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A Review of Repurposing Lithium-ion Batteries for Household Applications

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Abstract: As global sales of electric vehicles are rising rapidly; vast amounts of end-of-life batteries are expected to need treatment in foreseeable future. Using second life batteries in lower demanding applications, could prolong the life of Lithium-ion batteries (LiBs), and in turn provide economic and environmental benefits. The household context is seen as a potentially huge market for second life batteries. This study tries to better understand the current state of repurposing batteries for household applications, by investigating 1) proposals for household applications, as well as their current market availability, 2) what are considered the main barriers for further commercial repurposing of EV LiB batteries, and 3) how design can contribute to extend the lifetime of EV batteries within household contexts. Findings indicate that repurposing LiBs for household applications proves to be technically feasible, provides environmental benefits. Several market offerings have been identified. Through the literature analysed, it is found that repurposing LiBs for household applications has mostly been investigated from a technical, economic, and business model perspective. Contributions addressing the end-user perspective remains a paucity – an important stakeholder within the household context.

Introduction

Global Sales of Electric Vehicles (EVs) have risen exponentially in the past years (IEA, n.d.). As the Lithium-ion-batteries (LiBs) are usually abounded when the capacity has dropped below 80%, vast amounts of End-of-Life batteries (EoL) are expected to need treatment in foreseeable future. Current recycling processes are mature enough to be implemented in large scale, but still unable to recover all critical materials present in LiBs (Börner et al., 2022; Chen et al., 2019). As part of a circular loop, repurposing EoL batteries for less demanding applications presents itself as an attractive step in order to exploit the maximum economic value, whilst at the same time minimize the environmental impact of lithium-ion batteries (Harper et al., 2019).

Stationary Energy Storage Systems (ESS) has been proposed as such a suitable application Second-Life-Batteries (SLB), in both larger industrial scale systems and smaller residential applications (Hossain et al., 2019). As a shift towards a decarbonized future, the recent rise of renewable energy systems in the household sector, is foreseen to create a huge demand on energy storage solutions (Fernández Bandera et al., 2023). A task which repurposed LiBs could technically fulfil (Börner et al., 2022; Martín et al., 2022). The market is seen to be potentially huge (Cready et al., 2003; Zhao et al., 2021), and has the advantage of smaller to handle systems compared to their industrial scale siblings. Coming-of-age market examples within this context are Xstorage by Eaton, and the BeeBattery Home by Beeplanet factory.

Besides technical and economic aspects the end-user plays an important role in the adoption of new business models, which in the given context would be a homeowner or resident. Within the field of design, innovation and well-designed products – central elements in a business model - come from the intersection between economic viability, technical feasibility and desirability incorporating human aspects. Interdisciplinary design methodologies such as described by Buijs (2003), or design thinking

(Brown & Katz, 2011), emphasises human aspects such as needs, context, values, problems and behaviours.

A fair body of literature addressing various aspects of repurposing LiBs has started to emerge (Hossain et al., 2019; Hu et al., 2022; Shahjalal et al., 2022). This study tries to better understand the current state of repurposing EV batteries for household applications, and how design can contribute to a further market upscaling. The goal of this paper is to determine the state-of-the-art scientific knowledge concerning 1) proposals for household applications, as well as their current market availability, 2) what are considered the main barriers for further commercial repurposing of EV LiB batteries, and 3) how design can contribute to extend the lifetime of EV batteries within household contexts.

Method

The study is conducted as a literature review, including scientific and grey literature. A combination of relevant key words such as repurposing, remanufacturing, refurbishing, reuse, second life, batteries, household and residential were used. After an initial screening and removal of duplicates a total of 191 conference and journal articles were found. Using the inclusion criterion that articles had to address the second life of LiBs in household or residential applications, a set of 15 most relevant and recent articles were selected for the final analysis. Emphasis was put on household applications within the European context. Snowballing from the selected articles led to another 7 papers. The database Scopus was used for the analysis, because of general excellence coverage of industrial design, engineering, and technology research. Market offerings presented in Table 2 were found through the analysed literature and further searching on the internet.

Background

From EV use to SLB

Through charge/discharge cycles and operation condition of EVs, different ageing mechanisms are introduced inside an EV battery. A typical ageing trajectory is depicted in Figure 1. The trajectory is near to linear in the first stage, passing EoL at 80%. In the second

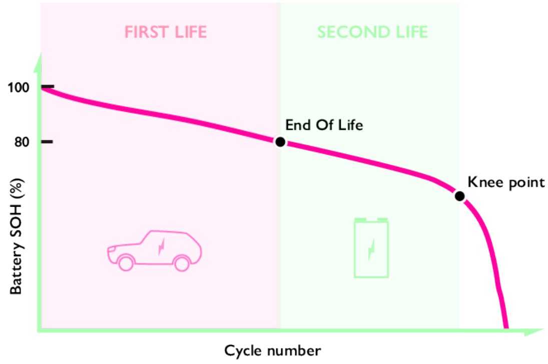

Figure 1. Ageing trajectory of LiBs. Adapted from Hu et al., (2022).

stage, a non-linear degradation is introduced after reaching the knee point. Due to safety concerns such as thermal runway leading to explosions and fires, all utilization of the battery should cease when the knee-point is reached (Hu et al., 2022). As indicated in Figure 1, a substantial number of cycles are still possible after EoL, before reaching the knee point (Hu et al., 2022). The total number of cycles before the knee point is also dependent on factors such as operating conditions in the first life, and battery chemistry (Hu et al., 2022; Martinez-Laserna et al., 2018).

At the EoL stage, LiBs are inspected and tested. Then a decision is made whether the battery pack should be reused, remanufactured, repurposed or recycled (Börner et al., 2022), based on SoH and lifetime expectancies. In the process of repurposing, the depth of disassembly (whole pack, module or cells) would impact cost, efficiency and safety (Hu et al., 2022). In a lower degree of disassembly, several components could also be reused, such as housing, busbars, battery management system (BMS) etc. (Montes et al., 2022). Direct repurposing of whole battery pack, being the most economically favourable option, would on the other hand provide uncertainty about the state of the modules and cells inside, which might lead to a shorter second life and cause safety concerns (Hu et al., 2022).

There are several uncertainties within the process of an EV battery emerging into a second life application. Montes et al. (2022) have developed a framework for battery assessment after first life which includes three stages (1) battery state evaluation, (2) evaluation of the technical viability of different solutions and (3) economic evaluation. Ideally one would seek for applications with a lower cycles rate and less power demands, which for example an ESS in a household context would represent.

Findings

Applications in research

This section presents applications studied and described in literature. In the context of household applications, it is found that repurposing LiBs as stationary storage for energy-time-shift strategies can help to reduce energy costs and relieve the electricity grid. According to the studies included in this work, the most promising solution seems to be a combination of ESS systems with photovoltaic (PV), as this allows households to maximise self-consumption. Table 1 gives an overview of relevant studies on ESS applications, mostly within the European context.

All studies analysed in this paper, investigated repurposed libs as energy storage within the household/residential context. Heymans et al., (2014) finds that a single ESS can shift the total energy consumption of 2-3 hours and calculates the benefits of peak-shaving on household level to be huge in grid scale. Repurposed libs as ESS are found to be technically feasible through several studies. Philippot et al. (2022) finds that an EoL of NMC-LTO chemistry can be used as an ESS for another 10 years, while Thakur et al. (2022) finds the extended lifetime to be 3-5 years in different combinations of vehicle to grid, PV and feed-in-tariffs. On the economical side, using repurposed ESS solely for load-shifting is found to be marginally profitable, and would to a large degree rely on governmental incentives in a Canadian context studied by Heymans et al. (2014). Repurposed batteries along with PV is found to have economic benefits for the homeowner, according to Assunção et al., (2016); Thakur et al., (2022). Nevertheless, there are notable discrepancies in cost calculations for the repurposing process of SLBs (Montes et al., 2022) and profitability (Martinez-Laserna et al., 2018). On an environmental note, Philippot et al. (2022) finds the second life duration, share of qualified batteries and the carbon footprint of the electricity mix to be important factors when considering reuse in EV vs repurposing. The repurposed ESS capability of household peak shaving and thereby reducing the use of gas-based peak-power is highlighted by Heymans et al., (2014); Martinez-Laserna et al., (2018) and Thakur et al., (2022) as another environmental benefit.

Applications in practice: examples of relevant market offerings

Several offerings based on repurposed batteries for the household context, are identified. Table 2 gives a non-exhaustive overview over examples of relevant business cases. Some of the cases have been identified through literature, but in order to provide an updated list, the list has been revised and expanded through resorting grey literature and the web. In line with the applications in research, most of the offerings are proposed for the ESS use case. One case is specifically targeting the Norwegian cabin market, which often are off-grid and relying on electricity by PV. An interesting concept is betterPack by Betteries, which provides a modular solution that can be used to power a variety of applications, such as electric vehicles, boats and replace generators in outdoor contexts. The case is not specifically targeting private households, but the offering is seen to be conceptually relevant. The company Hagal does not specifically address the household market but is included because of their new technology monitoring individual cells for better performance and safety (Bjørheim, 2022) which is seen to be relevant to the context of households.

Kielland & Skibstad (2022) interviewed manufacturers of SLBs in Norway, many offering solutions for the household context. It is found that the actors seemingly have managed to establish a customer base for their solutions. The main barriers pointed out in a Norwegian context, are the lack of market structure and national regulatory standards. Some of the actors also shares that they made a strategic choice to maintain a low price in order to get acquainted with the market and to attract customers. A low price whilst maintaining R&D activities, is made possible either by or in combination of public support systems, investors, and having other profitable branches (Kielland & Skibstad, 2022)

Relevant Use Case	Authors	EV Battery and Size	Method	Relevant findings	Region
Two scenarios for EOL LiBs investigated through LCA assessment: (1) SLB storage with PV in a Belgian Household and (2) reuse in EVs.	(Philippot et al., 2022)	Fiat 500x 7,6 kWh	Ageing test of NMC-LTO cells and empirical studies to model battery behaviour. LCA study of reuse in EV and repurposing as ESS.	Suitable for another ten years in a repurposed ESS. Repurpose scenario less polluting in a Belgian context compared to reuse in EV. Environmental benefits of repurposing depend on electricity mix and second life duration.	Belgium
Six different scenarios and two stages were designed to evaluate the benefits of EV LiBs for their full life cycle. In stage 1, the EV battery was used in the vehicle and in stage 2 it was repurposed as stationary energy storage. The six scenarios were combinations of Demand storage management, PV, vehicle to grid.	(Thakur et al., 2022)	Renault Zoe 41 kWh	Model based on datasets describing energy consumption of building, rooftop PV generation and wholesale electricity prices. Calendar and cycle ageing taken into account.	EV batteries can be extended 3-5 years as SLBs. SLBs can provide economic savings of 24%-77% depending on feed in tariffs and inclusion of PV, compared to the baseline scenario.	Zürich, Switzerland
SLB + PV in three different strategies. Two of them in the household context: 1) Maximising self-consumption in a Residential Household 2) Maximum self-consumption, Night cycle and peak shaving in Residential Household. And 3) fast charging of a city bus.	(Martín et al., 2022)	Nissan Leaf 4 kWh	Real life study of SLB + 4,5 kWp PV analysed and calculated for household context. Experimental validation for more than three weeks.	The two residential cases provide are experimentally validated. Strategy 1 and 2 provides a self-consumption of 59,8 and 58,9 %. Fast charging strategy (3) has higher degradation rate.	Navarre, Spain
Energy exchange to the grid with SLB and PV	(Assunção et al., 2016)	Nissan Leaf 24 kWh and Citroen C0 14,5 kWh	MATLAB simulation based on 2.4 kWp PV and a Nissan Leaf and a Citroen C0 were used for the analysis.	Even in the tenth year of operation the Nissan battery would allow for an reduction in the grid exchange of 79,7% for the Nissan battery, and 69,9% for the Citroen battery. The Nissan battery was break even after 9,53 years whereas the Citroen battery after 6,11 years.,	Portugal
Residential load following Investigating whether reduced electricity prices or auxiliary fees would encourage homeowners to acquire a SLB ESS.	(Heymans et al., 2014)	Chevrolet Volt 16.5 kWh	MATLAB Simulation Data from a residential Canadian load profile, and electricity pricing data used. Cycle efficiency taken into account.	A single ESS can shift 2 to 3 h of electricity used in a house. Incentives like reduced fees are needed to encourage implementation of Li-ion battery ESS. For only load-levelling, it is found to be economically favourable in the most optimistic conditions namely reduced auxiliary fees or big price differences between high-peak and low-peak hours.	Ontario, Canada

Table 1: Research studies investigating repurposed LiBs in household context.

Name	Offering	Region	Source
Eco Stor	First and Second life battery energy storage systems. Also offering household installations.	Norway	(ECO STOR, n.d.) (Bjørheim, 2022)
Beeplanet factory	Second life battery energy storage systems. Also offering household installations.	Spain	(BeePlanet Factory, n.d.)
Betteries	Second life battery energy storage systems. Modular solutions.	Germany	(Betteries AMPS, n.d.; Kuhudzai, 2020)
Eaton	Second life battery energy storage systems. Also offering household installations.	France	(*XStorage Home*, n.d.) (Bjørheim, 2022)
Alternativ Energi AS	Photovoltaic products sold in combinations with repurposed batteries as storage solution. Focusing on the Norwegian cabin market.	Norway	(Alternativ Energi AS, n.d.)
Hagal	Technology for monitoring and control individual cells. Factory built for repurposing.	Norway	(Hagal AS, n.d.) (Bjørheim, 2022)

Table 2: Relevant market offerings for the household sector.

Barriers and challenges

In the literature analysed, several barriers to a further market upscaling of repurposing LiBs for the household context have been identified (Table 3). The barriers and challenges are categorized into four levels from a household perspective: legislative, technological, market, and user.

On a legislative level, a lack of standards and regulations are seen to be an important barrier (Hossain et al., 2019; Hu et al., 2022; Jiao & Evans, 2018; Martinez-Laserna et al., 2018). This is also evident on a technological level, where a huge variety of types, forms, chemistries, and proprietary systems and information makes it difficult to achieve an efficient repurposing process according to Börner et al., (2022); Hossain et al., (2019); Reid & Julve, (2016). Several authors highlight the challenge of accurate Remaining Useful lifetime (RUL) predictions (Hu et al., 2022; Martinez-Laserna et al., 2018; Shahjalal et al., 2022), as this is seen to be vital ensuring safe and reliable operation of an SLB. Ineffective RUL predictions does also limit warranties and challenges liability (Börner et al., 2022; Bräuer, 2016). On a market level, repurposing costs are seen as an important barrier (Kielland & Skibstad, 2022; Montes et al., 2022). These are found related to a high degree of manual labour (Börner et al., 2022; Hu et al., 2022), and huge transportation costs due to the hazardous nature of Libs (Hossain et al., 2019; Jiao & Evans, 2018), amongst others. Safety is found to be another critical barrier as the high safety requirements for the operation in an EV would not change in second life operation within the household context (Börner et al., 2022), which is costly to ensure. Furthermore, (Shahjalal et al., 2022) underlines the availability of EoL batteries in need to be sufficient, and that an efficient production line and business models must be in place for a further upscaling of the repurposed LiB market.

The price fall of fresh batteries is indicated to become a potential barrier on a market level (Henze, 2022; Hossain et al., 2019), but is also seen to become a possible barrier at the user end. Shahjalal et al. (2022) argues that customers would rather choose new batteries when neglecting the environmental benefits of repurposed LiBs. According to Börner et al., (2022); Bräuer, (2016), a reduction in price must be given to the end-user for the disadvantage of reduced energy density and service life compared to new ones. Related to the safety aspect above, Börner et al. (2022) also exemplifies the consequences of a battery failure by referring to the Samsung Galaxy Note 7 case. The smartphone model had a battery design error that for some devices led to fire during charging. The product was taken of the market, and damaged customer trust.

Categories	Barrier description	Sources
Legislative	Lack of regulations and standards.	(Hu et al., 2022; Jiao & Evans, 2018; Martinez-Laserna et al., 2018)
Technological	Variable battery design, chemistry, and management system. Lack of design for disassembly. Lack of technology to perform automated repurpose process. High optimization for first life leads to mismatch for second life requirements. Unclear remaining useful lifetime, after EOL.	(Hossain et al., 2019; Martinez-Laserna et al., 2018; Montes et al., 2022) (Börner et al., 2022; Jiao & Evans, 2018) (Hu et al., 2022).
Market / SLB Repurposer	Battery availability. Price reduction of the new batteries. Transportation costs. Disassembly and repackaging costs. Liability. Limited data sharing between OEMs and repurposers.	(Shahjalal et al., 2022) (Hossain et al., 2019) (Montes et al., 2022; Zhao et al., 2021) (Börner et al., 2022; Jiao & Evans, 2018)
User	Safety and reliability uncertainty. Lack of awareness and information. Scepticism towards "used products". No incentives for using repurposed batteries, as is the case for other domestic green technology solutions (example from Norway).	(Börner et al., 2022; Hu et al., 2022) (Elkind, 2014; Shahjalal et al., 2022) (Jiao & Evans, 2018) (Kielland & Skibstad, 2022)

Table 3: Barriers for second life in household applications.

Consequently, the recall and lower sales figures led to Samsung loosing operating profits by 96% in the mobile division 2016 and shocked the whole mobile phone branch by reduced sales of 15% in 2016 (Edwards, n.d.). The case exemplifies that hazardous events can have severe negative impacts on stakeholders and highlights the effect of perceived trust. On a general note, Bräuer,(2016) calls for research addressing the challenges on the customer related to SLBs in the household context.

Potential solutions

A variety of potential solutions to the barriers above have been proposed in the analysed literature. Proposals such as the New EU regulatory framework for batteries (Halleux, 2021), which would require information on specification, and current state of the individual LiB to be easily accessible, is seen to have potential on the legislative level. On the technological level., cloud-based data gathering methods for RUL estimations as proposed by Li et al., (2021), and automated disassembly Zang & Wang (2022), could make the repurposing process more efficient, which also would benefit the market by reduced costs. Investigations of different business models is also found in i.e. Jiao & Evans (2018). These solutions would also address many of the barriers stated on the user level, nevertheless no material directly addressing the user is found in the analysed literature.

Discussion and Conclusions

Through the literature analysed, the household market is presented as potentially big, and a technically feasible way to locate EoL LiBs after an initial life in an EV, whilst providing environmental benefits before moving further to recycling. From a technical perspective, several studies have shown the feasibility of energy time shift and enhancing electricity self-consumption. From an economical perspective, studies i.e. (Assunção et al., 2016; Thakur et al., 2022) show that a combination with PV could provide savings for the homeowner. However, there is still uncertainty on the economic feasibility. Several examples of offerings have been identified, but these are arguably still to be seen as emerging.

Several challenges are recognized in literature on four different levels: legislative, technological, market and user (Table 3). Simultaneously literature also describes possible solutions, mostly on the technological and market level. Acknowledging that work is also being done on the legislative level, comparatively little research and insights can currently be found on the user level.

The success of business models concerning repurposed LiBs in a household context will largely depend on user acceptance, both objective and subjective perceptions taken into account. This comes forward in the current literature to the extent where only the lack of contributions on the user side in the development of a product-service system for repurposed electric vehicle batteries is mentioned (Bräuer, 2016). In the research studies analysed in this paper, the user is arguably seen as a consumer only considering the most profitable option in a specific context. But there are several aspects to consumer behaviour which are not addressed, as for instance needs, habits perceived benefits and perceived risks etc. Design research offers to investigate such perceptions and can inform business models to steer and focus offerings towards specific applications and user groups. The market example of Betteries would suggest that there are further applications than SLBESS for extended self-consumption, peak shaving and load levelling. The perceived safety aspect as indicated by (Börner et al., 2022), exemplifies the need for subjective factors to be taken into account. Furthermore, user research can investigate intrinsic and extrinsic motivations in order to raise awareness and desirability for SLB products, highlighted as important by Elkind (2014). By investigating the user perspective, business models can be informed to develop repurposed lithium-ion battery offerings that meet the specific needs and expectations of household users while ensuring safety and performance. This can lead to a more successful adoption of repurposed batteries in the household context, benefiting users, markets, and the environment.

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