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Views & Comments

Repurposing EV Batteries for Storing Solar Energy

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1. Introduction

Carbon neutrality has emerged as a global goal due to its pivotal role in addressing the challenges of global climate change. Before the United Nations Climate Summit was held in November 2020, 124 countries promised to reach net-zero emissions [1]. Solar energy is one of the important renewable energy sources that significantly curtail carbon emissions originating from fossil fuels. According to previous research, approximately 60% can be reduced compared with coal-fired power generation [2]. The promotion of solar energy is a promising strategy. According to the International Energy Agency's (IEA) Solar Photovoltaic (PV) report, the global annual solar PV generation will reach a remarkable 1300 TW·h in 2022, and this trend is set to continue its rapid expansion [3]. However, the challenge of decarbonizing energy system within the confines of "PV only" solar energy system persists. The crux of this solution is the efficient storage of solar energy. The integration of battery technology has significantly enhanced the value of solar PV systems across diverse technologies, rate structures, and geographical locations [4]. The incorporation of batteries into solar PV systems offers quite a few future prospects. The widespread adoption of electric vehicles (EVs) harmonizes seamlessly with the need for storage of solar energy. Against the backdrop of a global surge in EV popularity, a substantial influx of EV batteries is anticipated in the near future. Although these batteries may not satisfy the criteria for reuse in EVs after prolonged operation, they offer an ideal solution for stationary energy storage. In that scenario, the reconfiguration of used EV batteries is a plausible avenue for storage of solar energy.

In 2022, the global accumulated installed capacity of solar PV panels surged to 3.372 TW [5], marking the onset of the terawatt era. Solar energy is progressively gaining ground, claiming a larger share of future energy generation market. Currently, the leading countries and regions for solar PV installations are China, the European Union, the United States, Japan, Germany, India, Italy, Australia, Republic of Korea, and the United Kingdom. China will maintain its dominance by achieving an accumulated capacity of 253.4 GW by 2020, surpassing the European Union by over 102 GW. Notably, in 2020, China witnessed annual solar PV capacity additions of 48.2 GW, followed by 19.6 GW in the European Union, 19.2 GW in USA, 4.9 GW in Germany, 4.4 GW in India and 4.1 GW each in Australia and Republic of Korea [6]. This upward trajectory continued in 2021, with global installations estimated at 175 GW, surpassing the 2020 figures by 20.69% and reaching a capacity of 145 GW. Seven countries—including Australia, Spain, Greece, Honduras, Netherlands, Chile, and Germany—are projected to adopt solar energy to fulfill over 10% of their national demands.

The global electricity demand additions in 2022 and 2023 are estimated to reach 498 TW·h and 705 TW·h, respectively [7], which is equivalent to approximately 352 924 and 499 621 metric tonnes of CO_2 produced by fossil fuels, respectively, according to the Greenhouse Gas Equivalencies Calculator of the United States Environmental Protection Agency[†]. Such substantial electricity demands provide tremendous opportunity for solar energy to mitigate carbon emission. Management and storage of solar energy become imperative. Effective management and storage requires a robust mechanism. Various strategies, including demand management, aim to optimize the storage and utilization of solar energy during the daylight. EVs have also emerged as suitable energy reservoirs. One innovative scheme involves selling solar energy at reduced rates in EV parking lots to boost demand and storage capacity, effectively harnessing EVs as solutions for storage of daytime solar energy. Storage of solar energy play a pivotal role, with second-life EV batteries poised as promising candidates.

Fig. 1 illustrates the concept of repurposing EV batteries for storage of solar energy. In their initial phases of life, batteries serve the operation of EVs. However, after several years of use, these batteries may no longer satisfy the standards required for EV applications. At this stage, they are extracted from vehicles and grouped into large battery packages designed for stationary energy storage. During daylight, solar energy caters to the electricity grid's

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[†] https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator.

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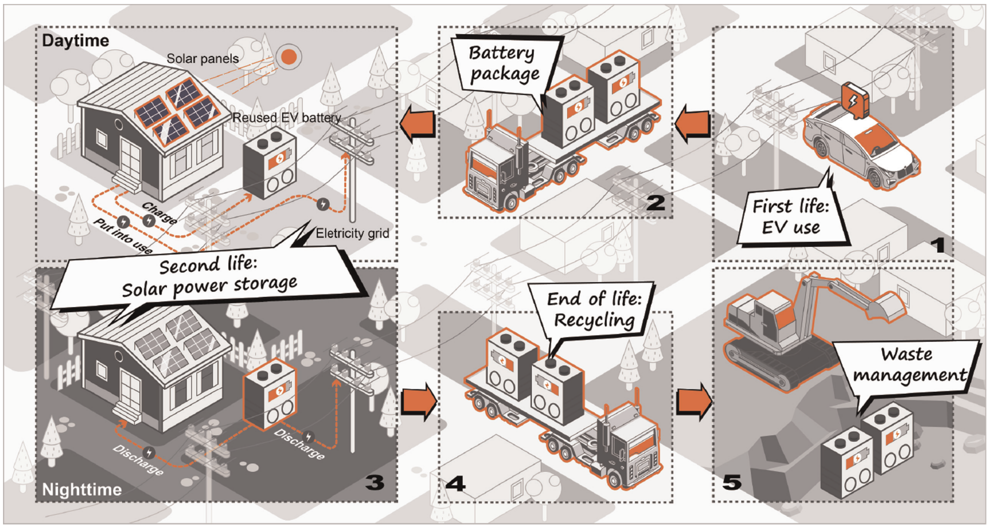


Fig. 1. Scheme of repurposing EV batteries for storing solar energy.

demands while simultaneously replenishing battery packages with additional generation. At night, the direct solar energy availability diminishes. In response, charged EV batteries discharge the stored energy into the grid to compensate for the absence of the sun. This system ensures a consistent supply of solar energy. Following this period of dynamic storage, batteries reach the end of their usable life and are subsequently recycled through waste management processes, such as landfilling or material recycling. This strategy significantly reduces the need to manufacture new batteries for storage, leading to substantial economic benefits.

Previous research has provided substantial evidence to justify this strategy. In the work of Kamath et al. [8], the authors discovered that the levelized cost of electricity was reduced by 12%–41% when repurposing existing batteries, as compared with manufacturing new ones. In addition, systems that incorporate local PVs and storage can help curtail usage of grid power. Economic simulations conducted by Horesh et al. [9] regarding their heterogeneous unifying battery reconditioning system demonstrated the ability to achieve a significantly lower repositioning cost for second-life batteries than for new Li-ion batteries. This approach can save 59 $\text{USD}\cdot\text{kW}^{-1}\cdot\text{a}^{-1}$.

In conclusion, second-life batteries have remarkable potential to reduce both operational and equipment costs. Prior research has yielded numerous operational technologies and strategies that have been proven to be more cost-effective compared with new batteries. National governments have begun exploring the feasibility of repurposing EV batteries at initial stage. The US Department of Energy enacted a Bipartisan Infrastructure Law centered on electric drive vehicle battery recycling and second life applications [10]. Numerous projects have explored the efficacy of second-life EV batteries for stationary energy storage. Although at the global level, there remains a lack of clear legislative and regulatory frameworks for the process of repurposing used EV batteries for energy storage, some real instances already exist in which retired EV batteries are repackaged and employed for storage of solar energy. An operational system comprised of 1300 old EV battery packs in Lancaster, CA, USA is a prime example [11]. This initiative was spearheaded by B2U Storage Solutions, marking the pioneering realization of the aforementioned concept. The Belgian startup Octave similarly designed a battery energy storage system (BESS) for stationary applications with plans for real-world implementation. The potential of this concept is immense, and it has garnered substantial public investment and dedication towards its actualization.

2. Global battery EV sales volume and battery manufacturing

The global shift towards battery EVs (BEVs) as replacements for traditional petrol and gasoline vehicles is gaining momentum. This transition is a crucial step in addressing climate change mitigation and achieving carbon neutrality. This shift is particularly vital because of the significant contribution of the transportation sector, which accounts for more than one-third of CO_2 emissions. In the leading nations at the forefront of solar PV installations, the adoption of BEVs is experiencing a period of rapid expansion. In 2021, the world sold 4.60 million BEVs [12]. To specify into regions, 1.30 million were sold in Europe, 2.96 million in Asia-pacific, 0.55 million in America, 0.02 million in Africa, and the Middle-East.

Even the advent of the COVID-19 pandemic has failed to cast a shadow on BEV sales. For example, global sales volumes in 2020 surged by 33% compared with 2019. Furthermore, these volumes were more than double in 2021, reaching 2.3 times that of 2020. By 2022, sales soared to a remarkable 7.3 million units, exceeding three times the figures for 2020 [12]. Reflecting these trends, McKinsey's projections suggest that by 2040, 70% of vehicles in Europe will be powered by electricity [13]. These data underscore the undeniable momentum and global resolution to steer towards the future driven by electric mobility. The current trajectory of BEV sales and battery production indicates a promising future, with a substantial influx of reusable EV batteries.

3. Global potential of second-life BEV battery for solar energy storage

After enduring harsh working conditions, including extreme temperatures, for several years, batteries often fail to meet the performance standards required for BEV operations. However, a significant usable capacity remains rendering it useful for other applications. Typically, BEV manufacturers offer battery warranty coverage for an average of eight years, which implies that batteries become reusable after this period, retaining approximately 70% of their original usable capacity. This massive volume of batteries presents a significant potential for storing generated solar energy. Following a series of industrial processes, these batteries are viable candidates for stationary energy-storage tasks.

McKinsey's estimation suggests that the global capacity of second-life lithium-ion batteries can exceed 200 $\text{GW}\cdot\text{h}$ [14]. If a proper market structure and policy support for reusing and renewing second-life batteries is established, the available storage capacity could be vast, making them an ideal choice for storing daytime solar energy. Current repurposing technologies and management strategies enable the repurposing of second-life batteries for highly reliable and efficient energy storage.

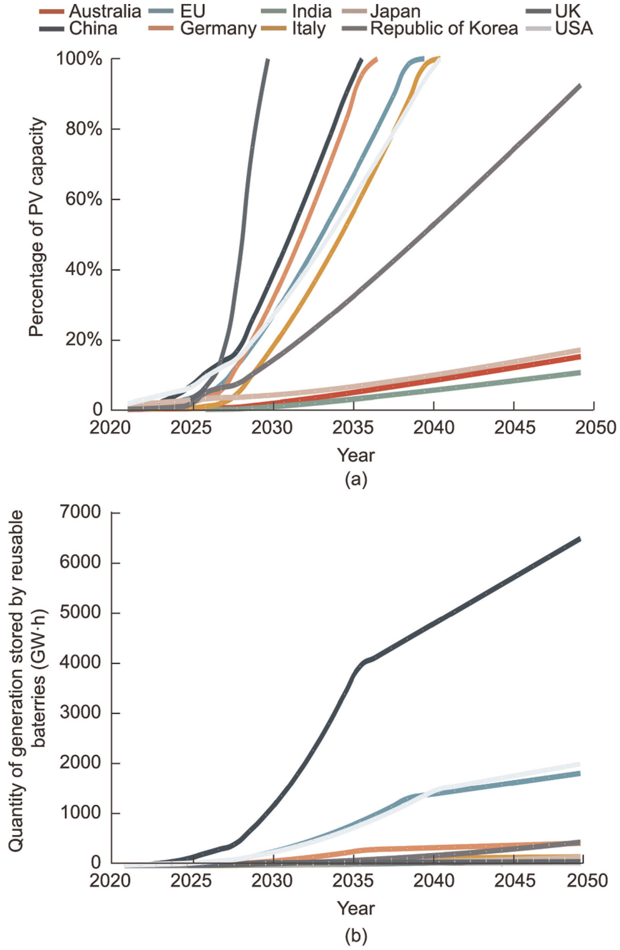
One of the solutions involves dismantling battery packs into smaller modules or cells that can then be repackaged into larger battery assemblies [15]. This method offers the advantage of assembling different classifications of BEV batteries based on chemistry, voltage range, and assessing their state of health. Given the varied operating conditions, the state of health can vary significantly, making health state testing crucial. Various test methods, such as capacity and pulse tests, incremental capacity analysis, and electrochemical impedance spectroscopy [16], address these issues. Another approach involves predicting the optimal time for retiring BEV batteries from their first life. Wang et al. [17] introduced a multi-objective optimization approach that predicts the most suitable retirement time based on the running time of a vehicle. These testing methods ensure that the reused batteries meet requirements for storage without causing further issues.

Currently, researchers have developed cloud-based battery state-of-health estimation and remaining useful life (RUL) prediction during vehicle operation, significantly reducing computation time [18]. Similar health-state batteries can be clustered to ensure improved consistency.

In this paper, we present a straightforward simulation of future PV installation capacity and the potential storage capacity of reusable BEV batteries. Our estimation is based on the 2021–2050 span and focuses on two key aspects: ① projected capacity of installed solar PV panels for power generation; ② potential of storing energy generated from solar PV panels by using reused BEV batteries.

(1) To estimate the quantity of installed solar PV panels for power generation, we gathered information on installed solar PV in 2021 from target countries and their growth rates over the past five years. Starting from 2022, we assumed that the number of newly installed solar PV remained constant, equal to the average value of the past five years, resulting in linear growth. Despite explosive growth rates in recent years, market saturation has become a possibility. Therefore, we adopted a conservative estimate up to the year 2050.

(2) Estimating the quantity of generated energy that can be stored by reused batteries involves two steps. The first step was to calculate the potential quantity of reused batteries. We collected data on the annual BEV sales over the past five years. Similar to the solar PV installation estimation, we conservatively projected linear growth in sales up to 2050. This allowed us to estimate the cumulative number of batteries retired per year. A crucial factor in this step is determining the lifespan of the BEV batteries. Previous research has provided evidence on the lifespan of first-life BEV batteries. Typically, after 5–8 years of usage, the battery capacity declines to 70%–80% [19], necessitating retirement or renewal. Zhu et al. [20] showed that after approximately 1000 incomplete charging/discharging cycles within 5–10 years, the functionality of a battery declines significantly. Based on these insights, we assume that after an average of eight years of use, 70% of the usable capacity remains, allowing batteries to enter their second life for stationary storage. The full battery capacity was set at the average value of existing battery types in the market, which was 64.1 kW·h. Based on these assumptions, we calculated the cumulative quantity of reused batteries and converted it into battery capacity (kW·h), representing the storage capacity of electricity. The subsequent step involved translating the cumulative battery capacity (kW·h) into the corresponding solar PV capacity (kW) considering the average solar irradiation over 24 h. This comparison allowed us to determine the percentage of solar PV coverage that is achievable using reusable BEV batteries.



(a)

(b)

Fig. 2. Simulation results of (a) percentage of PV capacity, with energy stored by reusable BEV batteries in world leading countries and (b) estimated daily stored solar energy.

In addition, we estimated the maximum amount of solar energy that can be stored by reusable BEV batteries for potential assessment.

The data for PV installations and BEV sales were obtained from Statista†, a comprehensive statistical data website that aggregates and provides reliable data from authoritative sources such as official governmental reports and international authorities.

The simulation results are shown in Fig. 2. Fig. 2(a) talks about the percentage of the PV capacity, with energy stored by the cumulative reusable batteries relative to the total installed capacity. A value of 100% indicates that all generated solar energy can be accommodated by reusable batteries. Substantial disparities were observed among the prominent countries. Specifically, in China, the European Union, and Germany, the cumulative reusable battery can fully store the solar PV generation between 2035 and 2040 (referred to as the "full storage year" hereafter). Italy and the United States exhibited a slightly slower trend, with the projected "full storage year" falling after 2040. Notably, the United Kingdom leads with the earliest "full storage year" of 2030. This variance may be attributed to the sluggish growth in solar PV installations juxtaposed with the rapid expansion in BEV sales.

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† https://www.statista.com/.

Conversely, we observed that the cumulative reusable batteries may not keep pace with PV installations by 2050 in some countries. In Australia, India, and Japan, the surge in solar PV panel additions outpaced BEV sales growth, resulting in the estimated percentage of PV capacity remaining below 20%. Across most leading countries and regions, there is a substantial potential for repurposing disposed BEV batteries as a storage media for solar energy.

Fig. 2(b) shows an overview of the estimated energy storage. A turning point can be observed in the lines where the growth becomes linear afterwards. The year of this turning point corresponds to the "full storage year" in Fig. 2(a). Prior to the turning point, the accumulated reusable batteries could not fully store the generated energy, although the growth of reusable batteries was rapid. This is reflected in the steep upward trend of the line. After the turning point, the reusable batteries reach saturation in storing solar energy, signifying the storage of all generated solar energy. Because we assumed linear growth in solar PV installations, the stored energy also followed a linear pattern.

Fig. 2(b) shows three distinct groups. The first is China, which has maintained its dominance in the total quantity of stored energy. The estimated stored energy in China will reach 4000 GW·h by 2036, and nearly 6500 GW·h by 2050. This corresponds to the swift growth in the adoption of solar energy and solar PV installations, as discussed in Section 1. The second group includes the United States and the European Union, with an estimated daily storage of approximately 2000 GW·h by 2050, roughly one-third of that of China. The third group encompasses the rest of the country, as represented by Germany and Republic of Korea. These countries exhibit around one-tenth the quantity of China. The growth in solar energy generation in this group is relatively slow and is projected to be less than 500 GW·h by 2050.

Thus, reusable batteries have considerable potential for storage of solar energy. However, in the current stage of battery industry development, there are still some barriers that must be overcome to fully implement the reuse of BEV batteries for storage of solar energy.

4. Future challenges and barriers

Despite their substantial potential in many leading countries, barriers prevent the reuse of BEV batteries for storage of solar energy. These barriers stem primarily from technological limitations, safety concerns, legislative and regulatory issues, and structural market challenges.

Various battery technologies bring difficulty in refreshing reused battery: Currently, there are numerous BEV manufacturers, including well-known names like Tesla, Toyota, Nissan, Hyundai, and Mini Cooper. Each manufacturer often employs distinct technological protocols to align with a specific product. These protocols encompass various aspects such as battery materials (lithium-ion, nickel–metal hydride, lead acid, and ultracapacitors), battery formats (cylindrical, prismatic, and pouch), and capacity. Even from the same manufacturer, different models use different batteries. This diversity presents a significant challenge in large-scale battery renewal processes that necessitate intricate assembly lines for renewal. With over 150 distinct BEV models currently available from different manufacturers and the anticipation of the global BEV market expanding, achieving mass renewal requires the establishment of standardized battery technology protocols.

Comprehensive framework and standard for reused battery test: Given the intricate range of usage scenarios, it is essential to thoroughly assess the extent of performance degradation. It is crucial to determine whether the collected batteries satisfy the prerequisites for storage of solar energy. Hence, it is necessary to formulate a standardized framework that outlines the performance specifications of repurposed batteries for storage of solar energy. This framework emphasizes on battery management and health status evaluation. This becomes particularly critical as the volume of disposed batteries increases, thereby demanding more streamlined and efficient methods.

Safety insurance: Although infrequent, there have been instances of newly manufactured EV batteries catching fire. When these batteries are repacked for storage of solar energy, they become concentrated, potentially leading to unforeseen damage and compromising safety if one or more batteries are ignited. This underscores the need for stringent safety protocols and robust management systems.

Economic value compared with new battery production: The cost of producing new EV batteries has decreased over the past few years. Despite recent slowdowns in productivity and logistics, costs are anticipated to continue to decrease in the long term. The price advantage of used batteries could be overshadowed by the declining cost of new batteries. Consequently, it is essential to comprehensively assess the economic value of reused batteries for storage of solar energy. This evaluation should determine whether to repurpose batteries for storage of solar energy or opt for new batteries for the storage and recycling of used batteries into new products.

Blanks of market regulations and legislation in most countries: While certain countries and regions such as China have taken steps in this direction, many others have yet to establish clear regulations and policies concerning reused and renewed EV batteries for both providers and consumers. The lack of defined technical specifications and declarations of responsibility hinder the growth of sustainable markets. A robust legislative framework is imperative for fostering a healthy market environment. A comprehensive set of regulations and laws for both consumers and providers should be implemented to ensure smooth and secure the operation of the market.

5. Summary

At present, the majority of countries have set clear carbon neutrality goals as a pivotal strategy for addressing climate change. Ensuring a consistent supply of solar energy is crucial for achieving this aim because solar energy is a vital clean energy source. The selection of a suitable solar energy carrier is paramount to ensure the steady flow of solar energy. The widespread adoption of EVs is bound to generate substantial quantities of batteries. Based on our estimations, the quantity of solar energy that can be stored differs significantly between countries. China is dominant in terms of quantity, with an estimated daily 4000 GW·h in 2036 and 6500 GW·h in 2050. The United States and the European Union will account for approximately one-third of China's stored generation of approximately 2000 GW·h in 2050. The rest of the countries are less than one-tenth of China. Representative countries are Germany and Republic of Korea. However, in the leading countries for solar PV installation, the potential capacity of these batteries is sufficient to store the generated solar energy and ensure a consistent solar energy supply. This estimation was based on the projected percentage of solar PV installations with the generated energy stored in reusable batteries in the simulation. Countries such as the United Kingdom, China, Germany, the European Union, and Italy exhibit the greatest potential in this regard. Many of them are expected to achieve 100% storage by 2040. However, realizing such a system requires overcoming several obstacles, including technological challenges, safety considerations, economic assessments, and the establishment of comprehensive market regulations and legislation. If these issues are addressed, the seamless advancement of repurposing used batteries for storage of solar energy holds promise.

References

[1] Wei YM, Chen K, Kang JN, Chen W, Wang XY, Zhang X. Policy and management of carbon peaking and carbon neutrality: a literature review. Engineering 2022;14:52–63.

[2] Wu X, Li C, Shao L, Meng J, Zhang L, Chen G. Is solar power renewable and carbon-neutral: evidence from a pilot solar tower plant in China under a systems view. Renew Sustain Energy Rev 2021;138:110655.

[3] The International Energy Agency (IEA). Solar PV [Internet]. Paris: The International Energy Agency; [cited 2023 Sep 14]. Available from: https://www.iea.org/reports/solar-pv.

[4] Schöniger F, Thonig R, Resch G, Lilliestam J. Making the sun shine at night: comparing the cost of dispatchable concentrating solar power and photovoltaics with storage. Energy Sources B Econ Plan Policy 2021;16(1):55–74.

[5] Enkhardt S. New global solar capacity additions hit 191 GW in 2022, says IRENA [Internet]. Berlin: PV Magazine; 2023 Mar 22 [cited 2023 Sep 14]. Available from: https://www.pv-magazine.com/2023/03/22/new-global-solar-capacity-additions-hit-191-gw-in-2022-says-irena/#:~:text=IRENA%20says%20developers%20installed%20295,solar%20was%20installed%20last%20year.

[6] The International Energy Agency (IEA). Snapshot of global PV markets 2021 [Internet]. Paris: The International Energy Agency; 2021. May 31 [cited 2023 Sep 14]. Available from: https://reglobal.org/snapshot-of-global-pv-markets-2021/.

[7] The International Energy Agency (IEA). Electricity market report 2023 [Internet]. Paris: The International Energy Agency; 2023. Feb [cited 2023 Sep 14]. Available from: https://www.iea.org/reports/electricity-market-report-2023..

[8] Kamath D, Arsenault R, Kim HC, Anctil A. Economic and environmental feasibility of second-life lithium-ion batteries as fast-charging energy storage. Environ Sci Tech 2020;54(11):6878–87.

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

[10] US Department of Energy. Bipartisan infrastructure law: electric drive vehicle battery recycling and second life applications. Washington, DC: US Department of Energy; 2022.

[11] Lewis M. This solar + storage system is made up of 1,300 second-life EV batteries [Internet]. Fremont: Electrek; 2023 Feb 7 [cited 2023 Sep 14]. Available from: https://electrek.co/2023/02/07/this-solar-storage-system-is-made-up-of-1300-second-life-ev-batteries/.

[12] Statista. Battery-electric vehicle sales worldwide from 2011 to 2022 [Internet]. New York City: Statista; 2023 Apr [cited 2023 Sep 14]. Available from: https://www.statista.com/statistics/1059214/global-battery-electric-vehicle-sales/.

[13] Eddy J, Pfeiffer A, van de Staaij J. Recharging economies: the EV-battery manufacturing outlook for Europe [Internet]. Neftchiler Avenue: McKinsey & Company; 2019 Jun 13 [cited 2023 Sep 14]. Available from: https://www.mckinsey.com/industries/oil-and-gas/our-insights/recharging-economies-the-ev-battery-manufacturing-outlook-for-europe.

[14] Engel H, Hertzke P, Siccardo G. Second-life EV batteries: the newest value pool in energy storage [Internet]. Neftchiler Avenue: McKinsey & Company; 2019 Apr 30 [cited 2023 Sep 14]. Available from: https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/second-life-ev-batteries-the-newest-value-pool-in-energy-storage.

[15] Cready E, Lippert J, Pihl J, Weinstock I, Symons P. Technical and economic feasibility of applying used EV batteries in stationary applications Report. Albuquerque: Sandia National Lab (SNL-NM); 2003.

[16] Hu X, Yuan H, Zou C, Li Z, Zhang L. Co-estimation of state of charge and state of health for lithium-ion batteries based on fractional-order calculus. IEEE Trans Vehicular Technol 2018;67(11):10319–29.

[17] Wang T, Jiang Y, Kang L, Liu Y. Determination of retirement points by using a multi-objective optimization to compromise the first and second life of electric vehicle batteries. J Clean Prod 2020;275:123128.

[18] Baumann M, Rohr S, Lienkamp M. Cloud-connected battery management for decision making on second-life of electric vehicle batteries. In: Proceedings of the 2018 thirteenth International Conference on Ecological Vehicles and Renewable Energies (EVER); 2018 Apr 10–12; Monte Carlo, Monaco. New York City: IEEE; 2018. p. 1–6.

[19] Lai X, Chen Q, Tang X, Zhou Y, Gao F, Guo Y, et al. Critical review of life cycle assessment of lithium-ion batteries for electric vehicles: a lifespan perspective. eTransportation 2022;12:100169.

[20] Zhu J, Mathews I, Ren D, Li W, Cogswell D, Xing B, et al. End-of-life or second-life options for retired electric vehicle batteries. Cell Rep Phys Sci 2021;2(8):100537.