Strategies for Sustainable Second-Life Battery Utilization in Electric Vehicles

Aditya Kumar Sharma

Zūm Services Inc. Redwood City, California.

Abstract

This research paper delves into the burgeoning field of electric vehicle (EV) battery reuse, exploring the multifaceted challenges and opportunities that accompany the transition toward sustainable urban mobility. With a focus on lithium-ion batteries' pivotal role in the EV market, the paper scrutinizes the barriers to mass adoption of electric vehicles, notably the high cost and environmental impact of battery production. Recognizing the potential of second-life battery applications, this study examines strategies for extending the operational lifespan of EV batteries beyond their automotive use, highlighting their applicability in stationary energy storage, grid services, and backup power systems. Through a comprehensive review, the paper outlines a systematic methodology to assess the technical and economic feasibility of repurposing EV batteries, alongside the environmental benefits and market opportunities this practice offers. It further investigates business model typologies suited to second-life battery applications, identifying collaborative, traditional, and integrative approaches that balance economic viability with sustainability goals. Addressing the intricate challenges within the second-life battery market, the research underscores regulatory ambiguities, technical performance concerns, and competition with newly manufactured batteries. It also explores innovative solutions, including blockchain technology and smart contracts, to enhance market transparency and stakeholder trust. By presenting case studies and current practices in battery repurposing, the paper provides insights into successful strategies and potential pitfalls, offering a roadmap for stakeholders to navigate the complexities of the second-life battery ecosystem. Ultimately, this work contributes to the discourse on sustainable transportation and energy systems, proposing actionable solutions to advance the global shift towards electrified and environmentally responsible mobility.

Keywords: Electric Vehicle Batteries, Battery Reuse, Sustainable Energy Systems, Second-Life Battery Applications, Business Models for Battery Repurposing.

I. INTRODUCTION

The advent of electric vehicles (EVs) represents a significant pivot in urban mobility, a transformation propelled not only by technological advancements but also by global exigencies, such as the recent pandemic outbreak. This shift towards electric mobility heralds a future where transportation is characterized by lower emissions, reduced noise pollution, and a diminished reliance on fossil fuels. At the heart of this transition lies the pivotal role of battery technology, particularly lithium-ion batteries, which are central to the operation and efficiency of EVs. However, the widespread adoption of electric vehicles is contingent upon overcoming several key challenges, including enhancing the electrical charging infrastructure, extending vehicle driving ranges, and, most critically, reducing the cost of battery packs.

The high cost of batteries remains one of the most significant barriers to the mass adoption of electric vehicles. Recognizing this, there has been a concerted effort from various stakeholders, including manufacturers, government entities, and the scientific research community, to innovate and implement strategies aimed at reducing battery costs. These strategies encompass a broad spectrum of approaches, from advancing battery technology and manufacturing processes to developing policies that incentivize the adoption of EVs. A notable area of focus has been on the sustainability of electric power production and distribution, emphasizing the need for environmentally friendly and economically viable solutions.

One promising avenue for reducing the economic and environmental impacts associated with batteries is the concept of battery reuse or second-life battery applications. As batteries reach the end of their useful life in electric vehicles, they may no longer meet the stringent performance requirements for automotive use but can still hold significant residual capacity. This residual capacity presents an opportunity for batteries to be repurposed for a wide range of secondary applications, such as energy storage systems that complement renewable energy sources like solar and wind power, backup power supplies, power for industrial machinery like forklifts, and even to support grid services including frequency regulation and peak shaving.

The potential for battery reuse not only offers a pathway to more cost-effective battery solutions but also contributes to environmental sustainability by extending the useful life of batteries and reducing the need for new raw materials. Moreover, the integration of second-life batteries into renewable energy systems can enhance energy resilience and security, further supporting the transition to a low-carbon economy. This research paper aims to explore the multifaceted challenges and opportunities associated with the reuse of electric vehicle batteries. It seeks to analyze the leading technologies that enable battery repurposing, assess the different types of batteries in terms of their suitability for second-life applications, and discuss the current state of the art in battery reuse practices. By examining the technical and economic feasibility, environmental impacts, and market opportunities, this work endeavors to shed light on the barriers and uncertainties facing the second-life battery market. Furthermore, it introduces novel discussions on the various business models, market types, and strategic approaches that can facilitate the growth of this emerging market. Through this comprehensive analysis, the paper aims to contribute valuable insights and propose solutions that address the complexities of battery reuse, ultimately advancing the global shift towards sustainable and electrified transportation.

II. METHODOLOGY

This systematic review was meticulously designed to adhere to a strict protocol, ensuring both the reproducibility of the research and the minimization of any potential biases. The methodology encompassed four distinct phases, each critical to the integrity and comprehensiveness of the review. Initially, the research embarked on defining the primary questions to be addressed, laying the foundation for a focused inquiry into the realm of second-life batteries and associated business models. Following this foundational step, the review established clear inclusion and exclusion criteria for the selection of studies. This critical phase ensured that the research remained tightly aligned with its objectives, including only those studies that directly contributed to the understanding of second-life battery applications, sustainable business models, and the broader implications for electric vehicle battery reuse.

The third phase involved a systematic search and identification of relevant literature. Leveraging a combination of carefully chosen keywords, such as "Business Models & Second-Life Batteries," "Sustainable Business Models & Electric Vehicles Batteries," and related terms, the search aimed to capture the breadth and depth of existing research in the field. This approach facilitated the identification of studies that span the intersections of business modeling, sustainability, and the technical aspects of battery reuse, acknowledging the growing interest in sustainable business practices within the electric vehicle industry. The final stages of the methodology focused on the critical evaluation and synthesis of the identified literature, followed by a comparative analysis and compilation of data from the various studies. This rigorous evaluation process was supported by the use of StArt software, enabling an organized and systematic review of the literature. Additionally, ATLAS.ti software played a pivotal role in importing scientific articles, allowing for a detailed analysis and compilation of concepts presented across the corpus of identified research.

Significantly, the review also highlighted the major findings from previous studies, acknowledging the existing body of knowledge while also identifying gaps and opportunities for further research. Despite the observed increase in publications related to sustainable business models and electric vehicle batteries, the review noted a relatively low focus on business models specifically tailored to second-life batteries. By addressing this research gap, the systematic review aims to contribute valuable insights and frameworks to advance the understanding and application of second-life batteries within the context of sustainable business practices in the electric vehicle sector.

III. CONCEPT

This section delves into the intricacies of developing sustainable business models for the reuse of batteries, raising critical questions such as the essence of a business model, the value it brings, and how it captures value through battery reuse. It explores the identification of target customers within the second-life battery market, strategies for marketing these batteries, and the essential attributes of an online platform that can enhance consumer trust in second-life batteries. Additionally, it considers the various market and transaction types possible within the second-life battery ecosystem and the uncertainties that accompany them. The term "business model" is subject to various interpretations, each tailored to the specific context in which it is employed. Numerous scholars have offered definitions, emphasizing the model's role in detailing the flow of products, services, and information, the stakeholders involved, and the mechanisms for generating revenue. For this review, a business model is understood as a framework for how an organization generates, delivers, and captures value, aiming to be scalable and replicable to ensure the company can meet demand efficiently.
Considering recent global crises, including the pandemic and geopolitical tensions, there is a pressing need for businesses to innovate and adopt new, sustainable models that can address both economic challenges and environmental concerns. This has led to a surge in interest in business models that not only foster economic growth but also address social and environmental issues, thereby supporting a sustainable economy. When considering the market for second-life batteries, parallels can be drawn with the used auto parts industry, involving diverse interactions among companies, their customers, and independent consumers. The study highlights three potential market scenarios: a closed market where manufacturers may opt to keep data proprietary to maintain competitive edges; an intermediary market fostering partnerships for logistics and storage solutions; and an open market facilitated by online platforms connecting buyers and sellers. Each model presents unique challenges and opportunities, from data security and brand reputation risks to contractual and logistical complexities. Blockchain technology is touted as a potential solution to enhance trust and transparency in these markets, offering secure platforms for transactions and information sharing. However, the open market model faces significant hurdles without such technology due to the difficulty of assessing the individual value of batteries and managing the risks associated with their second-life use.

IV. BUSINESS MODEL TYPOLOGIES FOR SECOND-LIFE BATTERY APPLICATIONS

Within the literature, five distinct business model typologies for second-life batteries have been identified, encompassing a traditional model, three collaborative models, and an integrative model. These models present a range of benefits and risks to various stakeholders involved in the lifecycle of a battery, from original equipment manufacturers (OEMs) to end-users and recycling entities. Despite the insightful discussions available, there remains a gap in fully understanding the cost implications associated with each business model, necessitating further exploration.

The traditional model is characterized by the OEM transferring the ownership and responsibility of the second-life battery to another entity, potentially safeguarding the OEM's proprietary knowledge but also distancing them from the investment risks associated with the second-life market. For the purchasing entity, risks include the future scarcity of second-life batteries and the high costs of testing and integration without access to detailed battery data. The absence of shared data could necessitate extensive testing to determine the battery's condition, increasing both costs and time to market, and possibly rendering the venture nonviable in the face of emerging battery technologies. Collaborative models advocate for shared data, responsibilities, and profits among companies, leveraging blockchain technology for enhanced trust and transparency. In the integrative model, there is a seamless partnership between the OEM and systems integrators, aiming for a synergistic approach to battery reuse. Challenges arise in trading used EV batteries due to customer concerns over performance and safety. Manufacturers are keen on protecting their brands and technologies, highlighting the need for secure, transparent data management and smart contract implementations to mitigate conflicts of interest.

Identifying the target market is crucial in formulating a business strategy for products powered by second-life batteries. This reuse offers value to residential and commercial consumers through cost-effective energy storage solutions (ESS) integrated with renewable energy sources, thereby reducing energy tariffs and fostering participation in energy arbitration. Energy producers and utilities can benefit from enhanced grid balance and operational efficiency, avoiding significant infrastructure investments. Furthermore, individual investors and companies in the battery, EV, and utility sectors can explore new revenue streams within the energy market. The value proposition is central to attracting customers in the second-life battery market, emphasizing the financial and non-financial benefits of choosing reused batteries. This could include cost savings, revenue generation, and increased flexibility in energy management for consumers, alongside environmental benefits like reduced greenhouse gas emissions and support for renewable energy integration. The value chain outlines the delivery mechanism of this value proposition, highlighting the need for environmental considerations, operational improvements, and financial strategies to support project development. Battery reuse presents opportunities for revenue generation across various applications, from enhancing the infrastructure of EV charging stations to reducing operational costs for energy utilities. It also underlines the potential to postpone the recycling phase, allowing for advancements in recycling technologies and methodologies.

V. CHALLENGES IN THE SECOND-LIFE BATTERY MARKET

Despite significant progress in the domain of battery technology, numerous uncertainties persist in the second-life battery market. A notable study identified seven distinct business model typologies within this sector, pinpointing uncertainties related to the future availability of batteries for reuse, their performance, lifespan, and warranty terms for consumers. One of the principal challenges highlighted is the competition between the cost of second-hand EV batteries and new batteries.

Adopting the lemon market theory, another investigation explored the evolution of business models from a product-centric to a service-centric approach. This shift emphasizes the reluctance of battery and car manufacturers to relinquish battery ownership for secondary usage, opting instead to offer usage rights, thereby altering their revenue models. The diversity in battery chemistry, primarily LiFePO4 and NMC, introduces further complexity, with manufacturers offering varied warranty periods, underscoring the need for future research to demystify the ideal warranty duration for these batteries. A systematic review pinpointed the regulatory ambiguity over the ownership and recycling responsibility of EV batteries as a significant barrier. This is compounded by the competition from increasingly affordable new batteries, the unpredictability of the second-hand battery supply, and the absence of standardized testing procedures. Additionally, concerns over technical performance at the end of the battery's first life and the logistics and costs of battery transportation and replacement are noted.

Qualitative research, incorporating interviews within the battery supply chain, revealed both opportunities and challenges. For OEMs, repurposing batteries presents a chance to delay recycling phases and tap into cheaper battery options for residential use. However, uncertainties regarding warranties, reliability, and costs loom large. The variation in battery construction complicates the repurposing process, making it difficult for intermediaries to adapt batteries for secondary use, with transportation identified as a significant cost factor. Regulatory gaps concerning recycling responsibilities, technical performance uncertainties in secondary applications, and the cost-effectiveness of repurposing efforts are recurrent themes. The looming scarcity of reusable batteries exacerbates these challenges. The market's viability is threatened by the decreasing price of new batteries, potentially rendering second-life options less economical. While incentives for new battery purchases exist in several countries, support for second-life battery initiatives remains sparse. The varied performance of batteries based on their initial application adds to the uncertainty, particularly in assessing their viability in secondary roles.

VI. ASSESSING SECOND-LIFE BATTERY APPLICATIONS

This segment delves into the current landscape and the successes and challenges encountered in projects involving second-life batteries, addressing queries about ongoing and completed projects, prevailing business models, and notable successes and failures in the realm of second-life battery implementation. Battery degradation is influenced by various factors, including usage conditions in electric vehicles (EVs), necessitating in-depth research to delineate the costs associated with capital, installation, maintenance, and the evaluation of second-life batteries. Defining these cost parameters is crucial for developing feasible business models that can navigate the intricacies of battery life, performance, safety, and reliability. The value chain for second-life batteries encompasses the extraction of batteries from EVs, potential remanufacturing, redirection to new applications, or integration into storage systems, defining the trajectory from battery inception to second-life application. This chain is contingent upon processing requirements, cost analysis, application conditions, and chain limitations, with the battery's remaining capacity and design features playing pivotal roles.

Battery assessment involves visual and extensive testing to gauge its health status, emphasizing the importance of understanding each battery's added value. Manufacturers, possessing comprehensive knowledge on battery degradation patterns and second-life application requirements, are ideally positioned to evaluate the reuse potential. Given the diversity in battery chemistry, energy density, and dimensions, the strategy for battery reuse must address several considerations, including the business model's competitiveness, technical requirements for initial and subsequent applications, and the logistics of battery recovery and remanufacturing.

Battery manufacturers face the task of navigating business risks and cost assessments for remanufacturing and logistics, determining the business model's viability, whether Business-to-Business (B2B) or Business-to-Consumer (B2C), and strategizing sales, support, and logistics. Various stakeholders, from manufacturers to startups, have vested interests in battery reuse. Critical factors include ownership and recycling responsibilities, highlighting the importance of industry cooperation to explore the second-life battery market, identify potential customers, and possibly collaborate on battery reuse. A business model's success hinges on its ability to generate and capture value, requiring a clear definition of the value delivered to customers and the activities essential for its realization.

Addressing challenges such as cost, range anxiety, recharge infrastructure, and charging time is paramount. Innovative business models propose solutions like utilizing second-life batteries in charging stations or energy storage systems (ESS) for homes, aiming to make EVs as economically viable as conventional vehicles. Success stories and pilot projects demonstrate the technical feasibility and potential business models for reusing EV batteries, highlighting applications in grid efficiency, stability, and renewable energy integration. However, the journey towards effective second-life battery utilization also includes acknowledging the lessons learned from unsuccessful ventures, such as Better Place's battery exchange station model, underscoring the importance of realistic market assessment, sound management, and cautious investment strategies. This exploration not only showcases the promising avenues for second-life battery applications but also reflects on the hurdles and failures, offering a comprehensive understanding of the landscape and guiding future endeavors in sustainable battery usage and business model innovation.

1. **Battery Degradation Model**:

- This formula can predict the remaining capacity of a battery after a certain number of charge-discharge cycles. It's crucial for estimating the lifespan of second-life batteries. A common model is the semi-empirical model which relates capacity fade to cycle number through an exponential relationship:
- $Capacity(C)=C0\times e^{(-k\times n)}$ Where C0 is the initial capacity, k is the degradation rate constant, and n is the number of cycles.
- Python code for the same is below :

```
import numpy as np
def battery_degradation(initial_capacity, degradation_rate, cycles):
    return initial_capacity * np.exp(-degradation_rate * cycles)
# Example usage
C0 = 100  # Initial capacity in Ah
k = 0.001  # Degradation rate constant
n = 500  # Number of cycles
remaining_capacity = battery_degradation(C0, k, n)
print(f"Remaining Capacity: {remaining_capacity} Ah")
```

2. **Cost-Benefit Analysis for Second-Life Battery Applications**:

- A formula to calculate the net present value (NPV) of deploying second-life batteries for various applications, considering initial investment, operational costs, and savings over time:
  $NPV=\sum_{t=1}^{T} \frac{(Rt-Ct)}{(1+r)^t} - I0$
- Where Rt is the revenue in year t, Ct is the cost in year t, r is the discount rate, I0 is the initial investment, and T is the total project duration.

- Python code for the same is below:

```
def net_present_value(revenues, costs, discount_rate, initial_investment):
    T = len(revenues)
    npv = -initial_investment
    for t in range(T):
        npv += (revenues[t] - costs[t]) / (1 + discount_rate)**(t+1)
    return npv
# Example usage
revenues = [10000, 12000, 14000]  # Revenue for each year
costs = [5000, 6000, 7000]  # Costs for each year
r = 0.05  # Discount rate
I0 = 20000  # Initial investment
NPV = net_present_value(revenues, costs, r, I0)
print(f"Net Present Value: {NPV}")
```

3. **Energy Storage System (ESS) Optimization**:

- Mathematical optimization to maximize the financial return or energy efficiency of an ESS using second-life batteries. This could involve algorithms for energy arbitrage or peak shaving, considering variable energy prices and demand charges.
- An example formula for energy arbitrage could involve maximizing the profit (P) from buying energy at low prices (Cbuy) and selling at high prices
- (Csell): $P = \sum(Csell - Cbuy) \times Es - O$ Where E is the energy stored and discharged, and O represents operational costs.
- Python code for the same is below:

```
def energy_arbitrage(buy_prices, sell_prices, energy_stored, operational_costs):
    profit = 0
    for Cbuy, Csell in zip(buy_prices, sell_prices):
        profit += (Csell - Cbuy) * energy_stored - operational_costs
    return profit
# Example usage
buy_prices = [0.1, 0.08, 0.09]  # Cost per kWh
sell_prices = [0.2, 0.22, 0.19]  # Price per kWh
Es = 100  # Energy stored and discharged each cycle
O = 10  # Operational costs
profit = energy_arbitrage(buy_prices, sell_prices, Es, O)
print(f"Profit: {profit}")
```

4. **Lifecycle Environmental Impact Assessment**:

- Formulas to calculate the reduction in greenhouse gas emissions or resource consumption by using second-life batteries instead of new ones. This could involve lifecycle assessment (LCA) methodologies to quantify environmental savings:
- $GHGsavings = GHGnew - GHGreuse$ Where GHGnew is the emissions from producing a new battery, and GHGreuse is the emissions associated with refurbishing and using a second-life battery.
- Python code for the same is below:

```
def ghg_savings(ghg_new, ghg_reuse):
return ghg_new - ghg_reuse
# Example usage
GHGnew = 50000  # Emissions from producing a new battery
GHGreuse = 20000  # Emissions from refurbishing and using a second-life battery
savings = ghg_savings(GHGnew, GHGreuse)
print(f"GHG Savings: {savings}")
```

5. **Market Analysis Models**:

- Economic models to analyze the supply and demand dynamics of second-life batteries, which could include pricing models based on battery condition, capacity, and market demand. A simple supply-demand equilibrium model could be used to predict the market price (Pm) of second-life batteries:

  Qs(Pm)=Qd(Pm)

  Where Qs is the quantity supplied, and Qd is the quantity demanded at the market price Pm.

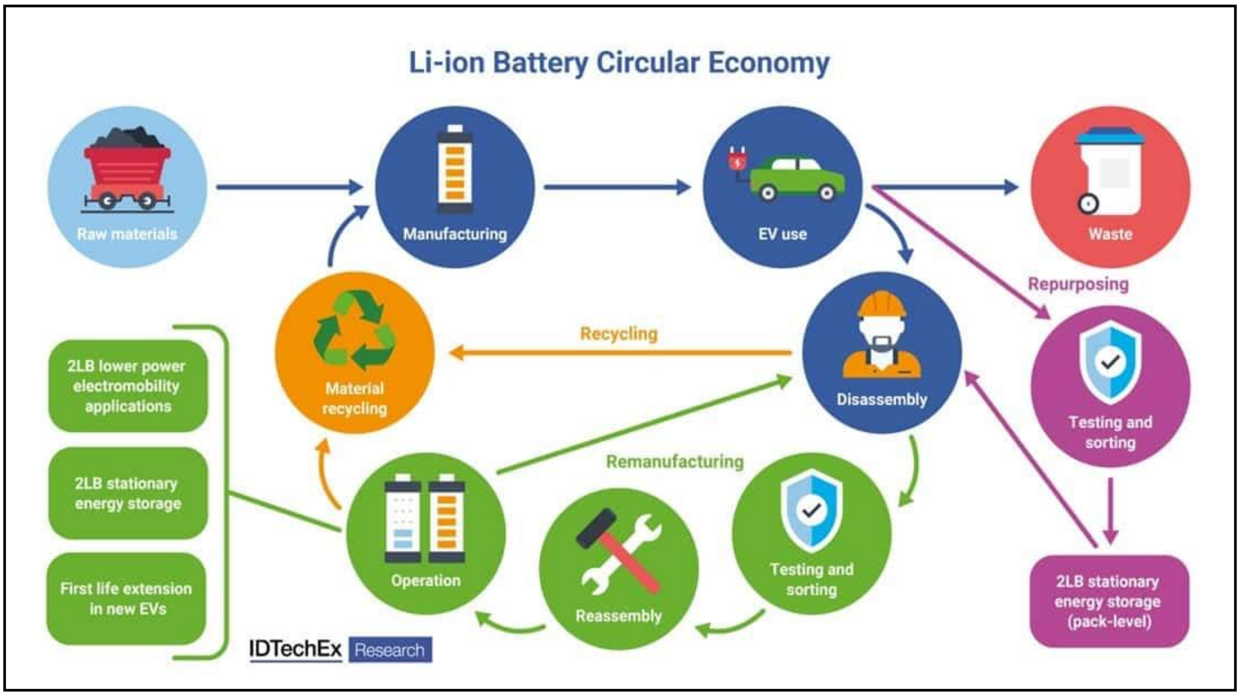

Figure 1: Battery Circular Economy

VII. APPLICATIONS OF SECOND-LIFE BATTERIES

This section seeks to unravel the potential applications for second-life batteries, assessing their suitability for less demanding uses, evaluating the viability and market size of various applications, and understanding how these applications impact battery degradation and deliver value to consumers. Second-life batteries hold promise for a range of applications, from peak demand management to renewable energy integration. They are particularly suited for off-grid and on-grid stationary uses, as well as mobile applications, offering a sustainable solution to variable energy demands.

Off-grid applications of second-life batteries provide an essential power source for isolated systems, supporting remote areas or operations disconnected from the main electricity grid. This use-case presents an opportunity to integrate with renewable energy sources, offering environmental and economic benefits. The telecom industry, especially in regions like India and China with extensive telecom infrastructure, stands to benefit from such energy solutions, replacing conventional diesel generators with cleaner, second-life battery-based systems. Additionally, industries with high energy demands, such as fresh food distribution centers, can leverage these batteries to meet their energy needs efficiently. For commercial and industrial electricity consumers subject to demand tariffs, second-life batteries offer a strategic solution to manage consumption peaks and avoid excessive charges from exceeding contracted demand. By integrating second-life batteries with renewable energy sources, consumers can effectively manage their energy use, reducing peak demand charges and fostering more sustainable energy consumption patterns.

The concept of distributed generation highlights the role of second-life batteries in enabling consumers to generate their own energy, potentially reducing the reliance on traditional energy providers. This approach not only empowers consumers but also challenges utilities to adapt their pricing models in response to changing energy landscapes. The application of second-life batteries in peak shaving—using stored energy to reduce consumption during peak periods—illustrates their capacity to stabilize the grid and offer economic benefits by lowering energy costs for consumers. This application aligns with the utility sector's goals of ensuring grid stability and reducing infrastructure investment needs by managing peak loads more effectively.

Emerging studies and models, such as those utilizing rule-based control or exploring artificial intelligence, aim to optimize the deployment of second-life batteries in these applications.

VIII. GRID OPTIMIZATION AND RENEWABLE INTEGRATION

In the realm of on-grid applications, energy arbitrage presents a transformative opportunity for utility companies to defer or diminish the necessity for constructing new power plants and reduce reliance on third-party energy purchases in the wholesale market. This model allows financial investors to purchase energy at lower prices and sell at peak rates, offering a practical approach to managing energy costs effectively. Customers benefit from energy arbitrage by shifting part of their energy consumption from peak to off-peak hours, significantly reducing their energy tariffs. For utility companies, this strategy minimizes operational costs and curtails the need for substantial investments in infrastructure.

The proliferation of second-life batteries enhances the integration of renewable energy sources (RES), serving as a crucial reserve to mitigate the intermittency of RES and fostering greater consumer participation in electricity supply and auxiliary services. The primary advantage of deploying large-scale grid-supporting storage solutions is the enhancement of power system reliability and quality. However, this comes with potential financial drawbacks and concerns over the safety and reliability of using EV battery storage units for energy support. Handling lithium-ion batteries improperly poses risks of explosion and fire, particularly in high-power demand applications. From an investment perspective, smaller-scale applications present less risk due to the vast number of residential and commercial consumers. Second-life batteries can also augment existing generator systems within buildings, allowing for energy storage and the sale of excess energy. Yet, urban applications may face challenges due to limited space and potential risks to nearby populations.

Another scenario involves consumers purchasing energy at lower rates, storing it in second-life batteries, and selling at higher prices. This requires careful consideration of technical factors like energy loss, discharge depth, and inefficiencies, which may impact the effectiveness of energy storage systems (ESSs). Customers could derive additional benefits by avoiding peak energy prices and relieving utility infrastructure load. ESSs can also enhance the quality and reliability of electrical energy consumption. In regions like California and New York, incentive programs encourage energy self-generation and storage to reduce peak demand and greenhouse gas emissions, offering financial incentives for energy storage adoption. Studies evaluating the return on investment for installing ESSs based on second-life batteries in Southern California suggest a payback period of around three years, considering current energy tariffs. Optimization methods applied to peak shaving applications show the economic viability of ESS installations at costs below a certain threshold, underscoring the potential cost savings through second-life battery utilization. Research into the economic feasibility of using second-life batteries for energy arbitrage in residential settings indicates the significance of government tax incentives in promoting job creation, renewable energy penetration, and reducing grid expansion investment needs. Case studies assessing the reuse impacts of batteries highlight the environmental benefits, despite not fully mitigating the impacts of EVs. It underscores the need for clarity on battery reuse responsibilities post-EV use, suggesting that the concept of extended producer responsibility alone may not address all supply chain conflicts.

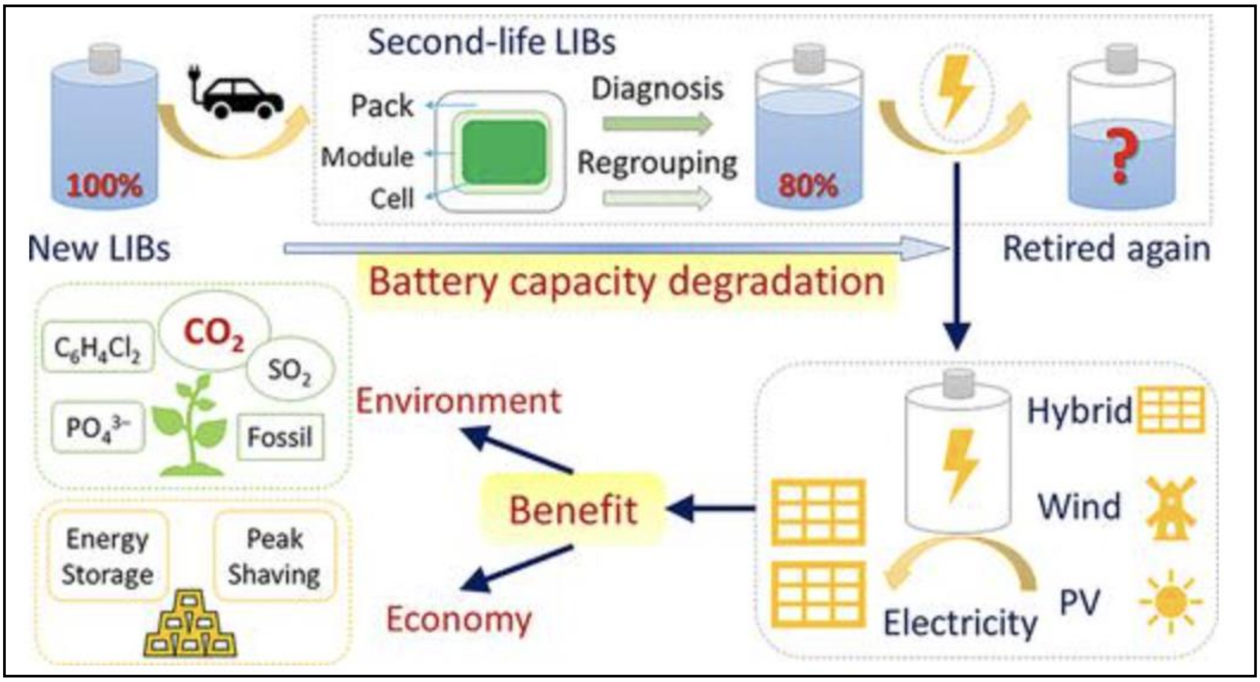

Figure 2: Second Life Battery State

In the context of on-grid applications, area and frequency regulation play a crucial role in ensuring the electrical power system (EPS) operates within regulatory standards. Variations in the fundamental frequency of the power system, often resulting from the disparity between generation and load, necessitate a robust frequency regulation system to maintain stability by adjusting the active and reactive energy. Traditional power plants, with their substantial inertia, face challenges in rapidly adjusting output to match swift load changes in the EPS. This gap presents an opportunity for second-life batteries to contribute effectively to area and frequency regulation, providing a nimble alternative to conventional generators.

Second-life batteries serve both up-regulation by injecting energy into the network and down-regulation by absorbing excess capacity, thereby maintaining a constant demand. This dual capability allows for efficient management of the electrical load, with energy absorbed or injected as needed, potentially turning into a revenue source by selling stored energy at higher prices during peak demand. The operational efficiency of second-life batteries in these roles, however, hinges on overcoming the inherent energy losses in storage. The economic viability of such applications depends on strategically selling stored energy when market prices are favorable.

Research into the lifecycle and operational viability of second-life batteries for supporting power generation plants emphasizes the necessity for comprehensive studies that account for constant demand fluctuations and the intricate dynamics of battery degradation. Regulatory frameworks, such as FERC Order 755 in the United States, have begun recognizing the value of faster and more efficient frequency regulation services, incentivizing the deployment of technologies like second-life batteries. These regulations underscore the potential for second-life batteries to enhance grid stability and support the integration of renewable energy sources. Investment analyses reveal that large-scale frequency regulation applications using second-life batteries can achieve economic viability, particularly for systems with capacities exceeding 5 MW. However, challenges related to the scalability and replicability of utilizing second-life batteries in this context remain, calling for further exploration and validation.

IX. EV CHARGING STATIONS, APPLICATION OF V2G AND CHALLENGES

The deployment of electric vehicles (EVs) necessitates the expansion of charging infrastructure, a domain where second-life batteries can significantly contribute. Despite the challenges of high implementation costs, second-life batteries offer a sustainable solution for off-grid EV charging stations, leveraging renewable energy sources for power. Vehicle-to-grid (V2G) technology capitalizes on the parked status of vehicles, allowing them to contribute energy back to the grid and alleviate peak demand pressures. This approach not only enhances grid reliability but also offers a mechanism to offset the initial costs of battery investment, making EVs equipped with second-life batteries viable for short-range and low-speed applications. Hybrid systems that combine the storage capabilities of batteries with the rapid charge and discharge rates of supercapacitors represent an innovative solution to balance cost and performance. However, optimizing these hybrid applications poses significant challenges. In summary, second-life batteries hold substantial promise for area and frequency regulation, offering a flexible and efficient alternative to traditional power generation methods. Their application in EV charging and V2G systems further underscores the potential of second-life batteries to contribute to a more sustainable and resilient energy ecosystem. Continued research and regulatory support are crucial to overcoming the existing barriers and fully unlocking the potential of second-life batteries in these applications.

The exploration into the second-life battery market reveals a burgeoning interest across the supply chain, driven by the potential to extend battery lifespan, maximize resource extraction, and profit from repurposing this valuable product. Recycling emerges as a pivotal phase, giving companies the time to refine their processes and tackle the separation of the "black mass" composed of critical materials like lithium, manganese, cobalt, and nickel. However, intermediary entities face substantial risks, including access to battery data, remanufacturing costs, and the competitive pricing of new batteries. Uncertainties persist, particularly regarding the stewardship of second-life batteries. In some jurisdictions, extended producer responsibility mandates the original distributor to manage the battery's end-of-life, yet the definition of "placing on the market" remains ambiguous and warrants further clarification.

This review underscores the need for systems to prognosticate battery health, facilitate timely maintenance, and monitor batteries in real-time. It advocates for business models that balance cost-efficiency and revenue generation while emphasizing sustainability to create value for both providers and consumers. Comparative analyses with previous studies highlight the importance of defining energy demand, current, voltage, and other technical specifications for secondary applications. These findings suggest that not all cells are suitable for reuse, with performance and degradation rates varying significantly among cells subjected to different aging processes. Investigations into second-life battery applications across charging stations, residential power, area regulation, and transmission deferral reveal varied impacts on battery aging. The research indicates that grid-connected and mobile applications may accelerate degradation, whereas off-grid uses tend to be less demanding on the batteries.

To assess economic viability, factors such as market size, operational frequency, and degradation levels must be considered. Studies suggest the residential sector as the largest market for second-life batteries, followed by telecommunications and commercial buildings, with other applications like renewable energy support and transmission deferral showing potential. The review highlights the strategic importance of navigating the second-life battery market, emphasizing the economic opportunities for companies to enhance revenue and share recycling costs. It notes the risk of insufficient battery supply for companies reliant on third-party providers and the potential loss of market and competitive edge when responsibilities are transferred to intermediaries. Challenges include the lack of standardized testing protocols for second-life batteries, underscoring the need for standards that ensure performance, reliability, and safety. The review calls for innovative testing methodologies that blend physical and virtual assessments to reduce costs and time.

X. CONCLUSION

Electric vehicles (EVs) stand as a pivotal solution for decarbonizing national energy matrices and achieving environmental objectives. Despite the promising growth of the EV market, further advancements in battery technology are essential to lower costs, enhance energy density, extend lifespan, improve performance and safety, and ensure sustainability. It's crucial for batteries at the end of their useful life to be efficiently collected, treated, and recycled to the greatest extent possible.

This review delves into the second-life battery market, exploring established business models, identifying barriers and opportunities for battery reuse, highlighting ongoing projects, and pinpointing key market players. The market segmentation into open, closed, and intermediary categories reveals distinct opportunities and challenges. Critical considerations include access to a battery's historical data, government incentives, the volume of batteries available for reuse, and the necessity for remanufacturing and testing to determine the battery's condition after its first life. Energy arbitrage, integration with grid-connected and off-grid power generation systems, energy provision for construction sites and events, peak shaving, energy storage at EV charging stations, and applications in short-range vehicles emerge as promising secondary applications for second-life batteries.

The study underscores the absence of public policies aimed at bolstering the infrastructure for the collection, reuse, and recycling of batteries. Implementing punitive and reward mechanisms could incentivize companies to meet sustainability targets or penalize those that fall short. While research into the second-life battery market has commenced, the exploration of business models specific to this sector is still in early stages. Challenges include a lack of standardization and the high costs associated with testing second-life batteries. Questions remain regarding the pricing of used batteries, responsibilities for battery reuse and recycling, and the complexity of the second-life battery market, which encompasses collection, testing, remanufacturing, and evaluating environmental impacts. The longevity of a battery in a secondary application is contingent upon its operational history in EVs, making lifespan estimation challenging due to the variable degradation rates of batteries under identical conditions.

Anticipating growth in research on second-life battery business models, there's a shift from traditional product-centric models toward service-oriented approaches. Future business models in the second-life battery market may focus on either selling the battery directly or offering a service enabled by products incorporating second-life batteries, such as EV charging services at stations equipped with these batteries. This evolution reflects the broader trend towards service-based models, indicating significant potential for innovation and sustainability in the second-life battery sector.

REFERENCES

1. Shareef H, Maytham SA, Mohammad A, Al-Hassan E. Review on home energy management system considering demand response, smart technologies, and intelligent controllers. IEEE Access. 2018;6:24498-24509.
2. Muller T, Most D. Demand response potentials: available when needed? Energy Policy. 2018;115:181-198.
3. Chau S, Kirschen D. Quantifying the effect of demand response on electricity markets. IEEE Trans Power Syst. 2009;24:1199-1207.
4. Ghorbani N, Kasaeian A, Toopshekan A, Bahrami L, Maghami A. Optimizing of a hybrid wind-PV-Battery system using GA-PSO and MOPSO for reducing cost and increasing reliability. Energy. 2018;154:581-591.
5. Shayesteh E, Elias M, Kohan N, Moghaddam MP. Security-based demand response allocation. Paper presented at: IEEE Power & Energy Society General Meeting. 2009.
6. Srivastava A, Passal SV, Laes E. Assessing the success of electricity demand response programs: a meta-analysis. Energy Res Soc Sci. 2018;40:110-117.
7. Zheng W, Wu W, Zhang B, Lin C. Distributed optimal residential demand response considering constraints of unbalanced distribution networks. IET Gener Transm Distr. 2018;12(9):1970-1979.
8. Asadinejad A, Rahimpour A, Tomsovic K, Qi H, Chen C. Evaluation of residential customer elasticity for incentive-based demand response. Electric Power Syst Res. 2018;158:26-36.
9. Jalili H, Siano P. Modeling of unforced demand response programs. Int J Emerg Electr Power Syst. 2021;22:233-241.
10. Alazemi FZ, Hatata AY. Ant lion optimizer for optimum economic dispatch considering demand response as a visual power plant. Electr Power Compon Syst. 2019;47:629-643.
11. Campos J, Csontos C, Harmat A, Csüllög G, Munkácsy B. Heat consumption scenarios in the rural residential sector: the potential of heat pump-based demand-side management for sustainable heating. Energy Sustain Soc. 2020;10:40.
12. Kwang HG, Kim J. Optimal combined scheduling of generation and demand resource constraints. Appl Energy. 2012;96:161-170.

13. Aalami HA, Moghaddam P, Yousefi GR. Modeling and prioritizing demand response programs in power markets. Electr Power Syst Res. 2010;80:426-435.
14. Sharifi R, Fathi SH, Moghaddam A, Guerrero JM, Vahidinasab V. An economic customer-oriented demand response model in electricity market. Paper presented at: International Conference on Industrial Technology (ICIT), IEEE conference; 2018:1149-1153.
15. Bie Z, Xie H, Hu G, Li G. Optimal scheduling of power systems considering demand response. J Mod Power Syst Clean Energy. 2016;4(2):180-187.
16. Elnozahy A, Ramadan HS, Abo-Elyousr FK. Efficient metaheuristic Utopia-based multi-objective solutions of optimal battery-mix storage for microgrids. J Clean Prod. 2021;303:127038.
17. Goudarzi S, Hassan W, Anisi MH, et al. ABC-PSO for vertical handover in heterogeneous wireless networks. Neurocomputing. 2017;256:63-81.
18. Basu M. Fast convergence evolutionary programming for multi-area economic dispatch. Electr Power Compon Syst. 2017;45:1629-1637.
19. Huo D, Gu C, Yang G, Le Blond S. Combined domestic demand response and energy hub optimization with renewable generation uncertainty. Energy Procedia. 2017;142:1985-1990.
20. Viana MS, Junior GM, Udaeta MEM. Analysis of demand response and photovoltaic distributed generation as resources for power utility planning. Appl Energy. 2018;217:456-466.
21. Nan S, Zhou M. Optimal residential community demand response scheduling in smart grid. Appl Energy. 2018;210:1280-1289.