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# Techno-economic feasibility of retired electric-vehicle batteries repurpose/reuse in second-life applications: A systematic review

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ABSTRACT

In line with the global target in decarbonising the transportation sector and the noticeable increase of new electric vehicles (EV) owners, concerns are raised regarding the expected quantity of Retired EV Batteries (REVB) exposed to the environment when they reach 70–80% of their original capacity. However, there is significant potential for REVB, after deinstallation, to deliver energy for alternative applications such as storing surplus. This systematic review evaluates state-of-art modelling/experimental studies focused on repurposing REVB in second-life applications. Technical and economic viability of REVB repurposing has been confirmed to solve the unreliability of cleaner energy technologies and mitigate the high investment of new storage systems. 40% of included studies considered hybrid systems with PV being a dominant technology where REVB was evaluated to be small-scaled and large storage systems. Additionally, successful attempts were conducted to evaluate REVB performance in providing grid services. It has however, been discovered intensive grid services applications like frequency regulation, was technically challenging due to demanding working requirements. Reviewed studies considered different prices for REVB due to lack of market regulation on REVB resale; similarly, technical parameters, including initial State of Health (SoH) and State of Charge (SoC) constraints were inconsistent due to lack of standardisation.

## 1. Introduction

According to [29], the share of electricity-powered cars has hit nearly 10% of the global car sales market in 2021, bringing the number of electric vehicles on roads up to 16.5 million. Additionally, electric car sales of the first quarter of 2022 outperformed the same period sales in 2021 by 75% which assures the global vision in electrifying the transportation sector. In agreement, a recent announcement has been made regarding the UK government's plan to in line with the government's substantial efforts in reducing pollutants emissions and acquiring climate targets [16] to phase-out Internal Combustion Engine (ICE) vehicles entering the market by 2030. To trigger a rapid energisation of the Electric Vehicle (EV) market, the UK government introduced funding schemes that offer contributions for eligible low-emission vehicle buyers and a further 75% contribution on purchase and installation costs of charge point via the Electric Vehicle Home Charger Scheme (Office for Zero Emission Vehicles, 2021). This has driven a rise in registrations of new EVs in the nation, as demonstrated in Fig. 1, there has been a 22.98% decrease in vehicle registration in 2021 compared to 2020. There has also been a noticeable increase in EV registrations, including Battery (BEV), Plug-in Hybrid (PHEV) and Hybrid Electric Vehicles. The aforementioned figures project encouraging numbers of electric vehicles on the UK roads in the upcoming years, reaching 49 million units in 2050 as per UK's target, particularly that petrol- and diesel-powered vehicles registration in 2021 experienced a noticeable decline in contrast to 2020.

Different types and models of EVs have different powertrain architectures; however, several core technologies, namely, battery, motor and electric drive, are dominant in all topologies. Although continuous monitoring of the healthiness of powertrain components occurs through management system technologies and periodic maintenance, yet battery-package becomes unable to perform as expected in a mobile application as it reduces the range of the vehicle when it reaches below 80% of its nominal capacity, which would require replacement with a newly installed battery. The substantial number of current and predicted functional EVs and the necessity of battery deinstallation after years of operation put forward several risks and opportunities.

Potential approaches for REVB after EOL are disposal, recycling and repurposing [1,25,27,35], where each method encounter risks and opportunities. Through conducted literature survey, Repurpose/reuse and recycle were used in conjunction; therefore, it is essential to define each

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**Abbreviations**

| | |
|---|---|
| **BEV** | Battery Electric Vehicle |
| **BMS** | Battery Management System |
| **EOL** | End-of-Life |
| **ESS** | Energy Storage System |
| **EV** | Electric Vehicle |
| **FCN-R** | Frequency Containment Normal Operation Reserve |
| **FR** | Frequency Regulation |
| **GHG** | Greenhouse Gases |
| **HEV** | Hybrid Electric Vehicle |
| **HUB** | Heterogenous Unifying Battery |
| **ICE** | Internal Combustion Engine |
| **LCA** | Life Cycle Analysis |
| **LMO** | Lithium-ion Manganese Oxide |
| **MHEV** | Mild Hybrid Electric Vehicle |
| **MSW** | Municipal Solid Waste |
| **NMC** | Lithium Nickel Manganese Cobalt Oxide |
| **NPV** | Net Present Value |
| **PHEV** | Plug-in Hybrid Electric Vehicle |
| **PV** | Photovoltaics |
| **RES** | Reconditioning with Energy Shuffle |
| **RES** | Renewable Energy System |
| **REVB** | Retired Electric Vehicle Battery |
| **RGS** | Reconditioning with Grid Services |
| **ROI** | Return on Investment |
| **SoC** | State of Charge |
| **SOH** | State of Health |
| **WT** | Wind Turbine |

term in the context of this paper. Repurpose or Reuse of REVB is the act of employing REVB in second-life applications, whereas recycling refers to methods conducted to recover resources (metals and other chemical materials) from the electrodes of the battery.

Retired EV battery-package if damaged, will be disposed of as Municipal Solid Waste (MSW) which would cause large undesirable waste to enter landfills. Discarding these batteries could potentially cause irreversible damage to the environment since they are made of heavy metals and chemicals [27,58]. Battery toxins have the potential to cause land and water contamination if soaked into the soil [8]. Habitats of thousands of living organisms could be compromised due to inappropriate battery disposal and chemical spillage [3]. Furthermore, transportation of the REVB to landfills could add to the greenhouse gas effect which is common with other REVB EOL approaches; repurpose and recycle.

Lithium-ion batteries (LIB) are widely used to power EVs; therefore, it is estimated that consumption of lithium elements will continuously surge due to (i) its low density and high electrochemical potential, allowing effective performance in dynamic and stationary applications [37] and (ii) availability of alternative battery storage system with equivalent behaviour is far from realisation [24,33,50]. Recycling retired LIBs saves 95%, 85% and 74% of the energy required to extract Aluminium, Copper and Iron, respectively, from virgin resources [38], hence mitigating a significant amount of greenhouse gas (GHG) emissions. Most of the current recycling technologies in developed countries' recycling facilities recover Nickel and Cobalt from spent LIBs and not Lithium [50]. According to [37], minimal scientific contribution to none, was found to address selective recovery of Lithium from retired LIBs, therefore improvements in current recycling approaches and development of new sustainable recovery methods of Lithium shall be carried out to obtain optimal management of Lithium resources. Pyrometallurgy methods have the potential to increase battery recycling capacity, however it requires high energy demand accompanied by toxins emissions and fails to recover high-quality Lithium [13]. Laboratory studies implemented successful hydrometallurgy recycling trials and demonstrated a high recovery rate and purity of resources [37]; this process involves leaching using inorganic acids and separation for strategic metals recovery [12]. Hydrochloric acid was used by [21] as a leaching acid, and results confirmed 99.4% recovery of Lithium from spent LIBs. However, it involves a complex and long process and requires significant financial investment [37,57], which could delay vast industrial implementation.

Another promising REVB EOL route is repurposing, in which modules are reassembled to meet the technical demands of less aggressive applications, including stationary energy storage applications. According to [25], repurposing REVB in secondary applications could result in reducing CO2 emissions by 65% in contrast to conventional energy generation. However, there exists a major technical challenge in that cascaded batteries shall undergo a process of several stages to operate safely and reliably in second-life projects, one of the commonly followed methodology is demonstrated in Fig. 2, which includes assessment, disassembly, clustering and reassembly [11]. Multiple stage processes would add financial costs to the initial capital cost of REVB which could divert investors' interest. Moreover, the difference in battery structure design and types used by EV manufacturers; makes the automated disassembly process of modules challenging [11,25].

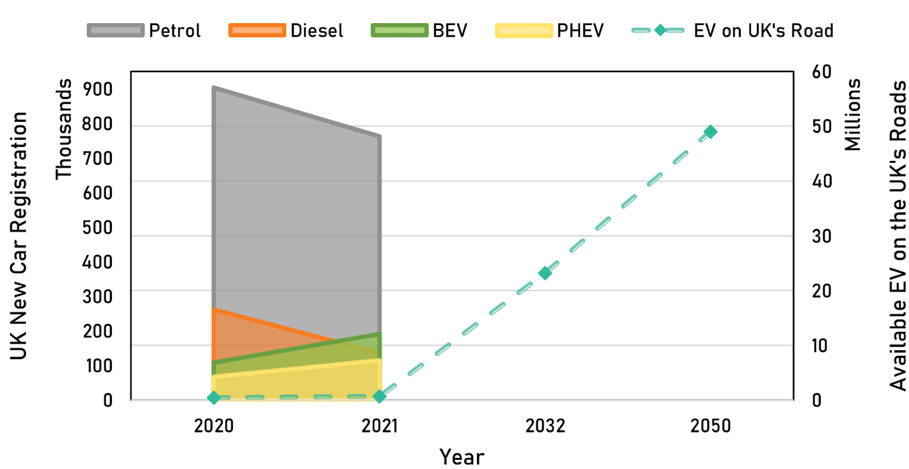


**Fig. 1.** New car registrations in the UK and estimated EV units on UK's roads, Data retrieved from: [49]; [14].

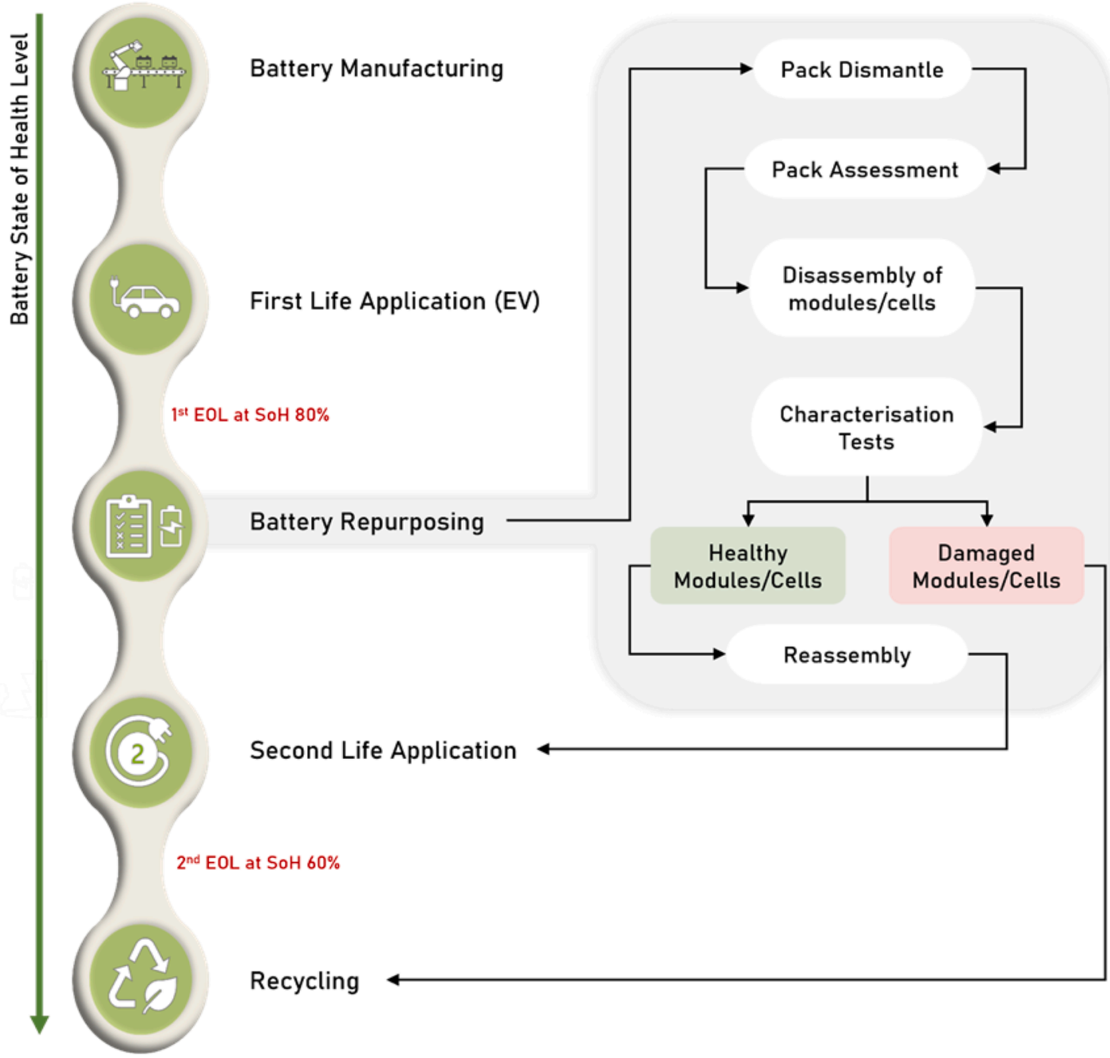


**Fig. 2.** REVB life cycle, adapted from [25].

However, there are other methodologies followed in industry that involves battery pack assessment and direct reuse in secondary applications without disassembling them to modules level which could mitigate the financial challenges accompanied with manual or automated modules disassembly and reassembly. Additionally, the figure shows second EOL of the battery as 60%, yet, this is not confirmed in literature and further research is required.

According to [30], the current world-wide energy catastrophe triggered the urge of accelerating cleaner energy production and emphasised the vital role of renewable energy technologies in the energy industry. In turns, grid-scaled energy storage has gained significant interest with the high low-carbon energy technologies penetration in energy production [32]. Energy storage systems (ESS) enhance the flexibility and reliability of renewable energy systems (RES) operation by shifting demand over time to reimburse instantaneous discrepancy between energy production and demand [22]. According to [18] the UK's RES generation in the third quarter of 2021, including solar, wind and hydro fell by 17% in contrast to the same quarter in 2020, due to less favourable weather conditions. This emphasises the challenges associated with RES production and solutions offered by ESS to compensate for these shortcomings in energy generation. Therefore, the UK government in 2022 awarded 7 million GBP funding to projects that develop advanced energy storage technologies to increase the resilience of RES generation, solve undesirable variations in energy production and increase low-carbon technologies' contribution to the UK's total energy production profile [17]. Realising the potential of integrating ESS in RES; reassembling REVB modules for repurposing in stationary RES applications could fulfil that requirement by providing techno-economic-environmental advantages, expanding the useful service lifetime of REVB and mitigating the initial high investment of fresh ESS. Examples of Industrial projects of ESS built from second-life EV batteries are described in [11,25,39].

There is a strong correlation between the technical performance of technological advances and their financial viability as it defines the critical parameters of decision-making with respect to investment and industrial implementation. According to [47], addressing the social, economic, environmental and technical aspects of a technology is an integral factor in decision making. Therefore, this paper aims to review the technical and economic perspectives of experimental and modelling experiments carried out to repurpose REVB in secondary applications. Economic and environmental aspects are excluded from the scope of this paper and shall be investigated further.

The remaining sections of the paper are divided as follows: Section 2 describes the contribution of this paper in contrast to previously published review papers, Section 3 demonstrates the methodology used to conduct the systematic review, Section 4 illustrates the outcomes of conducted review, Sections 5 and 6 critically evaluate and analyse the technical and economic aspects of second life batteries and Section 7 shows drawn conclusions.

## 2. Related work

Repurposing EOL EV batteries have attracted interest from a broad range of researchers to evaluate the technical and economic feasibility of second-life usage. Table 1 lists and describes previous work conducted to review the current state of REVB EOL.

The available literature review has drawn focus on finances beneath REVB second-life applications and the potential of being a successful sustainable business opportunity. Additionally, the process of Life Cycle Analysis (LCA) has been taken into consideration, analysing the environmental impacts of major phases of the reuse or recycling process. However, throughout the reviews it remains ambiguous on the technical challenges of repurposing REVB and what potential second-life applications have been evaluated to be successful; hence critical analysis of scientific field testing and computational modelling trials still need to be conducted. Previously published review papers have been majoritively narrative in scope, and there have previously been no systematic review papers published in this area. Hence, this systematic review paper aims to mitigate this deficit by investigating published research outcomes that discuss experimental/modelling experiments to evaluate the underlying innovative technical potential of REVB secondary usage and accompanied economics.

## 3. Methodology

The **first stage** of the systematic review was formulating a research question based on the gap analysis conducted in Section 2 on relevant review papers; the question addressed is '*How feasible is the reuse and repurpose of REVB in second life applications, from technical and economic perspectives*?'

**Stage 2** features the identification of a suitable search database; Engineering Village platform was considered as it features relevant indexing database, including Compendex, Inspec and Knovel, where the search command used was '(EV Battery) AND (Reuse OR Repurpose OR Recycle)'. The term 'Recycle' was included in the search command as some researchers cross-reference the terminology, referring to a second life.

In **Stage 3**, search results were screened and selected based on the following selection criteria:

| | |
|---|---|
| **Criterion 1:** | *Type of Paper:* Journal Article and Conference Proceedings OR Article. |
| **Criterion 2:** | *Year of Publication:* 2015 – 2022. |
| **Criterion 3:** | *Research Field:* Reuse/repurpose of spent EV battery packs in secondary applications. |
| **Criterion 4:** | *Content:* Studies addressing specific secondary applications from a techno-economic perspective are included. Studies addressing pure economics and Life Cycle Assessments are excluded. All Review Papers are Excluded. |

Criterions 1 and 2 were applied to the records automatically via the Refine feature in Engineering Village. The results were manually filtered against Criterions 3 & 4 of the selection criteria, and duplicate records were removed.

Selected scientific papers considering repurpose of REVB batteries are further classified based on the nature of the storage system application as demonstrated in Fig. 3.

## 4. Results

When search results were limited to years of publication being between 2015–2022, only 29.2% of articles were removed as illustrated in Fig. 4. This confirms that the development of sustainable reuse and recycling of spent EV batteries has gained researchers' attention in recent years to address the expected influx of REVB. Stages 3 and 4 included a screening of 400 records, and the majority of studies did not meet research criteria and were excluded, and only 3.54% (n=20) of all results (n=565) are included in the study.

The aforementioned search command was used to narrow the search results to only include those of interest. However, results have shown that the majority of studies focused on other research areas of REVB EOL as demonstrated in Fig. 5. Extensive research has been conducted on waste batteries management and supply chain techniques, demand and supply of critical metals and materials used in battery manufacturing. Along with newly developed design methods for energy storage devices manufacturing, circular economy models of REVB EOL and life cycle assessment studies analysing environmental-socio-economic pillars of battery production and EV takeover. As expected, an adequate number of articles were addressing REVB recycling approach as the search command included the term 'Recycle', which was also used as it could be easily used in conjunction with reuse. Furthermore, some records were inaccessible and duplicated, which were removed regardless of the addressed research field.

The global number of publications over time is illustrated in Fig. 6, growth behaviour of all studies is similar to included studies, however, there is a significant difference in the number of publications due to the focused research question discussed in this paper. Moreover, the linear trendline of included studies forecasts that there will be noticeable growth in publications considering reuse/repurpose of REVB over the upcoming years.

Interestingly, the largest number of papers considered in this study are publications of research centres and academic institutions located in China, as shown in Fig. 7. This could be due to the dramatic increase of EV sales in China in the past 5 years with particular emphasis on 2021's EV sales record where 3.3 million units were sold, outpacing global records [5]. However, evaluating the demographic distribution of publications concludes that development of sustainable reuse and recycle approaches of REVB is gaining global attention of both research centres and industries. Minimal contribution of UK research centres on the topic

**Table 1**
Published review papers on second-life EV batteries.

| No. | Title | Content |
|---|---|---|
| 1 | Feasibility of utilising second life EV batteries: Applications, lifespan, economics, environmental impact, assessment, and challenges [25] | • Review of state-of-art industrial projects.<br>• Economic and environmental evaluation of REVB.<br>• Comparative study on Residual Useful Life of batteries estimation methods.<br>• Challenges faced throughout second life batteries life cycle. |
| 2 | Circular economy considerations in choices of LCA methodology: How to handle EV battery repurposing? [45] | • Evaluation of available methods for REVB environmental impacts assessment.<br>• Presentation of Circular Economy considerations to support automotive original equipment manufacturers on REVB second life methodological decisions. |
| 3 | Towards sustainable business models for electric vehicle battery second use: A critical review [41] | • REVB repurposing assessment from a Sustainable Business Model perspective. |
| 4 | Transportation of electric vehicle lithium-ion batteries at end-of-life: A literature review [48] | • A study on challenges of repurposed and recycled REVB transportation and underlying costs.<br>• Regulatory framework and safety protocols of REVB shipment and storing in North America. |
| 5 | Recycle, Recover and Repurpose Strategy of Spent Li-ion Batteries and Catalysts: Current Status and Future Opportunities [20] | • A comprehensive review on metal recovery treatment approaches for spent lithium-ion batteries.<br>• Potential repurposing opportunities for recycled/recovered materials. |

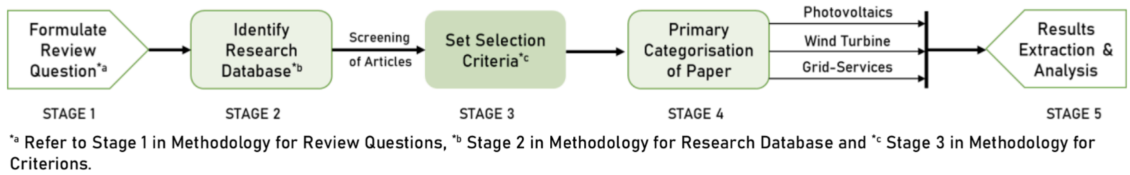


**Fig. 3.** Systematic Review Methodology. *a Refer to Stage 1 in Methodology for Review Questions, *b Stage 2 in Methodology for Research Database and *c Stage 3 in Methodology for Criterions.

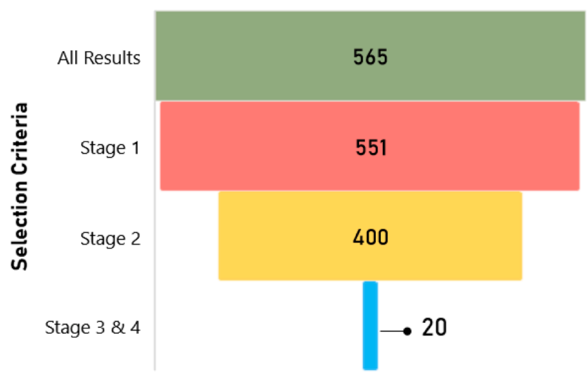


**Fig. 4.** Number of articles at each stage of selection criteria.

was present in the results, even though the quantity of EVs sold in the UK has witnessed a significant increase. This dictates that there is a necessity for funders to allocate funding to address the problem and for researchers to prepare proposals to call for funding. Table 2 lists relevant details regarding the studies included in this review paper.

A review of 21 papers that address specific scenarios of REVB repurposing in second life applications are included in this systematic review.

The returned results demonstrating repurpose scenarios for stationary applications with a focus on renewable energy systems are demonstrated in Fig. 8 divided into their respective categories. Repurposing REVB requires extensive technical and economic analysis with respect to the operating conditions of second-life applications. [55] investigated repurposing REVB in backup power, energy storage and grid frequency modulation applications. Backup power batteries are charged to provide energy once a sudden power outage occurs; hence, evaluating self-discharge characteristics is essential to determine the viability of used batteries. Results show a stable performance of the examined samples to be used as backup power systems as their discharge capacity was declining slowly while maintaining internal resistance constant as demonstrated in Fig. 9. However, within the associated study, constant internal resistance was obtained as the temperature was kept constant; variation in internal resistance could be noticed at different operating temperatures and SoC levels.

Fig. 10 demonstrates the effect of SoC and temperature on the

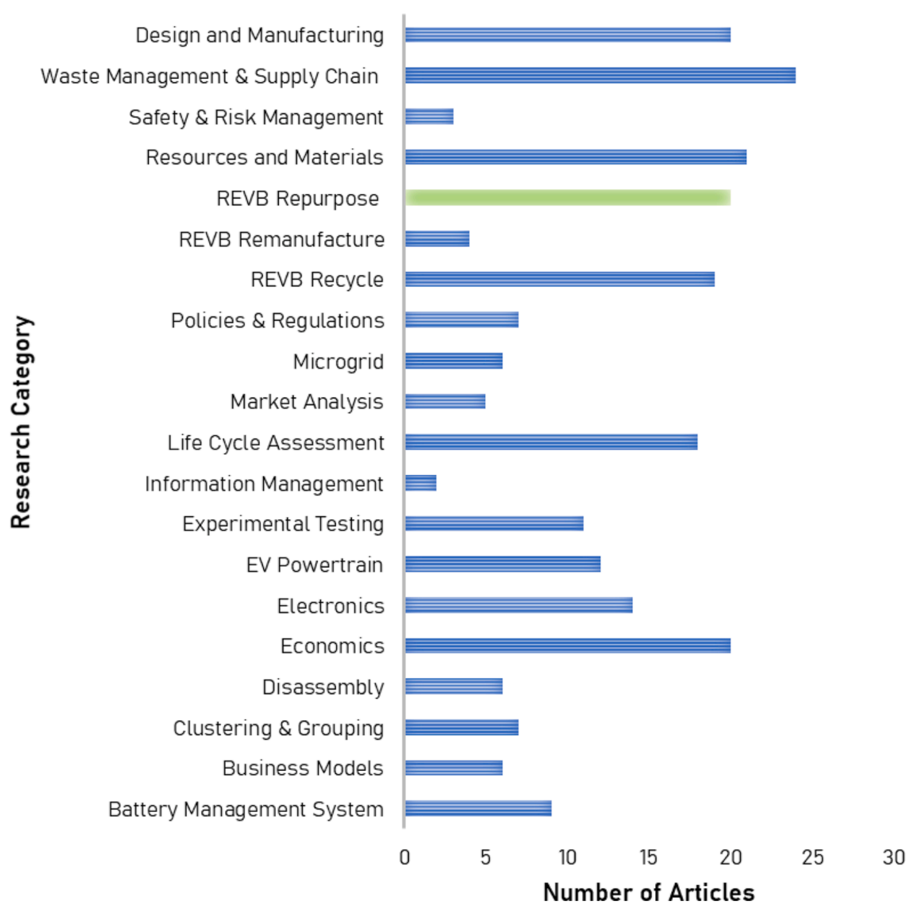


**Fig. 5.** Categorisation of screened records based on research area.

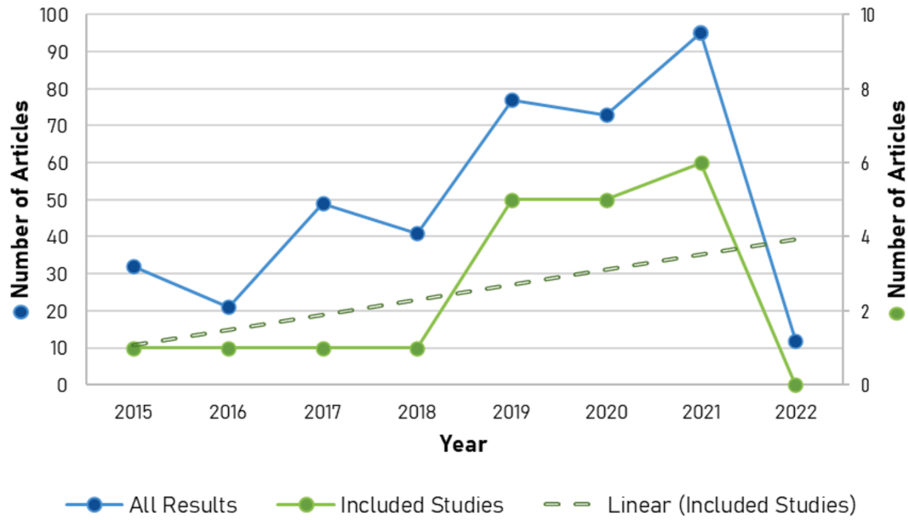


**Fig. 6.** Year-wise growth of publications.

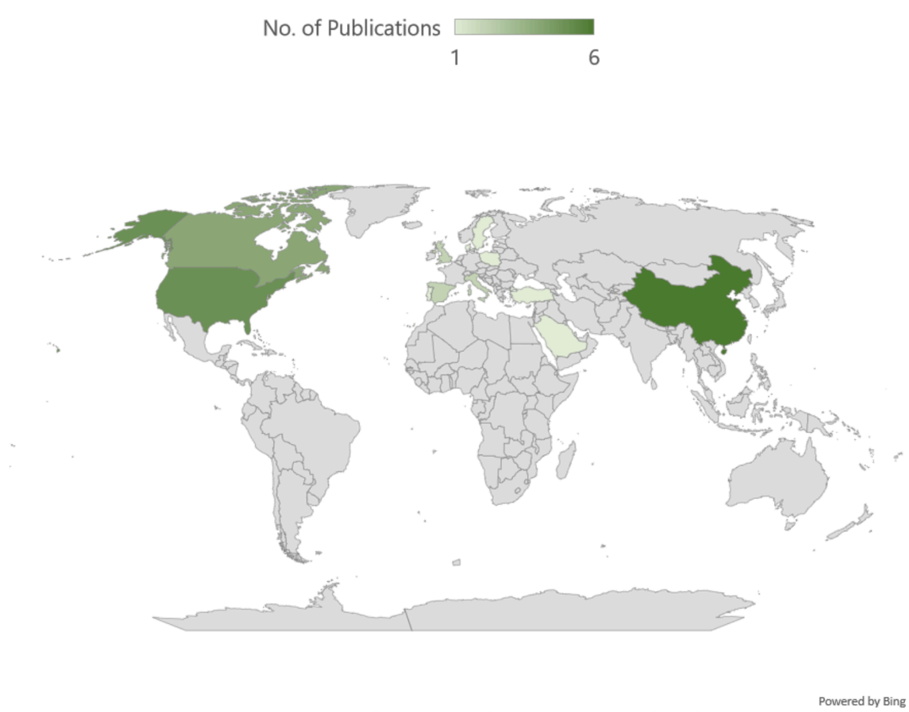


**Fig. 7.** Demographic distribution of reviewed studies with number of publications per country.

internal resistance of a battery and it can be noted that lower internal resistance values were obtained at higher temperatures whereas higher internal resistance at lower SoC levels. Furthermore, batteries were exposed to operating conditions of energy storage applications to solve the instability of renewable technologies' power production. Findings demonstrated that REVB could be used for a number of cycles exceeding 5000, particularly in low current density and large depth of discharge operating conditions. This indicates an encouraging potential for REVB repurposing in energy storage applications as experimental work confirmed that variations in capacity and internal resistance after a long period of time were minor, implying slow ageing behaviour of batteries.

For stabilising grid load and ensuring frequency rates are within smart grid standards ($\sim 50 \mp 0.2$Hz), a battery storage system would be required. When battery samples were exposed to working conditions similar to frequency modulation of smart grid applications, a significant reduction in batteries' internal capacity with a gradual minor increase of internal resistance was detected. With the obtained findings, it can be concluded that reusing REVB in smart grid frequency modulation applications is not technically feasible due to the intensive nature of its working requirements that could not be met by examined REVB characteristics.

Large-scale deployment of energy storage systems in microgrids is limited by a financial barrier, therefore [2] compare the installation costs of new and REVB storage systems using a novel microgrid planning model. Findings of the comparative study indicated that microgrid saves 1,321,514 USD (eq. to 985,486 GBP) when REVB system is installed. Nevertheless, the authors emphasise that it is essential to integrate a highly reliable Battery Management System (BMS) for the REVB storage system to ensure efficient performance.

[36] studied the economic feasibility of transforming small-scaled

**Table 2**
Studies included in the paper.

| Ref. | Paper title | Authors | Research institute(s) | Year of publication | Journal / Conference | Citations |
|---|---|---|---|---|---|---|
| [4] | Technical and economic assessment of the secondary use of repurposed electric vehicle batteries in the residential sector to support solar energy | André Assunção; Pedro S. Moura; Aníbal T.de Almeida | University of Coimbra | 2016 | Applied Energy Journal | 65 |
| [23] | Critical Power Demand Scheduling for Hospitals Using Repurposed EV Batteries | Denizhan Guven; M. Ozgur Kayalica; Gulgun Kayakutlu | Istanbul Technical University | 2021 | Technology and Economics of Smart Grids and Sustainable Energy | - |
| [53] | Repurposed electric vehicle battery performance in second-life electricity grid frequency regulation service | Chris White; Ben Thompson; Lukas G. Swan | Dalhousie University | 2020 | Journal of Energy Storage | 15 |
| [52] | Comparative performance study of electric vehicle batteries repurposed for electricity grid energy arbitrage | Chris White; Ben Thompson; Lukas G. Swan | Dalhousie University | 2021 | Applied Energy Journal | 5 |
| [7] | Life Cycle Assessment of repurposed electric vehicle batteries: an adapted method based on modelling energy flows | Silvia Bobba; Fabrice Mathieux; Fulvio Ardente; Gian Andrea Blengini; Maria Anna Cusenza; Andreas Podias; Andreas Pfrang | Joint Research Centre; Politecnico di Torino; Università degli Studi di Palermo | 2018 | Journal of Energy Storage | 84 |
| [10] | An evaluation framework for second-life EV/PHEV battery application in power systems | Songjian Chai; Ning Zhou Xu; Ming Niu; Ka Wing Chan; Chi Yung Chung; Hui Jiang; Yuxin Sun | Shenzhen University; Nanyang Technological University; State Grid Liaoning Electric Power Company Ltd.; The Hong Kong Polytechnic University; University of Saskatchewan; University of Liverpool | 2021 | IEEE Access Journal | - |
| [36] | Study on the economy of zero emission transformation of small coal-fired power plant based on SOFC and EV battery cascade utilization | S. Li; Y. Hu; L. Xiang; Y. Hu; Y. Zhou; Y. Chen | Xiangtan University; Hunan Electric Power Company | 2020 | 16th IET International Conference on AC and DC Power Transmission (ACDC 2020) | - |
| [28] | Modeling and multi-objective optimization of a stand-alone PV-hydrogen-retired EV battery hybrid energy system | Zhiyu Huang; Zhilong Xie; Caizhi Zhang; Siew Hwa Chan; Jarosław Milewskic; Yi Xie; Yalian Yang; XiaosongHu | Chongqing University; Nanyang Technological University; Warsaw University of Technology | 2019 | Energy Conversion and Management Journal | 52 |
| [56] | Co-optimized trading of hybrid wind power plant with retired EV batteries in energy and reserve markets under uncertainties | Sen Zhan; Peng Huo; Peter Enevoldsen; Guangya Yang; Jiangsheng Zhu; Joushua Eichman; Mark Z. Jacobson | Technical University of Denmark; SEWPG European Innovation Center; Aarhus University; National Renewable Energy Laboratory; Stanford University | 2020 | International Journal of Electrical Power & Energy Systems | 15 |
| [15] | Reuse of electric vehicle batteries in buildings: An integrated load match analysis and life cycle assessment approach | Maria Anna Cusenza; Francesco Guarino; Sonia Longo; Marina Mistretta; Maurizio Cellura | University of Palermo; University Mediterranea of Reggio Calabria | 2019 | Energy and Buildings Journal | 56 |
| [40] | Lithium-ion battery 2nd life used as a stationary energy storage system: Ageing and economic analysis in two real cases | H. Rallo; L. Canals Casals D. De La Torre; R. Reinhardt; C. Marchante; B. Amantea | Universitat Politècnica de Catalunya; SEAT S.A; Institut de Recerca en Energia de Catalunya; Av. Universitat Autònoma | 2020 | Journal of Cleaner Production | 18 |
| [55] | Study on the performance evaluation and echelon utilization of retired LiFePO4 power battery for smart grid | Xiaolong Xu; Jifu Mi; Maosong Fan; Kai Yang; Hao Wang; Jingbing Liu; Hui Yana | Beijing University of Technology; China Electric Power Research Institute | 2019 | Journal of Cleaner Production | 33 |
| [2] | Planning and Operation of Isolated Microgrids Based on Repurposed Electric Vehicle Batteries | Talal Alharbi; Kankar Bhattacharya; Mehrdad Kazerani | Qassim University; University of Waterloo | 2019 | IEEE Transactions on Industrial Informatics | 21 |
| [34] | Development and Demonstration of Microgrid System Utilizing Second-Life Electric Vehicle Batteries | Joseph Lacap; Jae Wan Park; Lucas Beslow | University of California | 2021 | Journal of Energy Storage | 3 |
| [46] | Reusing electric vehicle battery for demand side management integrating dynamic pricing | Shijie Tong; Tsz Fung; Jae Wan Park | University of California; | 2015 | 2015 IEEE International Conference on Smart Grid Communications (SmartGridComm) | 11 |
| [54] | Does energy storage provide a profitable second life for electric vehicle batteries? | Wei Wu; Boqiang Lin; Chunping Xie; Robert J.R. Elliott; Jonathan Radcliffe | Xiamen University; London School of Economics and Political Science; University of Birmingham | 2020 | Energy Economics Journal | 8 |
| [9] | Second-Life Batteries on a Gas Turbine Power Plant to Provide Area Regulation Services | Lluc Canals Casals; Beatriz Amante García | Universitat Politècnica de Catalunya | 2017 | Batteries Journal | - |
| [26] | Driving to the future of energy storage: Techno-economic | Noah Horesh; Casey Quinn Hongjie; Wang Regan; Zane | | 2021 | Applied Energy Journal | 4 |

(continued on next page)

**Table 2** (*continued*)

| Ref. | Paper title | Authors | Research institute(s) | Year of publication | Journal / Conference | Citations |
|---|---|---|---|---|---|---|
| | analysis of a novel method to recondition second life electric vehicle batteries | Mike Ferry; Shijie Tong; Jason Quinn | Colorado State University;, University of California San Diego; Utah State University | | | |
| [51] | Economic Analysis on Repurposed EV batteries in a Distributed PV System under Sharing Business Models | Yanyan Tang; Qi Zhang, Hailong Li; Yaoming Li; Boyu Liu | China University of Petroleum-Beijing; Mälardalens University | 2019 | Energy Procedia Journal | 7 |
| [42] | Economic Viability Assessment of Repurposed EV Batteries Participating in Frequency Regulation and Energy Markets | Sarah Robson; Abdullah M Alharbi; Wenzhong Gao; Amin Khodaei; Ibrahim Alsaidan | Smith College; University of Denver | 2021 | 2021 IEEE Green Technologies Conference (GreenTech) | - |

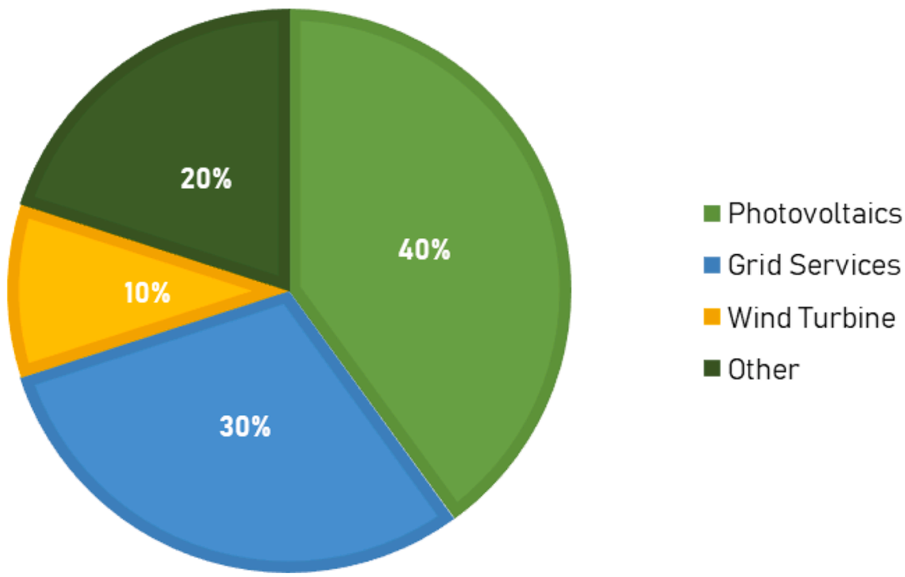


**Fig. 8.** Categorisation of reviewed scientific publications based on nature of secondary applications.

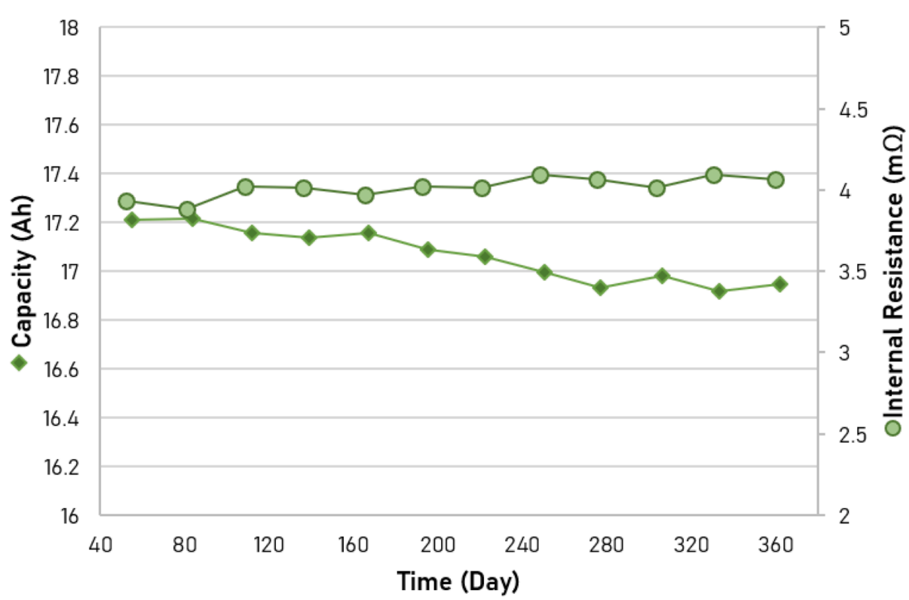


**Fig. 9.** Variation in capacity and internal resistance with respect to time under a back-up power discharging behavior, Data retrieved with permission from [55].

coal-fired power stations into hydrogen fuel cells plants with REVB systems, aiming to generate power with considerably lower emissions. The findings demonstrated that the proposed technology is economically unprofitable due to the expensive purchase cost of fuel cells and associated costs of technology development. However, the authors argue that it would be feasible in the future, particularly when

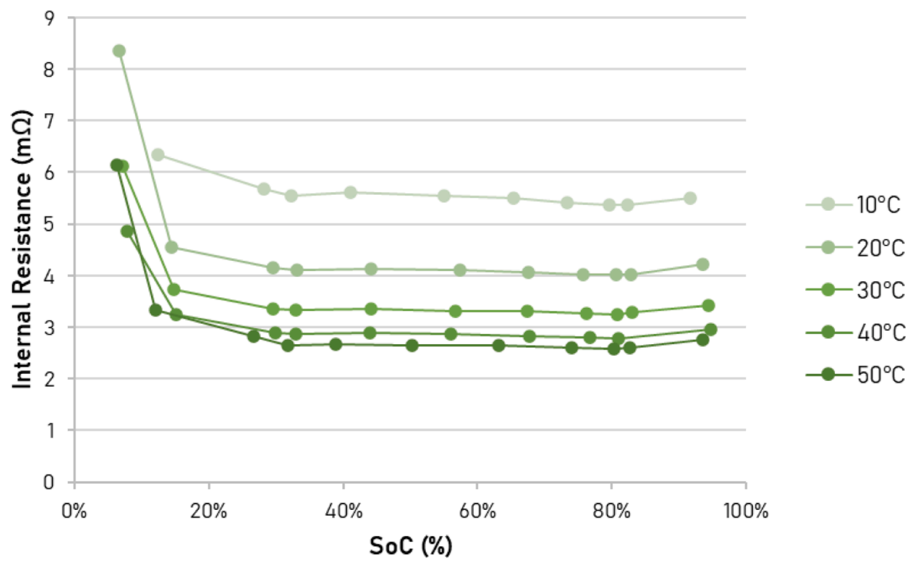


**Fig. 10.** Dependency of internal resistance (mΩ) on SoC (%) and temperature (°C), Data retrieved with permission from [34].

employed within green development cities. Considering the environmental advantages of the technology in mitigating tons of emissions caused by coal-fired power plants, its economic profile is significantly higher in contrast to other renewable energy technologies.

### 4.1. Energy systems with PV generation

The majority of studies (40% of included studies) considered hybrid systems with PV being a dominant renewable technology where REVB was evaluated to be small-scaled and large commercial storage systems. Applicable justification for adopting PV in most studies could include ease of small-scale experimental implementation, accessibility and low cost for research and development projects.

#### 4.1.1. Residential load profile

Multi-aspect investigation into reuse of REVB as a residential PV storage system was conducted to assess the technical and economic feasibility of second-life usage of REVB in RES [4]. A 2.4 kWp Photovoltaic (PV) array and 70% capacity Nissan Leaf (higher initial capacity) and Citroen C0 (lower initial capacity) REVBs were considered for the study. MATLAB Simulink was used to model the entire system composed of PV generation system, REVB with degradation effect and auxiliary devices, like boost converters to examine the performance of the proposed system in the long term. A BMS was developed to control the charging and discharging process of the battery to increase its Remaining Useful Life (RUL) and reduce the rate of degradation. Results have shown promising performance of the proposed system with appropriate controlling strategies to provide energy for the residential building. Only 17.9% of the first operational year load was fed from the grid, and the remaining energy was supplied by the PV system integrated with an energy storage pack composed of Nissan Leaf's retired battery.

Similarly, a system with a lower initial capacity REVB led to withdraw only 21.2% of the first year's load from the grid. Although one REVB had a higher initial capacity, similar performance was noticed in terms of reducing dependency on grid-fed energy. Therefore, a thorough analysis of the required energy storage capacity should be conducted depending on-demand load to avoid higher CAPEX (Capital Expenditure), since REVBs with higher initial capacity cost more. Moreover, results confirmed the cost-effectiveness of the proposed system as for the tenth operational year, both REVBs provided excellent benefits of reducing 79.9% and 69.6% of grid supply by large and small REVBs, respectively. Economic evaluation has confirmed that the payback period of the proposed residential storage system was 9.53 years for the Nissan Leaf and 6.11 years for the Citroen C0 battery.

A hybrid energy system for residential usage was proposed by [28] consisting of PV, hydrogen and REVB technologies with an appropriate optimisation method. The study includes mathematical modelling of the entire system with a simplified REVB capacity fade model to obtain power, SoC and capacity loss for an overall design perspective with a PV panel. For means of protection and optimal operation, a power management system was integrated to control power distribution among system components, focusing on REVB pack degradation. A multi-objective optimisation method was considered aiming to choose an optimum value of the system sizing variables. Simulation results of the optimization methods showed that the highest reliability of the system is achieved with a higher cost; similarly, adjusting the system to a relatively lower cost would lead to a fluctuated power supply and a less reliable system. Additionally, despite the economic benefits, the lowest reliable solution yields a higher energy waste which is a highly undesirable approach. Based on the discussed case study, it is essential to focus on the initial system parameters and sizing variables to have a reasonable and fair assessment of an energy system establishment. Similarly, REVB with the capacity fade model requires improvement to accommodate various working conditions and less idealised assumptions to obtain more precise results.

A comprehensive and adapted LCA framework was proposed by [7] that aims to examine the prospective environmental benefits of repurposing REVB to increase PV self-consumption of a residential building with a yearly consumption of 5.15 MWh. This assessment compares the following scenarios from a life cycle perspective; grid-connected house with 24 kWp PV installation and (i) fresh LMO/NMC energy storage device having a nominal capacity of 11.4 kWh and (ii) used LMO/NMC battery with 81.31% residual capacity. Model assumptions include a maximum DoD of 80% to prevent rapid degradation of the battery (maximum of one discharge cycle per day), and for each scenario, the model stops running when residual capacity hits 60%. Findings indicated that scenario (ii) enables mitigation of 93% of the Abiotic Depletion Potential of mineral resources and 58% of Global Warming Potential in contrast to scenario (i) life cycle. Study outcomes have verified the superior environmental advantages of replacing new energy storage devices with repurposed EV batteries in the abovementioned case study.

Specifications of the same LMO/NMC battery were applied in [15] study that aims to examine a system composed of an energy storage system made of REVBs and PV plant (24 kWp), installed in a grid-connected environmentally friendly residential building with yearly consumption of 25 MWh. Simulation of the energy system was conducted to compute enhancement in load match between PV on-site production and load profile, in addition to life cycle analysis of the examined energy system. 10 configurations of REVB storage system (9, 18, 36……90 kWh) were considered for simulation. Computational findings revealed that configurations 1 to 3 were not able to cover the entire examined timeframe (12 years), and REVB replacement would be required. However, configurations 4 to 10 were able to perform during the entire timeframe, which concludes that installing higher energy storage capacity systems yields to a longer lifetime. Furthermore, increased on-site PV generation was noticed in configurations with higher REVB total capacity, therefore, reducing reliance on grid electricity by a percentage ranging from 13% for configuration 1 and 53% for the 10$^{th}$ configuration. With regards to environmental analysis, installing REVB storage devices with increased capacity resulted in an enhancement in the overall environmental performance of the energy system, however, this would be an unfavourable economic consideration.

An experimental trial was conducted by [46] to investigate the reuse of REVB as a storage system in a power system composed of PV arrays (2.16 kW) and grid interface with appropriate side demand management of a family household. REVBs were assembled into 15 modules connected in series, where each module has 9 parallelly connected battery cells equating to an overall battery pack capacity of 12 kWh. The paper suggested integration of demand-side management strategy using day-ahead market prices forecasting data and customise energy management based on peak and off-peak hours for the following day accordingly. This allows the plant's management system based on SoC of the storage system and dynamic pricing to decide on excessive PV energy, either to be stored in REVB storage system or fed back to the grid and (ii) stored energy, either to discharge to the grid or support household demand. The examined system generated an average of 9.3 kWh of clean energy per day, where only 23% of stored energy was sent back to the grid, and 77% supported meeting household energy demand. Furthermore, PV-REVB system increased PV penetration by 69% and reduced grid energy withdrawal by 81%. Evaluating the technical viability of the proposed system for a small-scaled application was successful however commercialising the application will be dependent on REVB price, feed-in tariff prices and service lifetime.

#### 4.1.2. Commercial load profile

[23] proposed a linear programming power scheduling model of a grid-connected power system consisting of PV panels and spent EV batteries to ensure continuous electricity supply to a medium-sized hospital in Istanbul, Turkey to compensate for the consequences of a power outage. Essential constraints were set to adapt the model to the yearly demand of the sample hospital (2398.6 MWh), including uninterrupted supply throughout the day for critical hospital loads (emergency room, intensive care units and critical care resuscitation unit) and providing electricity continuously to operation theatres during office hours excluding Sundays. Technical characteristics of PV array (250 kWp) and REVB (100 kWh) were considered and repurposed REVB were set to fully charge only when the hourly grid rate is at the market clearing price. Results have shown that the annual demand of hospitals was met with a 9.4% reduction in electricity bills, saving 10,817.87 USD (eq. 8,067 GBP), 13.4% less dependency on grid electricity and mitigating 145.09 tons of $CO_2$ eq. emissions.

Correspondingly, [34] investigated the development of a commercially scaled microgrid that consists of a 164.5 kW PV system and 262 kWh REVB storage system (composing of REVB cells with an average SoH of 70%) to meet the load profile of 2 buildings with an average power consumption of 85 kW. The proposed system was designed, constructed and installed with a data server to store operational data, and SoC of the storage system was set to an upper and lower limit of 80% and 20%, respectively to slow the aging process of REVB cells, ensuring longer service life. These constrains restricted the actual usable capacity of the storage system to 157 kWh. Findings of the first operational year of the proposed microgrid showed an overall average reduction of 39% in peak-time energy use and 60% in maximum peak-time demand. Additionally, results showed that PV alone was not capable of substantially reducing demand charges in less preferable weather conditions in winter. However, integrating an ESS composed of REVB into the microgrid, ensured continuous operation of the microgrid to meet demand throughout the year resulting in enhanced performance and reliability of the microgrid and reduced energy costs. Further analysis showed that REVB storage system performed efficiently in contrast to other components, despite cells being moderately worn. Some technical issues were faced due to auxiliary electronics failure, unrefined control management strategy and poor BMS estimation of critical parameters. However, the study concludes that repurposing REVB in commercial-scaled applications is technically feasible, and no significant capacity variation was noticed after one year of operation.

[51] investigated economic analysis of REVB reuse in a PV system under a sharing framework, where it works by selling generated power from PV to the grid or other users in the community. The analysis model of this study included 4 cases; where cases (i) without REVB and shared PV, (ii) REVB without shared PV, (iii) REVB with shared PV among same category users (residential or commercial) and (iv) REVB with Shared PV among all users; schematic of scenarios is demonstrated in Fig. 11. Results of the model for 4 typical days of cases (iii) and (iv) showed a reduction in electricity expenses by 1.40 and 1.43%, respectively, in comparison to case (ii). Furthermore, PV self-consumption ratio was the highest for cases (iii) and (iv), reaching up to 99.71 and 100%, respectively, which exceeded the self-consumption ratio of case (i) by 7.57–7.86%. From an economic perspective, installing REVB with no shared PV equates to a negative Net Present Value (NPV) due to a relatively large investment of REVB initial cost. However, for cases (iii) and (iv), encouraging results were obtained in terms of REVB NPV due to the sharing business model approach.

### 4.2. Energy systems with wind turbine production

Examining an investment opportunity of installing spent EV batteries in operational offshore 21MW wind farms in Denmark to participate in the spot market and Frequency Containment Normal Operation Reserve (FCR-N) market was carried out by [56]. The proposed solution aims to normalise electricity price fluctuations, increase wind farm profitability and facilitate the repurposing of REVB in large-scale applications. Constrains and scenarios were modelled via the stochastic programming method. For retired batteries ESS, two cases were considered; namely, case (i) ESS composing of 1615 single REVB with 24 kWh capacity and 80% SoH; assumed to cost 15% of new battery pack price and (ii) ESS composing of 895 single REVB with 24 kWh capacity and 80% SoH; assumed to cost 30% of new battery pack price. Simulation results have revealed that both cases did not show encouraging results when the proposed system participated only in the spot market. However, highly lucrative results were obtained when the system forwards bids in FCR-N market. As for case (i), it would lead to 6.39 million DKK increase in yearly revenue and investment pay back in 4.27 years with 72.1% Return on Investment (ROI) over the wind farm's lifetime (assumed as 20 years). Similarly, case (ii) results showed that the system could have an increase in yearly revenue by 4.55 million DKK (eq. 0.5 million GBP) and investment pay back in 5.34 years with 37.07% ROI over 20 years. Despite the lower ROI of case (ii) in contrast to case (i) due to the initial higher price of REVB; the proposed hybrid system verified its financial benefits and could be a more profitable approach in the future, particularly since the prices of batteries are declining.

[10] proposed a framework to study the potential of installing REVB storage systems to mitigate forecast errors caused by load and wind turbine generation. Increased WT generation yields an increased number of forecast errors in the power system. The sensitivity study demonstrated that with 10% WT production, total cost savings remained

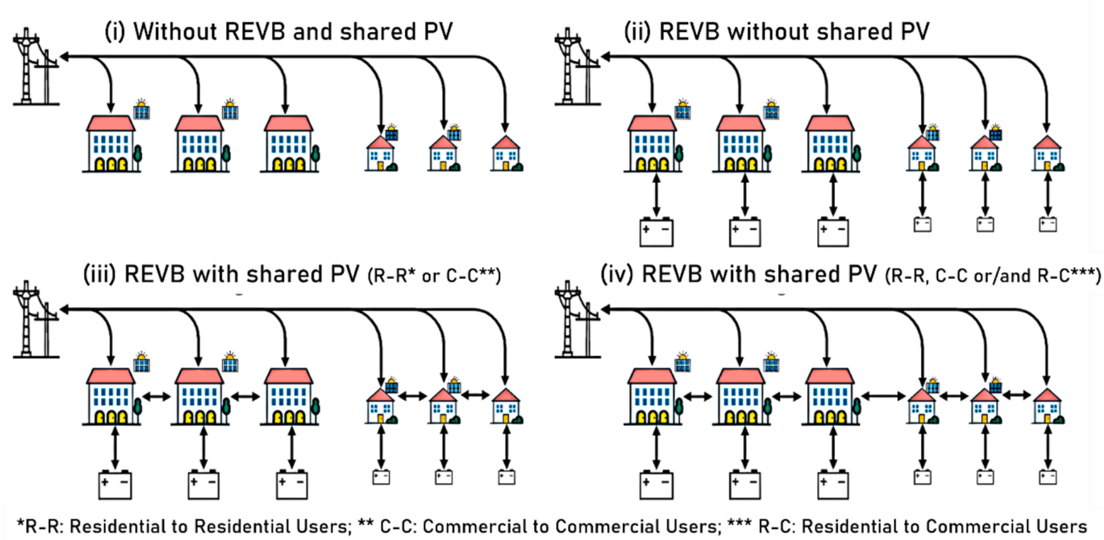


**Fig. 11.** Schematic demonstration of scenarios (i-iv), reused with permission [51].

approximately steadily low as demonstrated in Fig. 12 due to a few forecast errors. However, when WT generation ranged between 10% to 30%, cost savings experienced linear growth. After 30% of WT penetration, cost savings started to flatten, which is due to the limited capacity of the specified REVB storage system in the study. This emphasises the importance of appropriate sizing of ESS based on energy demand and capacity of the energy generation system as integrating a relatively low-capacity ESS in a high-capacity RES could result in minor cost savings or negative NPV.

### 4.3. Grid services

In addition to REVB integration with renewable sources, several attempts were conducted to evaluate REVB performance in providing grid services applications, where [42] compared REVB and new ESS performance for energy arbitrage and frequency regulation and the results confirmed the economic viability of REVB installation in grid services applications.

Moreover, [40] studied the integration of stationary energy storage composed of REVB in industrial applications to operate based on two grid strategies: namely, energy arbitrage and peak shaving. Energy arbitrage is a charging storage system during the lowest-priced period of the day, whereas peak shaving is charging batteries at the cheapest hourly rate and utilising it when the load exceeds maximum contracted power. The load profile of two industry cases was considered in the economic model developed in MATLAB: (i) a furniture factory with a contracted power of 80kW at tariff 3.0A and (ii) a hotel with maximum contracted power of 490 kW at tariff 6.1A. Simulation results have

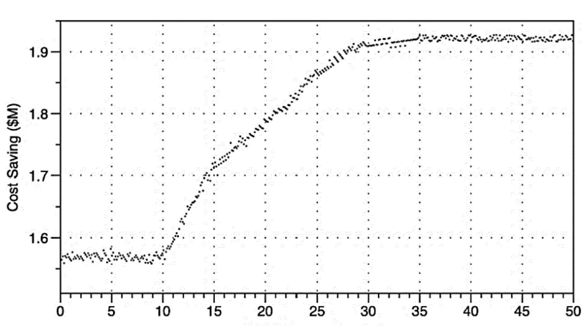


**Fig. 12.** Total cost saving in relation to WT penetration by [10].

revealed that the most suited capacity for cases (i) and (ii) are 200kWh and 5000kWh, respectively, which should achieve the highest financial savings. Moreover, for case (i), the investment payback period was calculated to be 11.33 years and an estimated system lifetime of 12.44 years, equating to 9.71% ROI. However, for case (ii) payback period is 18.21 years and an estimated lifetime of 13.07 years, resulting in –28.21% ROI; this is mainly due to the large investment in the 5000kWh energy storage system. Interestingly, it was noticed that the highest savings were obtained when the system operated on energy arbitrage strategy due to the constraint set for the peak shaving method. Based on the above findings, both cases are considered financially unfavourable due to negative gross profit in case (ii) and low profit in case (i).

In addition to RUL and load matching, other electrical energy performance metrics of REVB must be examined to gain a comprehensive technical feasibility study of investment. An experimental methodology was designed and conducted by [52] to evaluate the second life performance of seven different EV battery kinds with alternative characteristics using a duty cycle that emulates the behaviour of grid energy arbitrage service, where batteries are exposed to deep discharge cycles at 4h, 2h and 1h constant power rates. Electrical energy performance metrics of various battery samples were evaluated, namely, usable energy capacity, energy efficiency and energy density. To maximise the revenue of energy arbitrage service, it is beneficial to estimate the battery's ability to transfer a large amount of energy at quicker rates, and its ability to minimise losses and hence reduce waste energy. Experimental findings indicated that battery samples with higher energy efficiency had the highest usable capacity, which suggests a linear correlation between both metrics. Additionally, faster cycling rates resulted in lower energy efficiency and usable capacity, which could affect the profitability of characterised applications. As batteries with lower discharge capacity reduce revenue and lower efficiency percentage increases waste energy rates and hence increased energy purchase costs from the grid. Furthermore, in tests with a slower cycling rate (4h), variance in energy performance across examined batteries was minor, whereas, in tests conducted with 2h and 1h cycling rates, batteries were less efficient as both metrics experienced a reduction. In addition to profits, the footprint is an essential environmental and economical factor to be considered while deploying an energy system which emphasises the importance of evaluating the energy density metric of sample batteries. Results discovered that batteries with higher energy efficiency have lower energy density rates at all cycling rates performed. The inverse relationship between both parameters shall be examined thoroughly, taking into consideration the available resources for the project. For an energy arbitrage project with constrained space, REVBs with higher energy density would be suitable, however, energy efficiency could be lower, which could accompany increased energy purchase cost.

Another experimental study performed by [53] aimed to examine the energy and thermal performance of various slightly to moderately worn REVBs in Frequency Regulation (FR) grid service at several FR service offers. The findings of the study suggest that for batteries with similar nominal capacity, a battery with an active thermal management system could provide considerably higher FR power offers in contrast to passive thermal management equipped batteries. Although the thermal response of the active thermal management battery executed efficiently yields a higher revenue; the purchase price of the system is higher, hence a trade-off evaluation should be carried out based on the scope, deliverables and resources of the project. Furthermore, waste heat energy is reduced at higher energy efficiency which allows the battery to operate at higher FR offers. However, it was noticed that increased FR offers decrease batteries' energy efficiency, which could lead to increased losses and energy purchase costs.

[9] evaluated performance of REVB to be directly repurposed to support gas turbine systems that provide area regulation services under two operating conditions that vary in energy load aggressiveness. The main function of REVB storage system is to deliver or store energy in lack or surplus energy cases, respectively, to enhance the plant's response time to fluctuations and overall functionality. Results demonstrated variation in REVB degradation phenomenon, as it operated for 1508 full cycles on less demanding load requirements; in contrast, battery aging accelerated by 21.5% under higher load conditions where it operated for only 1241 full cycles until pre-set EOL at SOH 51.43%. Although the number of cycles is considered highly feasible for second life use, conditions considered in the study were 24 and 22 non-stop cycles per day which led life-span calculations to result in a lifespan less than 100 days. These conditions are not expected to occur in real scenarios, therefore realistic working behaviour of the system is required to obtain encouraging and reliable findings. REVB model used in the study considers linear battery aging, which does not consider nonlinear parameters, like ageing knee parameter, which is a setpoint where battery degradation rate accelerates.

In addition to the repurposing trials discussed, [26] presented a techno-economic analysis that evaluates reconditioning REVB using a Heterogenous Unifying Battery (HUB) system for two scenarios, namely, reconditioning with grid services (RGS) and reconditioning with energy shuffle (RES), where it aims to balance SOH of cells without disassembling and with continuous monitoring. RGS approach charges and discharges battery packs from and to the grid to implement required reconditioning at a particular time of the day, and RES charges the battery from the grid and discharges it to another battery which reduces the time of reconditioning as energy is not fed back to the grid. Both reconditioning approaches were compared with direct repurposing of REVB, and findings demonstrated that repurposing is the cheapest approach. However, all examined scenarios (RES, RGS and direct repurposing) are more economically profitable in contrast to the installation of a fresh energy storage system. All scenarios were determined to be highly economically feasible for power and energy applications; for the RGS scenario, the most economically viable applications were energy arbitrage and non-spin reserve; for the RES scenario, applications include demand charge reduction and frequency regulation. Despite promising results, reconditioning could impact the health of REVB pack since it involves extensive charging and discharging cycles which trigger the ageing rate and hence reduce service lifetime.

## 5. Critical technical parameters for second-life applications

Reviewed studies include experimental trials and modelling investigations of utilising spent EV batteries in second-life applications; therefore, the initial SoH of REVB at EOL is an essential technical parameter to estimate service lifetime. Illustrated in Fig. 13 is the initial SoH considered for each study; some studies include more than one initial SoH value due to the nature of experimental work adopted, [52, 53] conducted an experimental investigation on various types of REVBs with different initial SoH, ranging from 70% to above 90%. Batteries with SoH above 90% are considered operational for automotive applications and did not reach EOL. However, for the remaining studies, initial SoH ranged from 70 to 81.31%, the average of SoH values (excluding studies with multiple batteries) is 78.39%.

Furthermore, the residual capacity of REVB at EOL of second life application is an essential parameter that authors have used to identify the technical and economic feasibility of their hypothesis. As illustrated, specified 2$^{nd}$ life EOL among studies ranges from 50 – 60%; most economical and technical viability studies consider SoH within this range because it is unknown of REVB will be able to efficiently operate at a lower residual capacity. Additionally, due to degradation phenomena and particularly degradation knee parameter which is referred to as onset point when degradation rate transitions from low to accelerated. However, researchers are developing novel techniques to predict knee parameters of a battery using machine learning which will be efficient if integrated into a battery model and helps identify the approximate life cycle of the battery as in [19].

During charging and discharging of ESS, it is necessary to monitor SoC of batteries to ensure a safe and reliable operation. SoC margin used in studies (60% of included studies, n=12) is illustrated in Fig. 14, there is an evident difference in SoC constraints set by researchers. Upper SoC limit ranges from 80 – 100%, and lower SoC limit varies from 30 – 0%; 4 out of 12 studies specified maximum SoC as 80%, and the remaining studied considered SoC upper limit as 90% and above. Interestingly, [53] specified a lower SoC limit as 50%, which is higher than other studies and this is due to the nature of the application investigated. According to ISO 12405-4:2018, for life assessment batteries of electrically-propelled road vehicles, charge and discharge cycles shall be performed with SoC swing of 20 – 100% [31]. Evaluating SoC limits presented in Fig. 14 against standard requirements; all studies are within standardised SoC swing; besides lower SoC limits of 5 studies; where [9] however, this is focused on EV traction at first life. Therefore, it is necessary to set a safety margin for repurposing REVB to avoid accelerated degradation and to ensure a longer service lifetime due to their reduced residual capacity, particularly if repurposed in more aggressive scenarios. Significant variance in SoC margin and other technical parameters considered in the studies are a result of a lack of standardisation focusing on repurposing spent EV batteries. However, with the increased outlook on the topic, the Society of Automotive Engineers (SAE) has initiated efforts on developing the SAE J2997 standard, which scopes assessing REVB for safe second life applications; work is under progress [44]. Furthermore, a proposal for a standard for evaluating repurposed batteries is being worked on by UL to cover the clustering and sorting process of REVB intended for reuse [43].

## 6. Economic evaluation of REVB

No standard or regulation is addressing the resale price of REVB, therefore authors used estimated REVB costs in their economic models. Fig. 15 demonstrates the estimated REVB cost used in each study, as evident there is noticeable variation as some studies added up repurposing operational and labour costs, whereas others considered direct resale price. Hence, results were divided into 2 categories, namely: (i) REVB EOL cost and (ii) REVB EOL + repurposing cost; studies with estimated costs below GBP 50 are included in category (i) and the rest in (ii). The average of category (i) data equates to 36.91 GBP per kWh, which could be considered as direct resale price. Pricing of REVB is suggested to be denoted as a percentage of fresh battery price rather than a fixed value; this is because the capital cost of batteries is expected to dramatically decrease due to advances in secondary battery technology and increased demand. According to [6], the average Lithium-ion battery pack current price is 137 USD/kWh (eq. 103.56

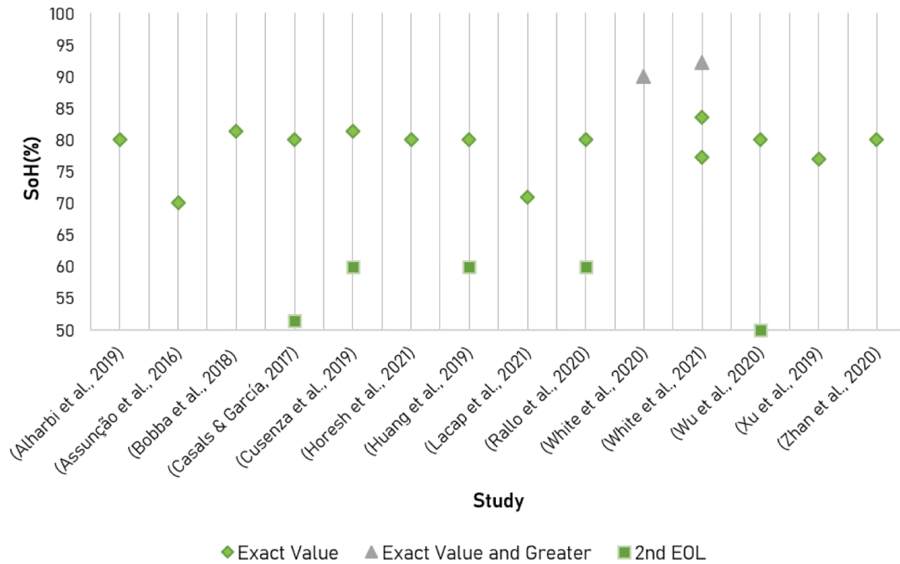


**Fig. 13.** Initial SoH of REVB used in modelling/experimental studies and specified SoH and 2nd life EOL.

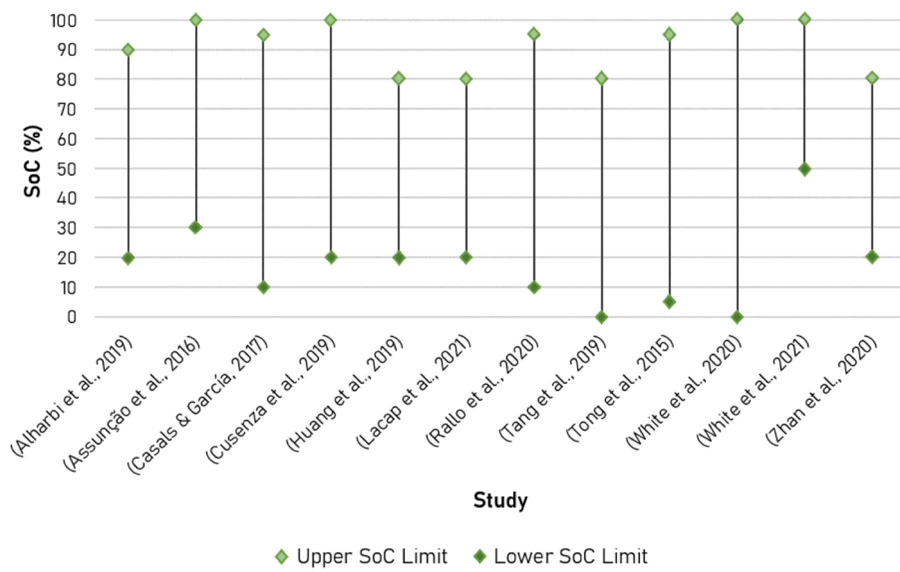


**Fig. 14.** SoC margin used per each study.

GBP), hence calculated average direct resale price equates to 35% (rounded to the first decimal place) of the new battery storage cost. A Lithium-ion battery price survey was carried out by [6] and observed an 18% learning rate when cumulative volume deployed on the market increases by double; based on this, battery pack cost is expected to hit 58 USD per kWh (eq. 43.80 GBP) in 2030. Considering 35% of new battery storage cost in 2030; REVB direct resale price is estimated to reach 15.33 GBP. Data included in category (ii) were not included in the calculations because [2] added up additional operational costs and [28] estimated REVB cost is based on a study conducted in an earlier period of time where energy storage devices were more expensive.

An economic assessment was conducted by [54] to evaluate the profit of reusing REVB in secondary applications where decision factors were based on battery remaining capacity, willing to sell factor and market price of a new battery. The evaluation included a model of REVB as an energy storage system operating based on energy arbitrage strategy. Results revealed that if an EV battery retires with 80% of its normal capacity and operates in second life applications until it reaches 50%, it is estimated to obtain 116 USD/kWh (eq. 86.50 GBP) profit and have a life span of 4.7 years (this is nearly 83.5% of new battery cost based on 2021 price market). However, this estimated profit is valid if the battery was abandoned at 50% of the remaining capacity therefore, there is further potential for the profit to be higher if REVB can be used for longer. Furthermore, the degradation rate considered in the study is based on constant laboratory test conditions; hence rate could vary in the realistic operating environment and with different battery types and brands due to differences in their chemical conditions. Evidently, higher remaining capacity and lower degradation rate would result in longer service time and hence could increase the profitability of the storage system but would increase the upfront cost. According to the willing to sell factor, it is suggested that maximum profit should be obtained from reusing REVB as the storage system is 100 USD per kWh (eq. 74.5 GBP), 77% is recommended to be an ideal remaining capacity for battery end of life.

Comparing the evaluated maximum profit of ESS operating as energy arbitrage application with calculated direct REVB resale price; a Benefit to Cost Ratio (BCR) of 2.02 is obtained, which indicates a positive net present value of the investment. Furthermore, these promising figures

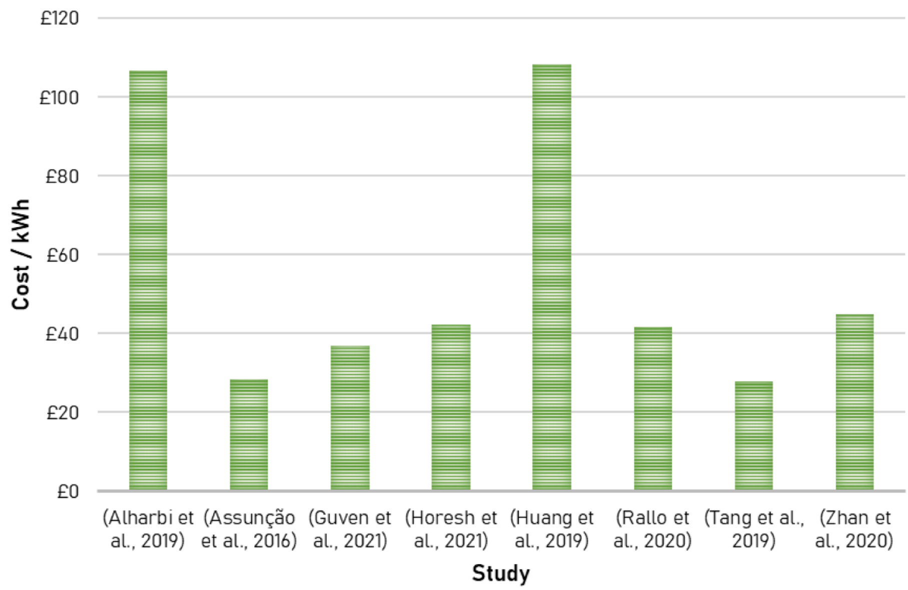


**Fig. 15.** Estimated REVB cost according to each study.

could significantly increase if REVB storage system service time lasted for longer than estimated and with the expected reduction in battery prices in the future. Nevertheless, calculated BCR does not consider REVB repurposing accompanied costs which could include labour, operational and acquisition costs; [2,28] evaluated repurposing costs of REVB with 80% SoH to be 58 - 59 USD (eq. 43.85 - 44.60 GBP). Adding 44.23 GBP to the direct resale price (36.91 GBP) and considering the evaluated profit of REVB with 80% used in energy arbitrage application (86.5 GBP); BCR equates to 1.07 which still indicates a positive NPV.

Referring to 50% of the research question stated in the methodology; it can be concluded that repurposing of REVB in secondary applications is highly feasible from an economic perspective.

## 7. Conclusion

Studies have shown promising results of repurposing REVB in second-life applications; all literature considered stationary technologies as second-life applications, and no contribution was noticed on less demanding mobile applications (like micro-EV cars or E-scooters). The majority of research was focused on the use of hybrid systems with PV technology, and this could be due to ease of access to data and equipment to conduct relevant research. Interestingly, residential and commercial-sized systems were studied, which encourages a wider range for REVB reuse as small and large-scaled ESS.

Experimental and computational modelling studies confirmed the technical viability of repurposing REVB to solve the unreliability of cleaner energy generation systems. However, using REVB in hydrogen fuel cell plants is a challenging approach due to the increased costs of fuel cells. Integrating ESS composed of REVB in a grid-connected PV system for residential load profile showed excellent technical and economic opportunities to meet energy demand and significantly decrease dependency on grid supply. Moreover, an essential framework to follow prior to ESS installation is conducting a thorough sizing analysis of required energy storage capacity based on the energy load profile to avoid increased CAPEX costs and payback period, ensuring a high rate of economic viability rate. In addition to reduced grid energy withdraw, PV-REVB system increases the PV self-consumption rate and production, which could be fed back to the grid, yielding an increase in the economic viability rate of the system if integrated with appropriate demand-side management strategies.

Similarly, REVB repurposing in commercial scaled applications was concluded to be techno-economically feasible with similar advantages obtained in residential profile scenarios. Furthermore, the minimal focus was drawn to other RES like wind turbine generation where only 10% of included studies considered wind turbine production; however, studies verified the technical and financial benefits of REVB integration in WT power systems. Integrating REVB ESS in hydro plants was not addressed by researchers; this could be due to the complexity of modelling/experimental work in contrast to other RES.

Besides examining REVB ESS in RES, 30% of included publications considered repurposing REVB to perform grid services, including energy arbitrage, frequency regulation and peak shaving. Most studies confirmed that although promising technical performance was noticed; repurposing REVB to perform grid services could be financially unfavourable due to intensive working requirements that yield to accelerated battery degradation and hence reduced service lifetime. frequency modulation of smart grid applications was found to be technically challenging due to the intensive nature of operating conditions that significantly accelerates the degradation of REVB.

Inconsistent constraints of SoC and EOL SoH were used among studies which are due to a lack of standardisation on utilising REVB in second-life applications. Initial SoH considered in reviewed studies ranged from 70 to 81.31%; 78.39% SoH was concluded to be a possible SoH of REVB at EOL from automotive applications. Specified 2$^{nd}$ life EOL among studies ranges from 50 – 60%; most economical and technical viability studies consider SoH within this range because it is unknown if REVB will be able to efficiently operate at a lower residual capacity. Similarly, different REVB prices were considered in each study which decreases the reliability of economic and technical feasibility of examined applications as the price is based on estimation rather than government regulations. The evaluated REVB direct resale price is 36.91 GBP per kWh obtained by taking the average of estimated REVB prices conducted by reviewed studies.

Various limitations were concluded from reviewed studies with major emphasis on the working behaviour considered to examine the technical performance of REVB as more realistic working conditions of assessed systems are required for reliable findings. Moreover, studies based on computational modelling used a simple REVB model with linear battery aging, which does not reflect the real characteristics of REVB. Therefore, an enhanced REVB model with capacity fade shall be developed using a dataset of REVB experimental assessments to obtain a more accurate prediction of REVB critical parameters. In addition, the authors focused on the importance of developing BMS with controlling strategies and thermal management customised for REVB to increase its

RUL and slow down the rate of degradation.

Reviewed scientific studies and BCR analysis conducted confirm the techno-economic viability of repurposing REVB in second-life applications including renewable technologies and grid services providing attractive investment opportunities that solve the expected issue of high influx of EV batteries and extend its lifecycle beyond automotive applications, implementing a sustainable circular economy approach.

## 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

No data was used for the research described in the article.

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