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Reuse of Electrical Vehicle Batteries for Second Life Applications in Power Systems with a High Penetration of Renewable Energy: A Systematic Literature Review

Reutilización de baterías de vehículos eléctricos para aplicaciones de segunda vida en sistemas eléctricos de potencia con una alta penetración de energía renovable: una revisión sistemática de la literatura

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Abstract

This article presents a systematic literature review on the reuse of electric vehicle batteries (EVB) for second-life applications in power systems. The end-of-life of these batteries represents a major environmental problem due to their composition and materials. The study aims to analyze the reuse of EVBs as a sustainable alternative for the environment. Additionally, it seeks to provide complementary services to facilitate the incorporation of intermittent unconventional renewable generation into the electrical grid. Through an exhaustive search of scientific publications indexed in prestigious digital catalogs and their subsequent systematic treatment, a selected group of 49 scientific articles published between 2018 and 2023 have been found in which the different opportunities, benefits and limitations of second-life energy storage systems oriented to boost a circular economy have been identified. The study concludes that, although the reuse of batteries has not yet been fully addressed or implemented due to existing challenges in terms of technology, costs, and regulations, it is of utmost importance to delve deeper into its analysis to improve efficiency and reduce the environmental impacts associated with the manufacturing, use, and disposal of such batteries.

Keywords: Battery energy storage system, Electrical vehicle, Second-life applications, Power systems, Renewable energy

Resumen

Este artículo presenta una revisión sistemática de literatura relativa al tópico reutilización de baterías de vehículos eléctricos (BVE) para aplicaciones de segunda vida en sistemas eléctricos de potencia. El fin del ciclo de vida de estas baterías representa un gran problema ambiental debido a su composición y materiales. El estudio tiene por objeto analizar la reutilización de las BVE como una alternativa sostenible para el medioambiente y, además, para brindar servicios complementarios que faciliten la incorporación de generación renovable no convencional de carácter intermitente a la red eléctrica. A través de una búsqueda exhaustiva de publicaciones científicas indexadas en catálogos digitales prestigiosos y de su posterior tratamiento sistemático, se ha llegado a un número selecto de 49 artículos científicos publicados entre 2018 y 2023. En ellos ha sido posible identificar las diferentes oportunidades, beneficios y limitaciones de los sistemas de almacenamiento de energía de segunda vida orientadas a impulsar una economía circular. El estudio concluye que, si bien la reutilización de baterías no está plenamente tratada ni implementada, debido a que aún enfrenta desafíos en términos de tecnología, costos y regulaciones, es de gran importancia profundizar su análisis para mejorar la eficiencia y disminuir los impactos ambientales que provocan su fabricación, uso y desecho.

Palabras clave: Sistemas de almacenamiento de energía en baterías, vehículos eléctricos, aplicaciones de segunda vida, sistemas eléctricos de potencia, energía renovable

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1. Introduction

The concerning statistics outlining the decline of fossil fuels and the consequences the world faces due to climate change have driven the development of new technologies. Among these innovations, the electric vehicle (EV) has emerged as a standout solution [1]. The escalating focus on decarbonizing transportation has resulted in a surge of electric vehicles on our roads, necessitating a continuous supply of charging infrastructure. As electromobility (EM) becomes more relevant for users, the demand for secondary batteries, also called rechargeables [2], increases. Among all the currently available options, lithium-ion batteries play a prominent role in the application of electric vehicles [1].

The demand for lithium-ion batteries has significantly increased in recent years due to the growth of the electric vehicle market. Although these batteries can last several years, they eventually lose their ability to hold a charge and must be replaced. Proper disposal of these batteries is crucial to prevent the release of toxic chemicals and reduce environmental impact [3]. In this context, electric vehicle battery reuse has emerged as a sustainable and cost-effective alternative [4]. Although the batteries may not be suitable for vehicles after losing their capacity, they can still have significant value for energy storage applications within a power system, as reported in studies in [5–8].

Beyond the environmental benefits, battery reuse can also be economically profitable [9] since a significant reduction in the cost of energy storage systems (ESS) and other products relying on lithium-ion batteries can be achieved for secondary applications. This becomes particularly important as the demand for ESS increases to support the integration of intermittent renewable energy sources into power systems.

Regarding electric vehicles (EVs), a battery is considered to have reached the end of its useful life when its charging capacity falls below 80% of its nominal capacity [10]. As a result, it is foreseen that in a few years, the storage of used EV batteries will become a significant problem from various perspectives. Finding an efficient way to recycle or reuse them is a sensitive environmental issue. However, the fate of EV batteries will depend mainly on charging habits and the temperatures to which they have been exposed. If a battery is in good condition, its components could be used as spare parts for other similar systems [11, 12]. A battery in good condition should maintain an acceptable storage capacity (generally above 80% of its nominal capacity), be physically intact without significant damage, have remaining life cycles, maintain proper chemical condition, have been operated under suitable temperature and charging conditions, and be equipped with effective battery management and communication systems. Otherwise, they could be used as a means to store energy in conjunction with distributed generation systems [13], such as photovoltaic [14] or wind generation [15]. With the notable increase in the use of renewable energies worldwide [16], the need to store surplus generated energy has become crucial. Currently, ESS play a pivotal role in ensuring stability in distribution systems (DS) during periods of high or low demand. For this reason, in the future, the inclusion of battery systems in DS should be considered, which could contribute significantly to reducing energy costs and improving specific quality indicators of the electric supply affected by the massive integration of renewable generation with high variability [17, 18].

The planet's resources are limited, and their extraction from nature often involves complex engineering processes. Therefore, it is necessary for all engineering fields that have contributed to the development of EVs to collaborate to find the most suitable environmental solution, considering the construction, maintenance, and recycling of batteries [19]. To address this issue, this article presents a systematic literature review focused on searching for technological solutions to reuse EV batteries for energy storage applications and providing ancillary services to power systems to facilitate the widespread integration of renewable energy. This review considers research conducted in the last five years by scientists and researchers worldwide.

2. Materials and methods

The systematic process of searching for literary sources that enrich the content of this research is carried out using the documented bibliographic review methodology, according to Codina [20]. The final result will be a systematic review based on high-quality scientific articles published, focusing on the reuse of EV batteries. Prestigious databases such as Web of Science, Scopus, and IEEE Xplore have been used as sources for searching bibliographic resources. Figure 1 shows a flowchart illustrating the procedure followed for selecting the studies.

2.1. Inclusion criteria

The literature review encompasses the search period from 2018 to 2023, employing the keywords: "second-life electric vehicle batteries," "renewable energy," and "grid support." Articles in English that are fully available online and address the reuse and/or recycling of EV batteries have been selected. The digital databases considered in this study are recognized for their prestige in the academic and research domains and for being subscribed to by many academic and research institutions worldwide. This makes them essential sources of information for a broad community of researchers, professors, and students. Therefore, accessibility to these resources is a crucial factor that must be considered in a systematic literature review Table 1 provides a concise summary of the selection criteria employed in the systematic review.

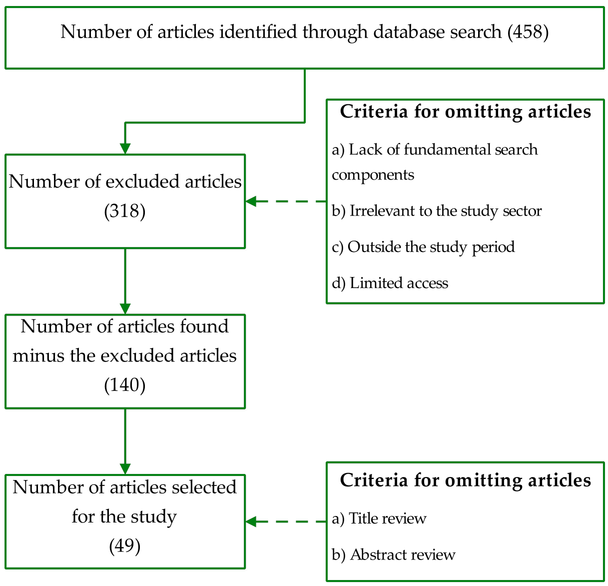

Figure 1. Flowchart of the process followed for study selection

Table 1. Criteria for article selection

Article	Selection criteria
Sector	Electrical engineering, renewable energy, sustainable technology
Language	English
Sources	Web of Science, Scopus, IEEE Xplore
Year of publication	2018-2023
Accessibility	Online access, full text
Relevance	Reuse of EV batteries with renewable energy
Search string	"Second-life electric vehicle batteries" AND "Renewable energy" AND "Grid support"

2.2. Study selection

The initial search yielded a comprehensive set of 458 scientific works. Subsequently, 318 articles were excluded due to the lack of fundamental search components (title, abstract, and keywords) and because they were outside the study period or had limited access, thus reducing the number of articles to a total of 140 with the characteristics shown in Figures 2 and 3. After reviewing the title and abstract of each article, 49 articles were selected to serve as the foundation for this study. This meticulous curation represents the essence of a systematic literature review, ensuring the incorporation of studies characterized by quality, relevance, and accessibility.

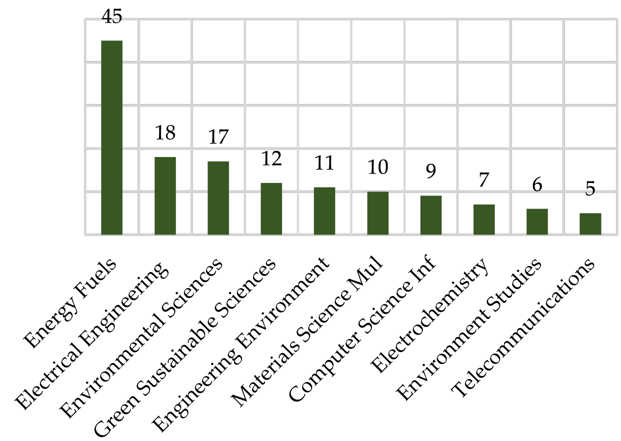

Figure 2. Classification of articles by areas Source: Web of Science

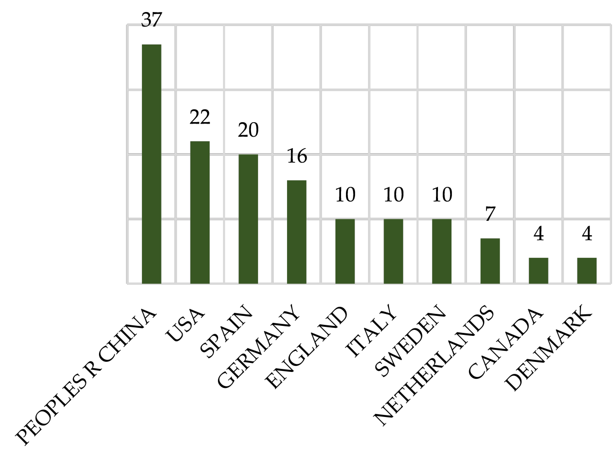

Figure 3. Classification of articles by country Source: Web of Science

2.3. Bibliometric analysis

Once the articles that meet the inclusion criteria defined in section 2.1 are selected, bibliometric analyses are conducted using the open-access program VOSviewer. This allows for exploring the relationships between the articles and presenting a graphical analysis showing nodes represented by keywords and the links or connections between each article. The position of the nodes in the visualization is determined by the clustering algorithm used by VOSviewer.

After selecting the articles for the study, they were imported into VOSviewer (version 1.6.19) [21], where a co-occurrence analysis was conducted to assess the relationships between the articles based on keywords. Finally, a network visualization was generated to facilitate the scientific literature's exploration and analysis of patterns.

Figure 4 shows the network visualization identifying four emerging groups. Four main clusters related to lithium-ion batteries, electric vehicles, second life, and energy-storage can be observed.

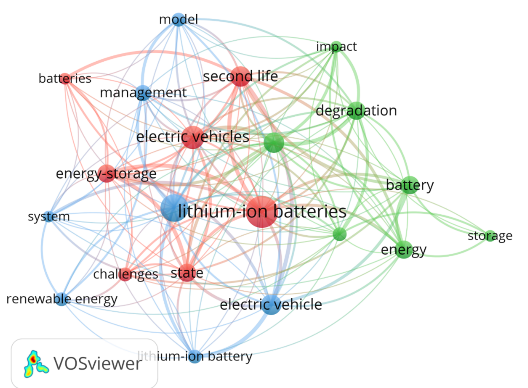

Figure 4. Network of words obtained through bibliometric analysis using the open-access program VOSviewer

3. Results and discussion

Figure 5 illustrates the evolution of bibliographic material related to the reuse of EV batteries between 2018 and 2023. The selection of studies to support this systematic review revealed a significant increase in publications starting in 2018, further escalating in 2022. This upward trend continues in 2023, considering the substantial number of articles published in the early months of this year. This indicator demonstrates the current relevance of the topic addressed in this study, whose fundamental aspects will be discussed in this section.

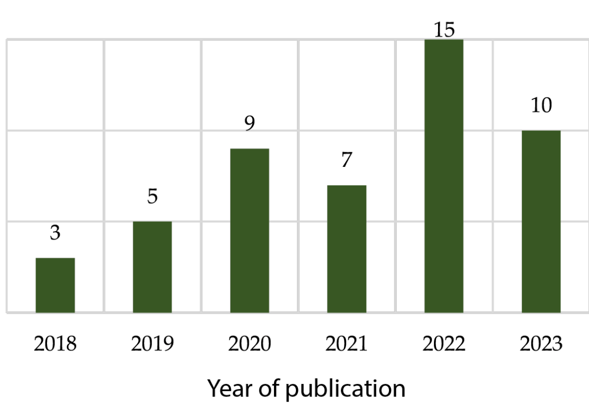

Figure 5. Classification by year of the selected publications

The following is a critical analysis based on the comprehensive review of the 49 selected articles, which address the challenges or barriers currently faced by reusing electric vehicle batteries. Additionally, some benefits offered by reusing to various stakeholders are highlighted, as well as the sectors interested in providing second-life to these batteries. Finally, the results obtained through the literature review on renewable energy storage in the second-life of EV batteries are presented.

3.1. Barriers and benefits of the reuse of EV batteries

In practice, projects involving the reuse of EV batteries seek to reduce dependence on fossil fuels [1], enhance the electrical grid's stability, reduce energy costs, etc. The inclusion criteria for renewable energies may vary depending on the specific focus and objectives of the study or project.

3.1.1. Barriers or limitations

- **Battery Type:** Not all available batteries are suitable for reuse projects. Primarily lithium-ion batteries will be reused because among their fundamental characteristics, they exhibit high specific energy and energy density, enabling them to operate in extreme temperatures and for more extended periods. This is in contrast, for example, to nickel-cadmium or lead-acid batteries, which tend to be discarded. Additionally, lithium-ion batteries are manufactured with more environmentally friendly materials [22].

- **Battery condition:** The condition and functionality of a battery must be determined [8–10]. Batteries in good condition can be reused for energy purposes, while those in poor condition may require repair or recycling processes.

- **Scale of use:** It is necessary to define the scale of use for the batteries, determining whether they will be used in small or large-scale projects [5]. This can influence the choice of storage technology and how the batteries will be integrated into the power system.

- **Storage technology:** It is necessary to determine the storage technology that will be used to reuse batteries, such as stationary or mobile storage [23]. Each technology has its specific characteristics and requirements, so it must be determined which one is most suitable based on the requirements of the final application.

- **Regulatory framework and Grid Code:** There should be a regulatory framework and Grid Code governing the reuse of EV batteries in the context of renewable energies. These regulations could include incentives or subsidies. In the European Union, new battery-use measures were implemented at the end of 2022 to increase the recycling of all types of batteries. The aim is to achieve recycling rates of 45% by 2023, 63% by 2027, and 73% by 2030 [24, 25]. On the other hand, in Spain, Real Decreto 265/2021 was enacted in April 2021, addressing the treatment of EVs at the end of their useful life and the handling of all their parts [26]. This aspect is crucial for fostering project initiatives in this field.

3.1.2. Benefits

- **Environmental impact:** It is essential to assess the environmental impact arising from the reuse of electric vehicle batteries in the context of renewable energies [5], emphasizing benefits such as reducing greenhouse gas emissions and decreasing carbon footprint. Likewise, it is crucial to consider the environmental impact associated with the production, repair, and recycling processes of these batteries.

- **Economic viability:** Acquiring a second-life battery will always be more economical than acquiring a new one [27]. Therefore, it is necessary to assess the project's economic viability, considering the costs associated with the acquisition, transportation, installation, and maintenance of the batteries, as well as the potential income generated from the sale of energy.

3.2. Main sectors interested in the reuse of EV batteries

Various sectors show potential interest in reusing and recycling the EV batteries. Among them are electric vehicle manufacturers, who could benefit from reducing production costs. Owners of electric vehicles with environmental awareness might also be interested, as it would provide peace of mind by ensuring proper handling of waste and hazardous materials and offering savings when acquiring a new battery. Recycling companies are also interested due to the growing demand for these types of batteries and the rising prices of raw materials used in their production. Governments concerned about environmental and safety issues could promote battery reuse to support the transition to a circular economy [28–30] and reduce the exploitation of natural resources.

A solution to minimize waste and maximize the reuse and recycling of resources is to implement a circular economy [28] in producing and recycling EV batteries. This involves designing batteries with easily removable and reusable components. It also entails using recycled and recyclable materials in manufacturing new batteries, which would significantly contribute to reducing the carbon footprint and decreasing the need to extract and process raw materials from nature [27]. Figure 6 provides a perspective of a circular economy applied to EV batteries.

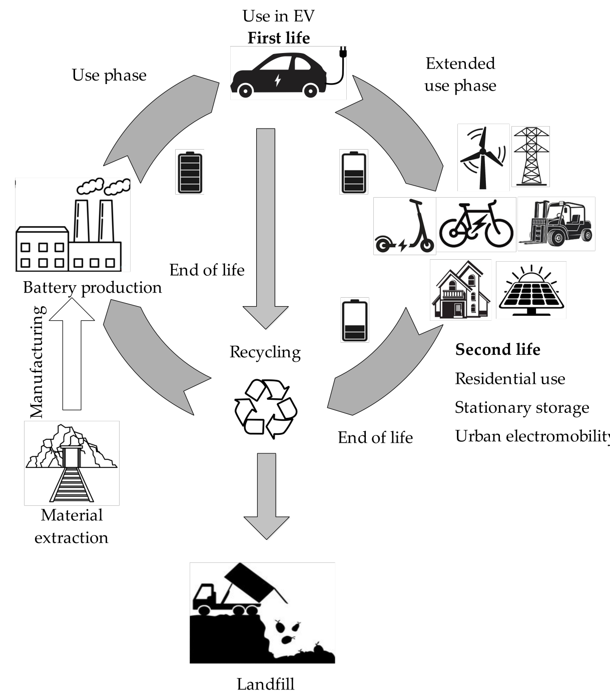

Figure 6. Circular economy perspective of the life of an EV battery. Illustration modified from [30]

3.3. Applications of EV battery reuse for renewable energy storage

The efforts invested in the literature review documented in this article have been primarily focused on presenting the main applications of the reuse of EV batteries in the field of renewable energy storage in an electrical grid. By addressing the established objective of the study and conducting a thorough search based on inclusion criteria, a total of 49 articles were gathered to analyze EV battery reuse in renewable energy storage. Of these, 26 articles specifically discuss the second-life of EV batteries.

The storage capacity retained by an EV battery at the end of its useful life, combined with the urgency to address global warming and environmental pollution, promotes the development of efficient and alternative technologies for the second-life application of EV batteries [31].

With the expansion of renewable energies worldwide, it becomes imperative to have energy storage systems [32], and the use of second-life EV batteries emerges as one of the viable solutions.

Stationary energy storage [23], involving the use of a bank of EV batteries on platforms located on a fixed surface, represents one of the most common applications for the reuse of EV batteries, especially those storing energy from renewable sources such as photovoltaic and wind [33]. This energy could meet demand when generation experiences significant variations due to the intermittent nature of solar or wind energy. This could be achieved by injecting energy into the grid or directly delivering surplus energy to users to cover their total or partial demand. Users representing a substantial load would be crucial to justify the implementation of storage systems, such as integrating battery systems in buildings [34–36] or educational institutions. A specific example of this application is the installation of solar panels and batteries in elementary schools in Kenya [37].

For residential users, low consumption implies reduced savings when using storage systems; therefore, their installation is only viable if they serve community installations [38]. Another published case study focused on a collective system of four homes. The electrical consumption behavior was analyzed over a week with the incorporation of a storage system using second-life electric vehicle batteries integrated with a photovoltaic system. As a result, a self-consumption rate of 69% was achieved, along with a reduction in peak power from 10.8 to 6.9 kW [39].

It is estimated that, from electric vehicles sold until 2020, there will be a storage capacity of retired batteries by 2028 ranging between 120 and 549 GWh. This availability can be utilized in implementing projects for small, decentralized and autonomous rural networks, contributing to developing rural communities in developing countries [40].

Research conducted on the island of Tenerife, Spain, estimates that by 2031, up to 83.2 MWh could be collected using second-life electric vehicle batteries integrated into wind power generation [5]. A study related to wind farms has developed a stochastic economic dispatch model for renewable energy at the megawatt level based on data from NASA batteries. This model assesses the temperature conditions and charging and discharging currents to which the batteries are subjected in a power system with ten generation units [41].

A study conducted in California, United States, demonstrated that economically, a project using second-life batteries is more advantageous than one considering new batteries in a combined photovoltaic energy project [27]. At the University of California, Davis, a microgrid was designed and built to investigate the effectiveness of second-life electric vehicle (EV) batteries in conjunction with commercial-scale photovoltaic generation. The first study's results, conducted over a year, indicate that EV batteries help reduce the load on an electrical grid and provide stability during peak hours, thus supporting the reuse of EV batteries [42]. In California, it is estimated that by 2050, the energy stored by second-life EV battery systems will represent 15 TWh per year, equivalent to 5% of the currently used energy [32].

An innovative and sustainable application for second-life EV batteries is fast-charging stations for EVs, where the batteries receive energy from renewable sources and then supply it to the EVs [43, 44]. In China, EV batteries were used as a backup for a communication station, supported by a technical-economic study endorsing their use [45].

Electric vehicle batteries reused in stationary storage can contribute to stabilizing the frequency of power systems [9], especially in those with a high percentage of unconventional renewable energy penetration or in weak systems such as island grids. The frequency of the electrical network depends on the variability of the load: when the demand for energy increases, the frequency of the electrical system decreases, and vice versa. In these systems, batteries play a crucial role in regulating the variability between demand and generation, providing energy to the system when demand increases and storing surplus generation during periods of low demand. This reduces the need for fossil generation sources, contributing significantly to reducing carbon emissions.

Another interesting application is power smoothing, which refers to the technique used to reduce fluctuations in electrical power production [46, 47]. Its goal is to improve the quality and stability of the energy source, which is crucial for sectors like industry or healthcare, where a power outage could lead to significant losses or severe consequences for human health. There are various methods to implement power smoothing in electrical generation systems, including using batteries or other energy storage systems, employing energy converters, or implementing advanced control and monitoring systems [48, 49]. Power smoothing, through the use of EV batteries, optimizes the utilization of second-life EV batteries as stationary energy storage systems [50, 51], thereby reducing fluctuations in electrical power production. This application is handy in renewable energy generation, such as wind or solar power [48], [52, 53], where power production is stochastically modeled and varies based on weather conditions. This technique contributes to improving the quality and stability of the energy source and represents a cost-effective and sustainable solution for reusing EV batteries [54].

The application of mobile energy storage considers using second-life batteries for smaller electric vehicles. This application can make urban electromobility more sustainable and reduce carbon emissions into the environment [23].

4. Conclusions

This study presents the results obtained by applying a systematic literature review methodology related to reusing electric vehicle (EV) batteries. The review process involved a thorough exploration conducted across reputable databases, including Web of Science, Scopus, and IEEE Xplore. In the initial stage, 458 relevant scientific papers were identified. Nevertheless, following an exclusion process that factored in criteria such as the availability of key components in the search, document accessibility, and inclusion within the study period (2018-2023), only 140 articles were selected. Finally, after a thorough review of titles and abstracts, 49 articles were carefully chosen as the foundation for this study.

The results indicate that, over the last five years, there has been a steady increase in the number of scientific works published in indexed journals addressing the concept of the second-life of electric vehicle batteries to provide energy support to power systems incorporating unconventional renewable generation.

The reuse of electric vehicle batteries has significant potential to reduce the carbon footprint of the transportation industry, contribute to the decarbonization of energy matrices, and support the stability and quality of energy in electrical systems. For this reason, research and development in this field must continue to advance to increase the energy efficiency of generation systems that utilize unconventional renewable energies. The ultimate goal should be establishing a circular economy system where electric vehicle batteries are reused in various applications, extending their lifespan to the maximum. This approach will help reduce the need for new batteries and, in turn, decrease the ecological impact of raw material extraction processes.

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