Clean Energy Technol J, Vol. 3, No. 2, pp. 62-72, December, 2025

Clean Energy Technologies Journal
Web page info: https://cetj.yildiz.edu.tr
DOI: 10.14744/cetj.2025.0006

CLEAN ENERGY TECHNOLOGIES JOURNAL

Technical Note

Establishing a pioneering laboratory for second-life battery applications: Enhancing energy storage and reducing environmental impact

Murat AKKUŞ[1], İbrahim ESKİ[2*], Ali Rıfat BOYNUEĞRİ[1,2]

[1]*Department of Electrical Engineering, Yildiz Technical University, Istanbul, Türkiye*
[2]*Clean Energy Technologies Institute, Yildiz Technical University, Istanbul, Türkiye*

ARTICLE INFO

Article history
Received: 20 March 2025
Accepted: 16 May 2025

Key words:
Aging; Battery; End-of-life; Laboratory; Second-life.

ABSTRACT

Battery technologies are important in advancing energy storage systems (ESS), particularly focusing on transitioning from end-of-life to second-life applications. This paper explores a variety of battery types including lead acid, lithium-ion, nickel-cadmium, and nickel-metal hydride, detailing their characteristics, applications, and the recycling challenges they present. Special emphasis is given to lithium-ion batteries due to their high energy density and widespread use in electric vehicles and portable devices. The limited lifespan of these batteries highlights significant economic and environmental challenges, emphasizing the necessity for efficient second-life usage and improved recycling strategies. To address these challenges, the establishment of a specialized battery research laboratory is proposed. The laboratory aims to enhance battery lifespan, optimize designs for second-life use, and advance recycling processes. Positioned as an innovation hub, this laboratory is expected to drive advancements in battery technology, fostering sustainable and economically viable energy solutions. The integration of theoretical analyses with practical case studies offers a comprehensive look at the current state and future potential of battery technology in ESS, underscoring its importance in achieving a more sustainable energy future.

Cite this article as: Akkuş M, Eski İ, Boynueğri AR Establishing a pioneering laboratory for second-life battery applications: Enhancing energy storage and reducing environmental impact. Clean Energy Technol J 2025;3(2):62–72.

INTRODUCTION

Due to technological advances and the increasing reliance on intermittent renewable sources like solar and wind, energy storage has become a crucial component of grid systems. Energy storage systems (ESS) are important technologies that enable the storage and conversion of electrical energy in different forms. Although various ESS such as supercapacitors and hydroelectric storage exist, batteries have become the most prevalent, particularly in electric vehicles (EVs), portable devices, and power grids. This widespread adoption is due to their ability to provide an environmentally friendly option for energy storage [1].

To reduce the negative effects caused by long-term use of traditional energy sources, clean energy sources have come to the fore in the fields of energy production and consumption. By encouraging the use of clean energy, elec-

***Corresponding author**
*E-mail adress: ibrahim.eski@yildiz.edu.tr

trification has become widespread in every field. However, the inability to store energy on a large scale has been a significant obstacle in this field. To overcome this obstacle, batteries have become critical for industrial and consumer applications, and their technology is constantly evolving. Next-generation batteries offer higher energy density and performance than traditional batteries [2].

In the battery industry, battery types such as Lead Acid (Pb-Acid), Lithium Ion (Li-ion), Nickel-Cadmium (NiCd) and Nickel-Metal Hydride (NiMH) are generally used [3]. In Lead Acid batteries, Pb is used as the cathode, Lead Dioxide (PbO_2) as the anode and sulfuric acid (H_2SO_4) as the electrolyte. $PbSO_4$ is formed in the reaction between lead dioxide and lead during charging. During discharge, this reaction occurs in reverse. This type of battery has low energy density but is suitable for high current applications. Besides, it is safe and low cost [4]. Lithium-ion batteries use lithium as the cathode, graphite (C) as the anode, and solid polymer electrolytes or liquid electrolytes as the electrolyte. During charging, lithium ions pass from the cathode to the anode. During discharge, this reaction occurs in reverse. These types of batteries have a high energy density, long life cycle, and are lightweight, but they have some disadvantages in terms of thermal stability, safety, and cost [5,6]. In Nickel-Cadmium batteries, nickel oxide-hydroxide is used as the cathode, cadmium is used as the anode, and aqueous alkaline solutions are used as the electrolyte. During charging, electrons flow from the nickel oxide-hydroxide cathode to the cadmium anode. During discharge, this reaction occurs in reverse. These types of batteries have high energy density and long cycle life, but they have disadvantages such as memory effect, environmental effects of cadmium and not being suitable for low current discharge [7,8]. Nickel-Metal Hydride batteries use nickel oxide-hydroxide as the cathode, metal hydride as the anode, and potassium hydroxide as the electrolyte. During charging, electrons flow from the nickel oxide-hydroxide cathode to the metal hydride anode. During discharge, this reaction occurs in reverse. While these types of batteries have advantages such as high energy density, high-rate capability, no memory effect and high tolerance against overdischarge, they have disadvantages such as self-discharge, charging efficiency and low life cycle [3,7]. Table 1 shows the comparison of the mentioned batteries in terms of nominal voltage, power density, energy density, charging efficiency, life cycle, self-discharge rate, charging temperature, discharging temperature [3, 9].

Highlights

- Second-life battery applications extend the usability of end-of-life (EOL) batteries in energy storage systems, reducing waste and supporting sustainability.
- Challenges in battery recycling include high costs and inadequate facilities, emphasizing the need for efficient second-life usage over traditional recycling methods.
- The proposed laboratory aims to optimize battery designs for first and second use, focusing on extending lifespan and enhancing performance.

Among these commonly used battery types, the most used battery type is lithium-ion batteries. These batteries are preferred in many portable devices and vehicles because they have high energy density, longer cycle life, low mass, and low self-discharge rate [5,6]. Lithium-ion batteries can be classified according to the use of different cathode materials. The use of different cathodes brings different features, advantages and disadvantages, and leads to significant variations in key performance metrics such as cycle life. This is why, as seen in Table 1, Li-ion batteries show a wide distribution in cycle life, ranging from 600 to 3000. According to different cathode types, lithium-ion batteries can be classified as follows: Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$ or NMC), Lithium Iron Phosphate (LFP), Lithium Nickel Cobalt Aluminum Oxide ($LiNiCoAlO_2$ or NCA), Lithium Manganese Spinel (LMO), Lithium Titanate (LTO), Lithium Nickel Alloys (Li-Ni).

NMC cathode used in Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$) batteries uses a mixture containing the elements nickel, manganese, and cobalt. By adjusting the proportions of the elements in the NMC cathode composition, it is possible to produce materials with varying characteristics. [10]. Lithium Iron Phosphate (LFP) is generally preferred for high safety and low cost, but its energy density is slightly lower than other lithium-ion battery types [11]. Lithium Nickel Cobalt Aluminum Oxide (NCA)

Table 1. Comparison of some battery technologies.

Battery type	Nominal voltage (V)	Power density (W/kg)	Energy density (Wh/kg)	Charging efficiency (%)	Cycle life	Self-discharge rate (%/month)	Charging temperature (°C)	Discharging temperature (°C)
Li-ion	3.2-3.7	250-680	100-270	80-90	600-3000	3-10	0 to 45	-20 to 60
NiCd	1.2	150	50-80	70-90	1000	20	0 to 45	-20 to 65
Lead Acid	2	180	30-50	50-95	200-300	5	-20 to 50	-20 to 50
NiMH	1.2	250-1000	60-120	65	300-600	30	0 to 45	-20 to 65

uses a mixture containing the elements nickel, cobalt, and aluminum. These cathodes are generally preferred for high energy density and long life cycle [12]. Lithium Manganese Spinel (LMO) contains lithium manganate ($LiMn_2O_4$). These batteries are generally preferred for low cost and high safety. However, they are also noted for their capacity fade during cycles, particularly at high temperatures [13]. Lithium Titanium Oxide (LTO) contains lithium titanat ($Li_4Ti_5O_{12}$). These batteries are generally preferred for their high safety, long cycle life and fast charge/discharge features [14]. Lithium Nickel Alloys (Li-Ni) contain alloys of lithium and nickel in various proportions. These batteries are generally preferred for their high energy density and low cost [15]. Table 2 shows the comparison of the lithium-based battery types mentioned above in terms of cathode material, anode material, nominal voltage, cycle life, energy density, cost and safety. In addition, comparisons of the relevant battery types in terms of energy density and specific energy are given in Figure 1 [3,16].

The growing adoption of EVs and the development of higher-capacity batteries are key drivers behind the increasing prevalence of battery usage. However, currently the lifespan of the batteries is not at the desired levels. This situation prevents the full potential of developments in battery technology from being used. The short lifespan of batteries causes increased costs and difficulties in achieving sustainability goals. In addition, batteries that have been retired from use pose a major waste problem because they contain environmental risks due to their chemical structure. Especially with the widespread use of EVs, it is expected that a significant amount of used EV batteries will emerge in the coming years. This situation further increases the importance of waste battery management and second-life battery (SLB) applications.

The increasing cumulative capacity of used EV batteries shows that the importance of second-use batteries is increasing and that they have a supporting role in ESS. Figure 2 shows how the supply of second-life lithium-ion batteries is today and where it is expected to reach by 2030 [17].

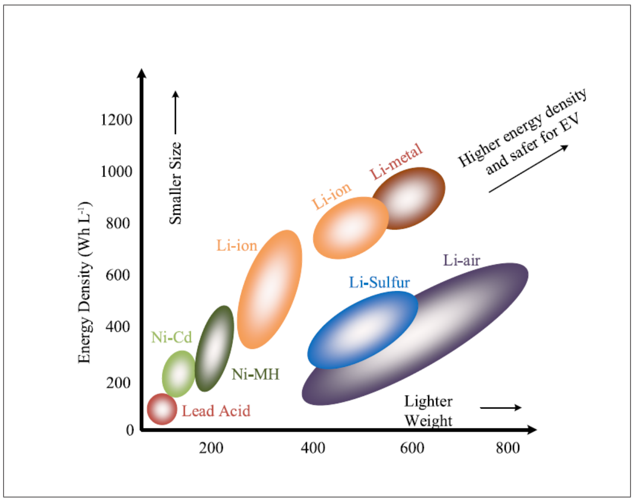

Figure 1. Energy density and specific energy comparison of different batteries [3].

Although recycling of batteries is very important in terms of providing the raw materials required for battery production, it has remained far from being a solution to the waste battery problem because of the reasons like the lack of advanced recycling techniques for each battery chemistry, lack of global or regional waste battery collection networks, high recycling costs, and the inadequacy of recycling facilities. Instead, reusing batteries after their first use (i.e. second-life usage) makes a great contribution to solving the waste battery problem [18]. In addition, batteries, which still have the potential to provide high energy after their first use, only separate the valuable metals and similar materials they contain through recycling, meaning that their potential is mostly lost.

Table 2. Comparison of the lithium-based battery types.

Battery type	Anode material	Nominal voltage (V)	Cycle life	Energy density (Wh/L)	Cost	Safety
Lithium Iron Phosphate ($LiFePO_4$)	Graphite	3.2	High	Low	High	Safest Li-ion cell chemistry
Lithium Cobalt Oxide ($LiCoO_2$)	Graphite	3.6	Medium	High	Low	Highest safety concern
Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$)	Graphite	3.6	Medium	High	Medium	Good safety
Lithium Manganese Oxide ($LiMn_2O_4$)	Graphite	3.7	Low	Low	Medium	Good safety
Lithium Nickel Cobalt Aluminum Oxide ($LiNiCoAlO_2$)	Graphite	3.6	High	High	Medium	Safety concern required

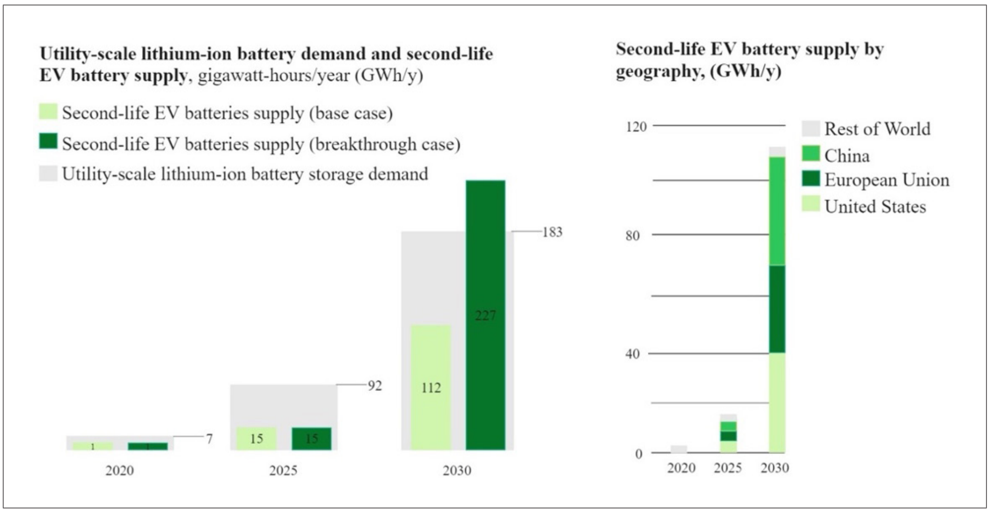

Figure 2. Second-life lithium-ion battery supply: Present and future.

Second-life applications include evaluating used batteries in ESS, power backup systems, renewable energy integration, and other areas. In addition to extending battery life, these applications help utilize resources more effectively and reduce environmental impacts. Additionally, second-life applications are economically advantageous because the value and performance of used batteries can still be maintained. Therefore, considering and encouraging second-life applications during battery design and usage stages is an important strategy to create a sustainable battery ecosystem. This approach should be considered an important step towards a more sustainable future, both environmentally and economically.

In this context, various studies have explored how second-life batteries can be effectively reused in different sectors. These studies examine the technical feasibility, economic viability, and environmental benefits of second-life scenarios in real-world applications. Table 3 provides an overview of literature studies that explore how second-life EV batteries are used in various scenarios [19].

Laboratories investigating the optimal design of batteries in the first and second use stages, aging tests and second use possibilities, and studies conducted in this field, increase awareness about the efficient use of batteries and enable an important step to be taken for an environmentally friendly energy future. In this process, critical parameters such as battery chemistry, size, cover, and cooling system must be optimized by considering the relevant constraints and requirements [42]. Thanks to these optimized parameters, the batteries will exhibit the desired performance and minimize the materials used while providing maximum performance and life. This approach will support sustainability and efficiency goals by making significant contributions to the world ecosystem. Additionally, it will facilitate the integration of renewable energy sources and increase energy efficiency by increasing the ESS' efficiency.

Many companies operate in the field of battery design and optimization. However, services for the optimal design of batteries used in second-life applications are not yet widely available. Batteries with secondary use potential play an important role in ESS and other applications. Therefore, specially designed services are needed to increase the performance, efficiency and durability of end-of-life (EOL) batteries [43]. These services must consider factors such as battery chemistry, capacity management, storage conditions and safety to ensure that batteries use their second life in the most efficient way. Encouraging R&D studies in this field will make significant contributions to an economy that adopts an environmentally sustainable approach.

Infrastructure, Technological Capacity of the Laboratory and Research & Development Activities

Battery technologies are becoming increasingly crucial worldwide, especially in EVs, renewable energy integration, and energy storage. This rapid advancement has created a strong demand for qualified personnel skilled in battery design, production, testing, and second-life applications, as well as R&D. Collaboration between academia and industry plays a vital role in training these experts. Organizing specialized training programs, workshops, and knowledge-sharing platforms will help develop young talent and foster innovation. Strengthening human resources in battery technologies is essential for building a sustainable future.

Battery testing laboratories and a limited number of battery aging laboratories are established in many areas, including the private sector. However, many of these laboratories were established for the purpose of producing battery cells, producing battery stacks from cells, or testing batteries for specific usage needs. The lack of an impartial and non-profit central battery design laboratory is felt. These laboratories are generally designed to suit the specific needs of the organizations. However, there is no laboratory that can record

Table 3. Overview of application scenarios and cases of second-life EVBs.

Category	Application Scenario	Function	Reference
Power generation	Renewable energy power station	Renewable energy integration, smoothing control, reducing curtailed electricity	Wind-Hamidi et al. [20], Alhadri et al. [21], BYD [22], PV-Koch-Ciobotaru et al. [23], Saez-de-Ibarra et al. [24], Leung [25], Fitzpatrick [26]
Grid	Power transmission and distribution network	Alleviate grid congestion, offer ancillary support to the network, and delay the expansion of power transmission and distribution capacity	Neubauer et al. [27], Lacey et al. [28], Eyer and Corey [29]
End-user	Communication base station,	Backup power stage	Li [30], Yan [31]
	EV charging stations,	EV charging	Jiao et al. [32], Han et al. [33], Kamath et al. [34]
	Mobile energy storage device,	Community EV charging Power supply for camping trailers	Potevio New Energy [35]
	Low-speed electric vehicle,	EV energy storage	Nissan Energy [36]
	Street lamp	Energy storage for lamp	Zhang et al. [37], Zhao [38]
	Uninterrupted Power Systems (UPS)	Emergency power	Zhu et al. [39]
	Residential energy storage	Emergency power, reduce electricity costs	Canals Casals et al. [40], Neubauer et al. [41]

battery data for all types of battery cells and environmental conditions, match and make sense of these data using artificial intelligence, test next-generation battery technologies at the cell level and report their performance according to environmental conditions. Moreover, a laboratory that details the optimal application selection, sizing and pricing for the reuse of batteries by considering second-life applications will have a unique position internationally.

As a result, increasing battery usage and their short lifespan leads to serious economic problem due to the use of rare-earth elements. To solve this problem, it is important to use resources in the most efficient way. The second use offers the potential to be used in other applications for up to 8-10 years after the batteries have reached their EOL [44]. However, the second use issue is not yet widespread and faces various obstacles including concerns about planning, security, financial management, and market acceptance. These factors are important challenges that need to be overcome for second use applications to become widespread and potential opportunities to be utilized [45].

The battery laboratory to be established will address the interests of a wide range of sectors that use batteries including important areas such as white goods, EVs, micromobility, telecommunications, defense industry, space industry, and electricity distribution, production, and transmission. These sectors will both play a role as customers for battery design and development and become battery providers for second-life use. In this way, batteries that have reached the end of their first life in one sector can be used as cheap energy storage units in other sectors. This will create an ecosystem and enable the recycling and reuse of batteries with reduced capacity.

This approach aims to use resources more efficiently and ensure environmental sustainability. Moreover, in some cases, the needs of battery firms are based solely on data. Rather than each company setting up separate laboratories, a centralized facility offering data and testing services can more effectively meet sector requirements. Furthermore, inefficiencies and flawed designs stemming from the lack of competent personnel increase costs and reduce the battery performance.

Especially in products that go directly to the end-user, high battery costs cause decision changes and raise questions in terms of reliability. Batteries that have completed their first life in applications that require high C ratio, power and energy density, such as EV and defense and space industries, can be used for another 8-10 years in applications that do not have volume and weight problems, such as UPS and grid level storage systems. However, this opportunity cannot be utilized due to lack of testing, analysis and experts.

The laboratory to be established will enable next-generation battery materials to be tested in real application conditions in cell form. This step will accelerate the transformation of materials into commercial products and enable processes such as valuation and sale of patents. Moreover, academic and R&D studies on second-life applications are limited and there is not enough data for realistic aging processes of batteries. There is a lack of data, especially regarding the performance of aged batteries in applications and the parameters required for design. With the establishment of the laboratory, aging data will be collected and analyzed in this regard. These data will constitute an important resource for second-life applications of batteries and will support the industry's efforts in this field.

In universities and R&D centers, a lack of scientists and employment in the relevant field is observed. These institutions have difficulties in recruiting qualified personnel. It is aimed for universities and R&D centers to meet this need with activities such as establishing laboratories, in-house internships, trainings and personnel exchange. In this way, competent personnel will be provided to the sector and research and development studies will be carried out more efficiently. In addition, training and information sharing through laboratories will contribute to the strengthening of universities and R&D centers in their areas of expertise.

In Figure 3, the important stages in the battery laboratory to be established is given. The process begins at the cell and stack levels, where monitoring of internal resistance, thermal and mechanical design, and appropriate storage conditions are critical to ensure baseline performance. During storage and operation, the battery is exposed to temperature variations, state-of-charge changes, and aging, which affect overall capacity and reliability. Electrical and thermal protections must be implemented to ensure safe operation over a prolonged period, ideally up to ten years.

As batteries retire from their first life, proper evaluation during vehicle parking duration allows early identification of degradation patterns. In the second-life stage, economically viable reuse applications are explored in consumer electronics, small-scale e-mobility, or ESS. Finally, environmentally responsible recycling is essential to recover valuable materials like nickel, manganese, and lithium while minimizing waste. Each phase in this cycle forms a critical part of the second-life battery workflow.

Subunits of the Laboratory

The aim of this project includes the establishment of various subunits to promote developments in battery technologies and support specialization in this field. In line with this objective, a total of nine interconnected subunits have been designed to cover the entire lifecycle of batteries—from performance evaluation and second-life optimization to economic assessment, user awareness, and training. These subunits collectively form a comprehensive and multidisciplinary research and development infrastructure that can support both industrial and academic needs in the battery sector. The overall system architecture is given in Figure 4.

Each subunit has been structured to fulfill a specific role within this ecosystem. These include the Cell Aging Subunit, Stack Analysis and Aging Subunit, Battery Design and Optimization BMS Design Subunit, Data and Visualization Center, Next-Generation Battery Test Subunit, Economic Battery Management System Subunit, Training Center, and Awareness Center. Additionally, the infrastructure is supported by a mobile application interface designed to make battery monitoring accessible to all user profiles.

The Cell Aging Subunit aims to conduct research to increase batteries' performance and lifespan by examining the aging processes of battery cells. The obtained here will be held in the database and used in the Battery Design Center of the laboratory, and designs for the second use will be based on these data. This subunit will also play an important role in testing the durability of battery materials and structures for long-term use and monitoring their performance.

The Stack Analysis and Aging Subunit of the laboratory is dedicated to evaluating the performance and aging behavior of battery stacks composed of multiple cells. By subjecting these stacks to various charge/discharge cycles, thermal conditions,

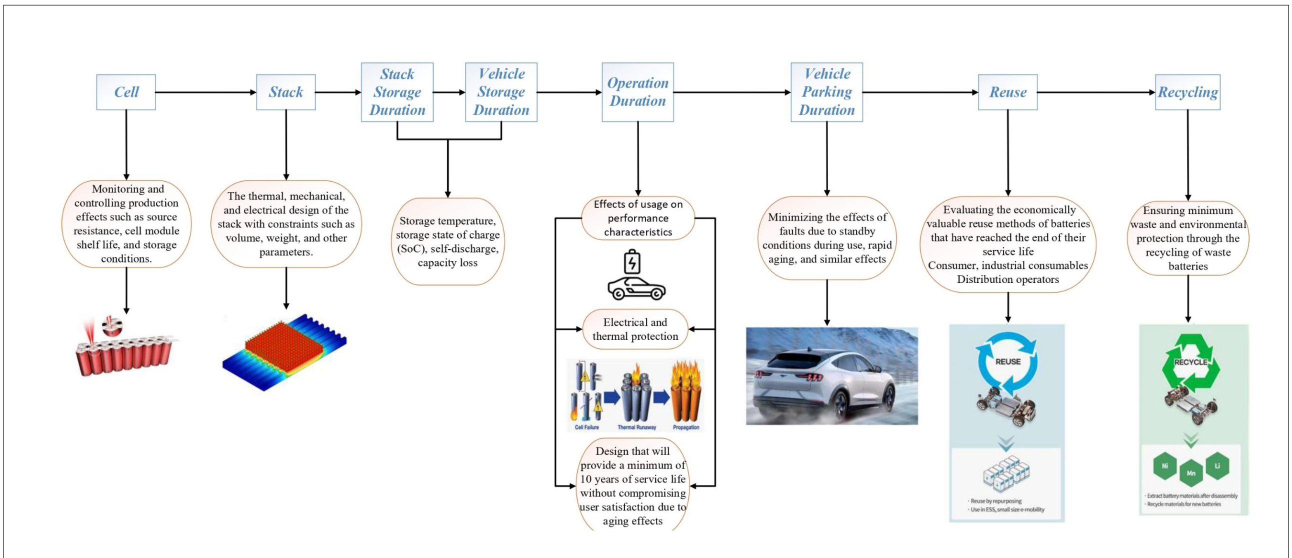

Figure 3. Important stages in the battery laboratory to be established.

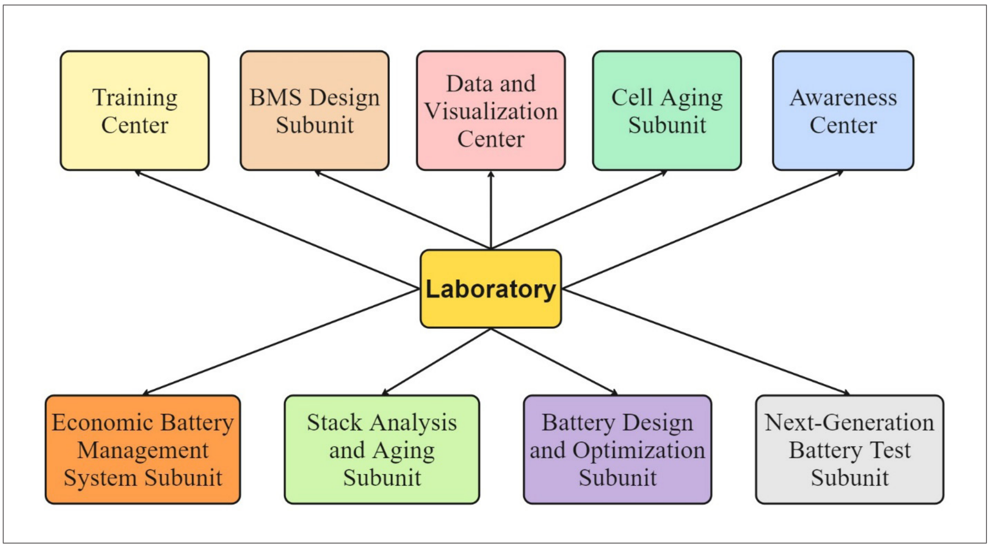

Figure 4. The subunits of the laboratory.

and usage profiles, this unit aims to identify degradation patterns and performance losses over time. The test results will help determine the suitability of these stacks for continued use or second-life applications. Moreover, the findings from this subunit will support the development of standardized testing protocols and contribute to the design of safer and more durable battery systems suited for daily-use scenarios.

The Battery Design and Optimization Subunit aims to increase the energy density, efficiency, and reliability of battery systems by employing advanced design and optimization techniques. This subunit will not only support internal R&D activities but also offer external battery design services for industrial and institutional partners. Initially, its primary focus will be on the design and optimization of newly developed battery systems, where various parameters such as cell configuration, thermal control, and electrical layout will be fine-tuned to meet application-specific requirements. In addition to new battery designs, the subunit will also play a key role in the reuse of aged batteries by utilizing performance and aging data collected from other laboratory units. By incorporating this data into the design process, the subunit will develop second-life battery systems that are both cost-effective and operationally safe. This dual-function approach—addressing both first-life and second-life battery design needs—positions the subunit as a critical component in achieving a circular battery economy and promoting sustainable energy storage practices.

Figure 5 illustrates the conceptual structure of the smart Battery Management System (BMS) developed within the BMS Design Subunit. This unit is dedicated to enhancing battery safety, performance, and lifespan by focusing on the design and optimization of advanced BMS architectures. A key approach involves leveraging large-scale data acquired from battery testing processes, which is then analyzed using artificial intelligence and deep learning algorithms. Through this data-driven strategy, the system can predict battery health status and remaining useful life with improved accuracy. In addition to its AI-driven capabilities, the smart BMS incorporates a modular hardware and software design, enabling flexible integration and rapid prototyping. As seen in the figure, the platform utilizes next-generation, high-efficiency hardware components that contribute to power savings and increased reliability. Furthermore, an integrated approach underpins the entire system, ensuring cohesive operation among sensing, control, and communication layers.

The Data and Visualization Center is a subunit that aims to facilitate the monitoring and control of battery systems

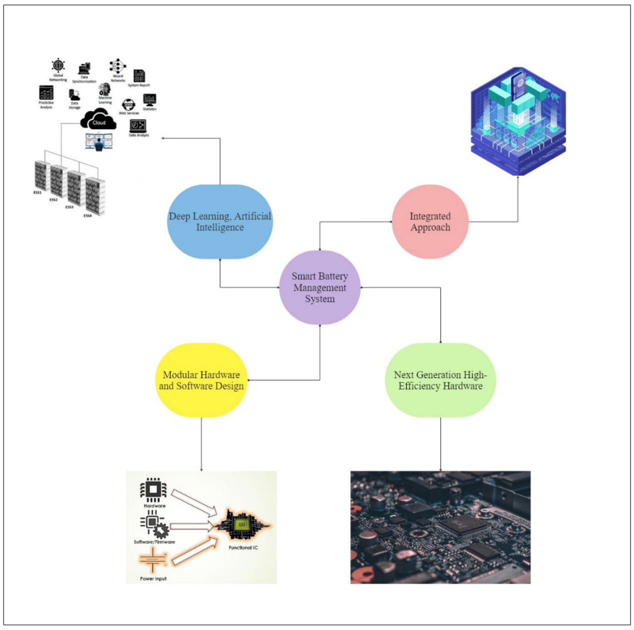

Figure 5. The block diagram of smart Battery Management System (BMS).

by collecting and analyzing data on battery performance and presenting them in a way that is understandable to users. In addition, the data in this center will be processed with artificial intelligence and form the infrastructure of the software to be used in BMSs.

The Next-Generation Battery Test Subunit is designed to establish a comprehensive and advanced testing infrastructure for evaluating the performance, durability, and safety of innovative battery technologies. Within this unit, developed battery materials are first assembled into test cells, which are then subjected to controlled testing conditions using a climate control chamber to simulate various environmental parameters such as temperature and humidity. The electronic load/source unit applies dynamic charge/discharge profiles to the battery cells, while a main computer provides real-time signal control and data acquisition. All measurement results—such as voltage, current, temperature, and capacity—are recorded and analyzed through integrated software tools. After testing, the center delivers detailed technical reports and performance evaluations, enabling standardization and benchmarking of next-generation battery cells under aging and operational stress conditions. The block diagram of the battery cycle aging test setup is given in Figure 6.

The Economic Battery Management System Subunit aims to conduct cost analyzes to ensure that battery systems are economically sustainable and to develop strategies to increase the economic value of energy storage projects. In addition, it is a system that will analyze the market values and price projections of second-life batteries as they transition from the first life to the second life within the optimum time.

The Training Center is a subunit that aims to organize training programs on battery technologies and train qualified human resources in accordance with the needs of the

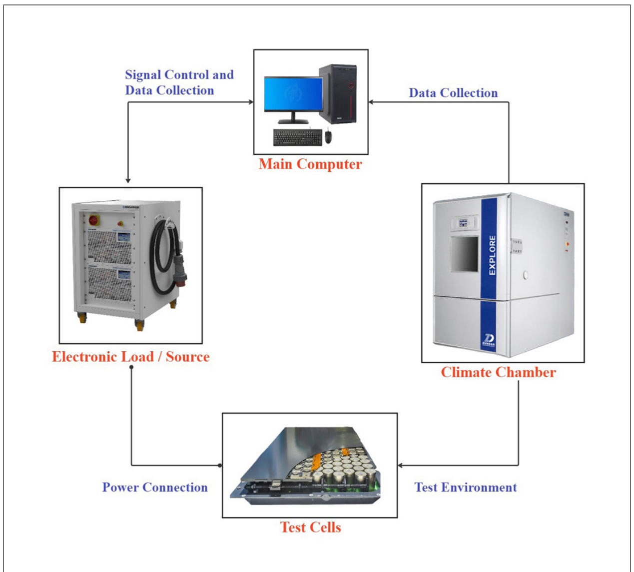

Figure 6. The block diagram of battery cycle aging test.

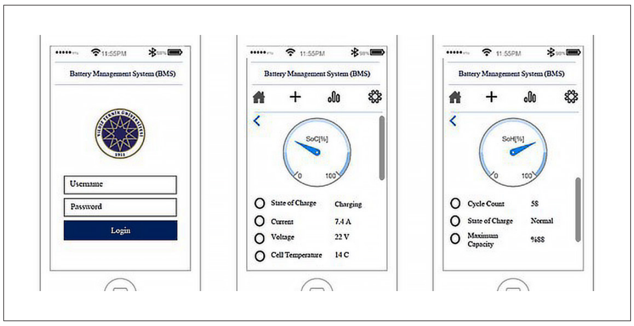

Figure 7. Conceptual mobile application interface.

sector. By creating modular, classified training contents and plans, a training center will be established to meet the employment needs for the private sector and the public, including technical personnel at all levels, as well as manager and planner levels.

The Awareness Center is a subunit that aims to increase the society's knowledge about the benefits, use, recycling and sustainability of battery technologies. By informing the society about the mentioned issues, this center will extend the average battery life in the country and will also raise awareness in the relevant sectors about sustainability-supporting practices such as recycling and second use.

In the final stage, all data regarding the SoH and optimum sizing of the battery will be presented as output by developing a software. The mobile application, which can run on both Android and iOS platforms, will create a user interface in this context. The interface will be designed by creating a user experience in which even people who are unfamiliar with technology can easily use the application. On the first page of the application, the user will be asked for login information to enter the system. On the other screen, the user will be able to examine technical values such as SoC and SoH values of the storage device, charge and discharge status, current, voltage, cell temperature, total number of cycles, whether the storage device is usable or not, and the status of its maximum capacity. A conceptual mobile application interface is given in Figure 7.

By establishing these subunits, it is aimed to achieve goals such as developing battery technologies, increasing performance, determining safety standards, ensuring economic sustainability, training qualified human resources and raising public awareness. These subunits will contribute to the country's leading position by supporting innovations in battery technologies and will enable an important step towards the sustainable energy future.

CONCLUSION

As global demand for energy storage continues to rise alongside the proliferation of EVs and renewable energy sources, the challenges of battery lifecycle management have become increasingly critical. Conventional battery recycling methods, while essential, remain limited in scale and efficiency, often failing to fully address the economic and environmental consequences of EOL batteries. In this context, second-life applications emerge as a highly viable and sustainable alternative that not only extends battery lifespan but also significantly reduces waste and resource consumption.

This paper presents an overview of major battery technologies and emphasizes the growing need for second-life battery usage. The proposed laboratory, with its advanced technological infrastructure and specialized subunits, aims to establish a unique ecosystem that facilitates the reuse of EOL batteries in various applications, from ESS to small-scale mobility solutions. The laboratory's holistic design—including its focus on aging analysis, battery design optimization, smart BMS integration, economic evaluation, and data management—ensures that batteries can be repurposed safely and efficiently. Moreover, by bridging academic research and industrial needs, the lab supports the development of standards and practical solutions suited to real-world challenges.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that support the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

REFERENCES

[1] Worku MY. Recent advances in energy storage systems for renewable source grid integration: A comprehensive review. Sustainable 2022;14:5985. [CrossRef]

[2] Rey SO, Romero JA, Romero LT, Martinez AF, Roger XS, Qamar MA, et al. Powering the future: A comprehensive review of battery energy storage systems. Energies 2023;16:6344. [CrossRef]

[3] Ranjith Kumar R, Bharatiraja C, Udhayakumar K, Devakirubakaran S, Sekar KS, Mihet-Popa L. Advances in batteries, battery modeling, battery management system, battery thermal management, SOC, SOH, and charge/discharge characteristics in EV applications. IEEE Access 2023;11:105761–105809. [CrossRef]

[4] May GJ, Davidson A, Monahov B. Lead batteries for utility energy storage: A review. J Energy Storage 2018;15:145–157. [CrossRef]

[5] Deng D. Li-ion batteries: Basics, progress, and challenges. Energy Sci Eng 2015;3:385–418.

[6] Goodenough JB, Park KS. The Li-ion rechargeable battery: A perspective. J Am Chem Soc 2013;135:1167–1176. [CrossRef]

[7] Shukla AK, Venugopalan S, Hariprakash B. Nickel-based rechargeable batteries. J Power Sources 2001;100:125–148.

[8] Pistoia G, Liaw B. Behaviour of lithium-ion batteries in electric vehicles. 2018.

[9] Khawaja Y, Shankar N, Qiqieh I, Alzubi J, Alzubi O, Nallakaruppan MK, et al. Battery management solutions for li-ion batteries based on artificial intelligence. Ain Shams Eng J 2023;14:102213. [CrossRef]

[10] Lv Y, Huang S, Zhao Y, Roy S, Lu X, Hou Y, et al. A review of nickel-rich layered oxide cathodes: Synthetic strategies, structural characteristics, failure mechanism, improvement approaches and prospects. Appl Energy 2022;305:117849. [CrossRef]

[11] Li F, Liu Q, Hu J, Feng Y, He P, Ma J. Recent advances in cathode materials for rechargeable lithium-sulfur batteries. Nanoscale 2019;11:15418–15439. [CrossRef]

[12] Purwanto A, Yudha CS, Ubaidillah U, Widiyandari H, Ogi T, Haerudin H. NCA cathode material: Synthesis methods and performance enhancement efforts. Mater Res Express 2018;5:125507. [CrossRef]

[13] Alikin D, Slautin B, Kholkin A. Revealing lithiation kinetics and battery degradation pathway in LiMn2O4-based commercial cathodes via electrochemical strain microscopy. Batteries 2022;8:220. [CrossRef]

[14] Han X, Ouyang M, Lu L, Li J. Cycle life of commercial lithium-ion batteries with lithium titanium oxide anodes in electric vehicles. Energies 2014;7:4895–4909. [CrossRef]

[15] Lu Y, Zhang Y, Zhang Q, Cheng F, Chen J. Recent advances in Ni-rich layered oxide particle materials for lithium-ion batteries. Particuology 2020;53:1–11. [CrossRef]

[16] Wu Z, Christofides PD. Economic machine-learning-based predictive control of nonlinear systems.

Mathematics 2019;7:494. [CrossRef]
[17] Engel GS, Hertzke P. Second-life EV batteries: The newest value pool in energy storage. İstanbul: McKinsey & Company; 2019.
[18] Li S, Sun F, He H, Chen Y. Optimization for a grid-connected hybrid PV-wind-retired HEV battery microgrid system. Energy Proced 2017;105:1634–1643. [CrossRef]
[19] Dong Q, Liang S, Li J, Kim HC, Shen W, Wallington TJ. Cost, energy, and carbon footprint benefits of second-life electric vehicle battery use. iScience 2023;26:107195. [CrossRef]
[20] Hamidi A, Weber L, Nasiri A. EV charging station integrating renewable energy and second-life battery. Proc Int Conf Renew Energy Res Appl 2013:1217–1221. [CrossRef]
[21] Alhadri M, Zakri W, Esmaeeli R, Mohammed AH, Hashemi SR, Barua H, et al. Analysis of second-life of a lithium-ion battery in an energy storage system connected to a wind turbine. 2019 IEEE Power and Energy Conference at Illinois (PECI), Champaign, IL, USA, 2019, pp. 1–8. [CrossRef]
[22] BYD. Your battery partner. 2022. Available at: https://www.bydbatterybox.com/news Accessed Feb 02, 2026.
[23] Saez-De-Ibarra A, Martinez-Laserna E, Koch-Ciobotaru C, Rodriguez P, Stroe DI, Swierczynski M. Second life battery energy storage system for residential demand response service. Proc IEEE Int Conf Ind Technol 2015:2941–2948. [CrossRef]
[24] Saez-De-Ibarra A, Martinez-Laserna E, Stroe DI, Swierczynski M, Rodriguez P. Sizing study of second life li-ion batteries for enhancing renewable energy grid integration. IEEE Trans Ind Appl 2016;52:4999–5007. [CrossRef]
[25] Leung C. PV systems with second life li-ion battery technology (Master thesis). Murdoch, Australia: Murdoch University Division of Science and Engineering; 2012.
[26] Fitzpatrick A. Electric car batteries get a second life storing solar power. Axios 2023. Avaialble at: https://www.axios.com/2023/02/07/electric-car-batteries-solar-power-storage Accessed on Feb 02, 2026. [CrossRef]
[27] Neubauer J, Smith K, Wood E, Pesaran A. Identifying and overcoming critical barriers to widespread second use of PEV batteries. Natl Renew Energy Lab 2015:23–62. [CrossRef]
[28] Lacey G, Putrus G, Salim A. The use of second life electric vehicle batteries for grid support. IEEE EuroCon 2013:1255–1261. [CrossRef]
[29] Eyer J, Corey G. Energy Storage for the Electricity grid: Benefits and Market Potential Assessment Guide. Virginia, USA: Sandia National Laboratories; 2011. p. 1–191. [CrossRef]
[30] Liang L. Research on electric vehicle lithium battery retired echelon use in communication base station. Heilongjiang, China: Harbin Institute of Technology; 2018.
[31] Yan Z. Design of base station backup power system constructed with ladder battery. IOP Conf Ser Mater Sci Eng 2019;677:032011. [CrossRef]
[32] Dongsheng J, Jinguo Z, Jie Z, Zhongjun C, Xianglong L. Economic operation analysis of energy storage system based on echelon-use batteries. 2014 China International Conference on Electricity Distribution (CICED), Shenzhen, 2014, pp. 499–503. [CrossRef]
[33] Han X, Liang Y, Ai Y, Li J. Economic evaluation of a PV combined energy storage charging station based on cost estimation of second-use batteries. Energy 2018;165:326–339. [CrossRef]
[34] 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 Technol 2020;54:6878–6887. [CrossRef]
[35] Potevio New Energy. Exploring mobile charging projects via echelon use of retired batteries. 2017.
[36] Schmidt B. Camping gets a recharge with second-life Nissan EV batteries. The Driven 2019.
[37] Zhang GMTP, Yang F, Tang W, Alexander M, Forastiere L, Kumar N, et al. Analysis of the development of the new energy vehicle power battery echelon use industry. Infect Dis Poverty 2019;8:76–78.
[38] Zhao G. Resource utilization and harmless treatment of power batteries. 2017.
[39] Zhu QJM, Wu Z, Huang Y, Zhou S. Analysis of the application of echelon use batteries in solar streetlights. Sol Energy 2020;2:56–60.
[40] Canals Casals L, Amante García B, González Benítez MM. Aging model for re-used electric vehicle batteries in second life stationary applications. 2017:139–151. [CrossRef]
[41] Neubauer JEJ, Pesaran A, Williams B, Ferry M. Techno-economic analysis of PEV battery second use: Repurposed-battery selling price and commercial and industrial end-user value. SAE Technical Paper 2012-01-0349, 2012. [CrossRef]
[42] Streb M, Ohrelius M, Klett M, Lindbergh G. Improving Li-ion battery parameter estimation by global optimal experiment design. J Energy Storage 2022;56:105948. [CrossRef]
[43] Lai X, Huang Y, Gu H, Deng C, Han X, Feng X, et al. Turning waste into wealth: A systematic review on echelon utilization and material recycling of retired lithium-ion batteries. Energy Storage Mater 2021;40:96–123. [CrossRef]
[44] Nováková K, Pražanová A, Stroe DI, Knap V. Second-life of lithium-ion batteries from electric vehi-

cles: Concept, aging, testing, and applications. Energies 2023;16:2345. [CrossRef]
[45] Hossain E, Murtaugh D, Mody J, Faruque HMR, Sunny MSH, Mohammad N. A comprehensive review on second-life batteries: Current state, manufacturing considerations, applications, impacts, barriers potential solutions, business strategies, and policies. IEEE Access 2019;7:73215–73252. [CrossRef]