few discharges happen annually. We limited the results for the IMB market to only the three listed scenarios as these are the top-shelf scenarios compared to the other less likely profitable scenarios.

Finally, we examined how the best-case scenario of a 10 MW LFP system containing 90 % SOH cells and a one-hour duration will return financially in the QLD Spot market for different investment costs as a percentage of a new system cost. As it is discussed in the Methodology section, 70 % of the new BESS price is assumed in all the so far analyses. While results in Fig. 3(a) show how sensitive the IRR is to the different percentages of capital investment. As it can be observed, by taking a range of 75–100 % of capital investment of a new BESS, the IRR is changing in a range of 21.5 to 11.2 % for this arrangement. Also, the sensitivity of payback periods to these changes is represented in Fig. 3 (b). According to these results, if a system's Capex is as much as a new BESS's cost, it is still paying back before its service life (6.5 years as stated in Table 3), although it might not be an attractive financial case for investment. However, there might be other incentives that drive such investments in terms of enabling sustainability schemes from the local authorities, for which this study can be used as a baseline for their evaluations.

4. Conclusion

This work aimed to investigate the second use feasibility of two Li-

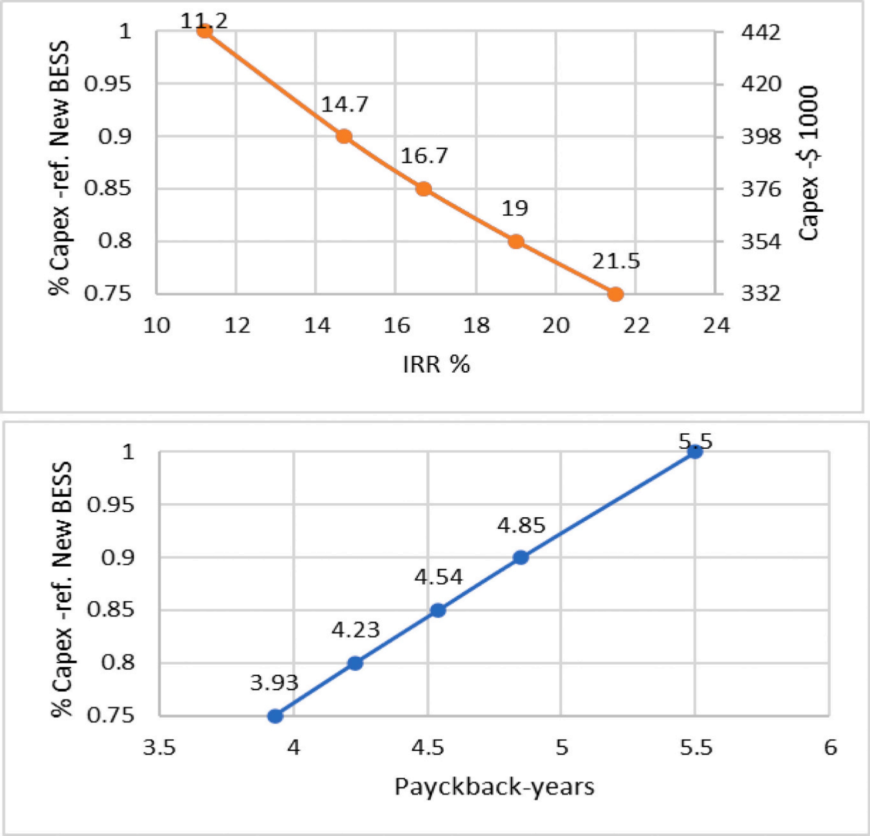


Fig. 3. (a) IRR and (b) payback sensitivity to percentage capex of new BESS for 10 MW and 1-hour duration LFP case study in QLD market.

ion battery chemistries commonly used in EVs, as there is a new trend in the automobile market in shifting toward LFP chemistries. Even though LFPs provide lower energy density compared to NMC batteries this strategy is taken by some to address the scarcity of cobalt material in NMC's cathodes. The second use business model in this work is created around retired batteries' second application for energy arbitrage trading in two different markets i.e., the QLD Spot market and the Irish IMB market. An optimization algorithm has been developed for the decision-making for battery participation. The model has been tested for different BESS sizes with different duration and battery chemistries. Results show a justifiable financial return for a 10 MW medium-size system with a one-hour duration containing retired LFP cells with an initial 90 % SOH in a competitive market such as QLD. Whereas the same system specification is not working best for the Irish IMB market as it is not as incentivized as the QLD market. For NMCs, on the other hand, such services are not financially promising even in the QLD market.

Furthermore, a sensitivity analysis to the percentage capital investment as percentages of a new BESS shows that LFP batteries' financial feasibility is marginally justifiable when we are equalizing the capital investment to be the same as the new systems. This is a baseline analysis showing that if batteries are subsidized in energy-competitive markets such as QLD toward creating sustainable second-life business models, their financial feasibility is effectively achievable. The authors recommend future investigations evaluating the impact of such incentives in similar markets.

CRediT authorship contribution statement

Narjes Fallah: Conceptualization, Methodology, Formal analysis, Validation, Investigation, Visualization, Writing – original draft. **Colin Fitzpatrick:** Project administration, Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The codes are shared in the supplementary document. The market data used is a public data with linkes provided in the manuscript.

Acknowledgements

This work was supported by the Environmental Protection Agency (Ireland) (Project Codes 2019-RE-PhD-3) and the EU H2020 project Si-Drive (Grant Agreement 814464).

Appendix A

Appendix A-1
The capital cost estimation of Li-ion NMC and LFP batteries for various durations.

Battery type	Unit	1 MW			10 MW		
		0.5 h	1 h	2 h	0.5 h	1 h	2 h
LFP	$/kWh	$648	$514	$447	$533	$442	$396
	Total cost	$324	$514	$894	$266	$442	$792
NMC	$/kWh	$657	$522	$455	$542	$451	$405
	Total cost	$328	$522	$911	$271	$451	$811

Appendix A-2
The O&M cost estimation of Li-ion NMC and LFP batteries.

Parameters	Value for 1 MW system
O&M cost	LFP: 2.52 $/kWh NMC: 2.57 $/kWh

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.est.2023.107740.

References

[1] N. Fallah, C. Fitzpatrick, S. Killian, M. Johnson, End-of-life electric vehicle battery stock estimation in Ireland through integrated energy and circular economy modelling, Resour. Conserv. Recycl. 174 (2021), 105753.

[2] M.A. Rajaeifar, P. Ghadimi, M. Raugei, Y. Wu, O. Heidrich, Challenges and recent developments in supply and value chains of electric vehicle batteries: a sustainability perspective, Resour. Conserv. Recycl. 180 (2022), 106144, https://doi.org/10.1016/j.resconrec.2021.106144.

[3] J. Baars, T. Domenech, R. Bleischwitz, H.E. Melin, O. Heidrich, Circular economy strategies for electric vehicle batteries reduce reliance on raw materials, Nat. Sustain. (2020) 1–9.

[4] L. Schwich, M. Küpers, M. Finsterbusch, A. Schreiber, D. Fattakhova-Rohlfing, O. Guillon, B. Friedrich, Recycling strategies for ceramic all-solid-state batteries—part I: study on possible treatments in contrast to Li-ion battery recycling, Metals (Basel) 10 (2020) 1523.

[5] K. Richa, C.W. Babbitt, N.G. Nenadic, G. Gaustad, Environmental trade-offs across cascading lithium-ion battery life cycles, Int. J. Life Cycle Assess. 22 (2017) 66–81.

[6] M.H.S.M. Haram, J.W. Lee, G. Ramasamy, E.E. Ngu, S.P. Thiagarajah, Y.H. Lee, Feasibility of utilising second life EV batteries: applications, lifespan, economics, environmental impact, assessment, and challenges, Alexandria Eng. J. 60 (2021) 4517–4536.

[7] N. Horesh, C. Quinn, H. Wang, R. Zane, M. Ferry, S. Tong, J.C. Quinn, Driving to the future of energy storage: techno-economic analysis of a novel method to recondition second life electric vehicle batteries, Appl. Energy 295 (2021), 117007.

[8] E. Braco, I. San Martin, P. Sanchis, A. Ursúa, D.-I. Stroe, Health indicator selection for state of health estimation of second-life lithium-ion batteries under extended ageing, J. Energy Storage 55 (2022), 105366.

[9] M. Cheng, A. Ran, X. Zheng, X. Zhang, G. Wei, G. Zhou, H. Sun, Sustainability evaluation of second-life battery applications in grid-connected PV-battery systems, J. Power Sources 550 (2022), 232132.

[10] J. Lacap, J.W. Park, L. Beslow, Development and demonstration of microgrid system utilizing second-life electric vehicle batteries, J. Energy Storage 41 (2021), 102837.

[11] N. Wilson, E. Meiklejohn, B. Overton, F. Robinson, S.H. Farjana, W. Li, J. Staines, A physical allocation method for comparative life cycle assessment: a case study of repurposing Australian electric vehicle batteries, Resour. Conserv. Recycl. 174 (2021), 105759.

[12] Y. Al-Wreikat, E.K. Attfield, J.R. Sodré, Model for a payback time of using retired electric vehicle batteries in residential energy storage systems, Energy 259 (2022), 124975.

[13] X. Xu, W. Hu, W. Liu, D. Wang, Q. Huang, Z. Chen, Study on the economic benefits of retired electric vehicle batteries participating in the electricity markets, J. Clean. Prod. 286 (2021), 125414.

[14] J. Geng, S. Gao, X. Sun, Z. Liu, F. Zhao, H. Hao, Potential of electric vehicle batteries second use in energy storage systems: the case of China, Energy 253 (2022), 124159.

[15] Y. Wang, B. Tang, M. Shen, Y. Wu, S. Qu, Y. Hu, Y. Feng, Environmental impact assessment of second life and recycling for LiFePO4 power batteries in China, J. Environ. Manag. 314 (2022), 115083.

[16] J. Dunn, M. Slattery, A. Kendall, H. Ambrose, S. Shen, Circularity of lithium-ion battery materials in electric vehicles, Environ. Sci. Technol. 55 (2021) 5189–5198.

[17] X. Lai, Y. Huang, C. Deng, H. Gu, X. Han, Y. Zheng, M. Ouyang, Sorting, regrouping, and echelon utilization of the large-scale retired lithium batteries: a critical review, Renew. Sust. Energ. Rev. 146 (2021), 111162.

[18] L.C. Casals, B.A. García, F. Aguesse, A. Iturrondobeitia, Second life of electric vehicle batteries: relation between materials degradation and environmental impact, Int. J. Life Cycle Assess. 22 (2017) 82–93.

[19] Y. Zhao, O. Pohl, A.I. Bhatt, G.E. Collis, P.J. Mahon, T. Rüther, A.F. Hollenkamp, A review on battery market trends, second-life reuse, and recycling, Sustain. Chem. 2 (2021) 167–205.

[20] M. Wayland, Tesla Will Change the Type of Battery Cells it Uses in all its Standard-Range Cars, 2021.

[21] Lazard, LAZARD's Levelized Cost of Storage Analysis—Version 7.0, 2021.

[22] SEMO, Imbalance price report. https://www.sem-o.com/market-data/dynamic-reports, 2021.

[23] AEMO, Aggregated price and demand data [WWW Document]. URL, https://aemo.com.au/energy-systems/electricity/national-electricity-market-nem/data-nem/aggregated-data, 2021.

[24] S. Zhan, P. Hou, P. Enevoldsen, G. Yang, J. Zhu, J. Eichman, M.Z. Jacobson, Co-optimized trading of hybrid wind power plant with retired EV batteries in energy and reserve markets under uncertainties, Int. J. Electr. Power Energy Syst. 117 (2020), 105631.

[25] S. Banerjee, Contravention between NPV & IRR due to timing of cash flows: a case of capital budgeting decision of an oil refinery company, Am. J. Theor. Appl. Bus. 1 (2015) 48–52.

[26] N. Fallah, C. Fitzpatrick, How will retired electric vehicle batteries perform in grid-based second-life applications? A comparative techno-economic evaluation of used batteries in different scenarios, J. Clean. Prod. 361 (2022) 132281.

[27] A. Maheshwari, M. Heck, M. Santarelli, Cycle aging studies of lithium nickel manganese cobalt oxide-based batteries using electrochemical impedance spectroscopy, Electrochimica Acta 273 (2018) 335–348.

[28] L. Lam, P. Bauer, Practical capacity fading model for Li-ion battery cells in electric vehicles, IEEE Transactions on Power Electronics 28 (2013) 5910–5918.

[29] V. Viswanathan, K. Mongird, R. Franks, R. Baxter, 2020 Grid Energy Storage Technology Cost and Performance Assessment, Energy (2022).

[30] K. Mongird, V. Viswanathan, J. Alam, C. Vartanian, V. Sprenkle, R. Baxter, 2020 grid energy storage technology cost and performance assessment, Energy (2020).

[31] W. Cole, A.W. Frazier, C. Augustine, Cost projections for utility-scale battery storage: 2021 update. National Renewable Energy Lab. (NREL), Golden, CO (United States), 2021.