RESEARCH AND ENGINEERING INNOVATION PROJECTS OF THE NATIONAL ACADEMY OF SCIENCES OF UKRAINE

https://doi.org/10.15407/scine21.06.019

ZAPOROZHETS, A. O. [1, 2, 3] (https://orcid.org/0000-0002-0704-4116),
and KOSTENKO, G. P. [1] (https://orcid.org/0000-0002-8839-7633)

[1] General Energy Institute of National Academy of Sciences of Ukraine,
172, Antonovych St., Kyiv, 03150, Ukraine,
+380 44 294 6701, info@ienergy.kyiv.ua
[2] Yuan Ze University,
135, Yuandong Rd, Taoyuan, 320, Taiwan,
+886 3 463 8800, iadept@saturn.yzu.edu.tw
[3] Center for Information-analytical and Technical Support of Nuclear
Power Facilities Moni-toring of the National Academy of Sciences of Ukraine,
34A, Acad. Palladin Ave., Kyiv, 03142, Ukraine,
+380 44 502 1233, cnpfm.info@gmail.com

SECOND-LIFE ELECTRIC VEHICLE BATTERIES IN UKRAINE'S ENERGY SECTOR: SWOT ANALYSIS AND MARKET EVALUATION

Introduction. *The rapid expansion of electric vehicles (EVs) has raised pressing concerns about the disposal of lithium-ion batteries. Their repurposing for second-life applications has offered a cost-effective and environmentally sound solution, contributing to grid stability and advancing the circular economy. In the Ukrainian context, second-life batteries have presented additional value by enhancing energy security and facilitating the integration of renewable energy sources.*

Problem Statement. *Despite these advantages, the large-scale deployment of second-life EV batteries in Ukraine has faced significant technical, economic, and regulatory challenges. The absence of standardized state-of-health assessment methods, well-defined integration strategies, and comprehensive market analysis has necessitated a structured SWOT analysis.*

Purpose. *This study aims to evaluate the potential for deploying second-life EV batteries in Ukraine through a SWOT analysis and to determine their suitability for grid integration and energy storage applications.*

Materials and Methods. *A SWOT analysis has been employed as the primary methodological framework, supplemented by market assessment, regulatory review, and economic feasibility evaluation. The analysis has drawn upon international case studies, policy documents, and empirical data on battery degradation, performance, and lifecycle extension.*

Citation: Zaporozhets, A. O., and Kostenko, G. P. (2025). Second-Life Electric Vehicle Batteries in Ukraine's Energy Sector: SWOT Analysis and Market Evaluation. *Sci. innov.*, 21(6), 19—37. https://doi.org/10.15407/scine21.06.019

Results. *The SWOT analysis has confirmed that second-life EV batteries provide a cost-effective solution for energy storage, grid stability, and the promotion of a circular economy. However, critical challenges have included the lack of technical standards, uncertainties regarding operational lifespans, and regulatory deficiencies. Identified opportunities have encompassed state incentives, innovative business models, and rising demand for flexible storage solutions. At the same time, threats have stemmed from competition with next-generation battery technologies, cybersecurity risks, and market volatility. Strategic actions have been proposed to address these challenges.*

Conclusions. *Second-life EV batteries have demonstrated significant potential to strengthen Ukraine's energy security and to support the expansion of renewable energy. Successful implementation, however, requires targeted regulatory frameworks, financial incentives, and robust management systems. Future research should focus on advanced degradation modeling, market design mechanisms, and effective integration into the national energy system.*

Keywords: second-life EV batteries, energy storage, grid integration, circular economy, energy security, renewable energy, sustainability.

In recent years, transportation and power supply sectors have become the main contributors to environmental pollution in the EU. According to the European Environment Agency (2022), energy supply accounted for 26% of greenhouse gas emissions, while transport contributed 23% [1]. The widespread use of internal combustion engines exacerbates climate change risks and deteriorates air quality, highlighting the urgency of transitioning to electric vehicles (EVs) [2]. This shift is particularly critical for private cars and urban public transport, including municipal bus fleets, service vehicles, taxis, and delivery systems [3]. Ukraine's commitment to international environmental goals reinforces the need for electrification.

By 2030, the European Commission projects that EVs will make up half of urban transportation [4], significantly reducing harmful emissions and noise pollution. Similarly, Ukraine's National Transport Strategy aims for full electrification of municipal transport by 2030 [5]. As of January 2023, Ukraine had 10.2 million vehicles, with 8.8 million being passenger cars [6]. Transitioning these to EVs is expected to yield substantial environmental benefits.

The rise in EV adoption also presents opportunities for secondary use of EV batteries [7]. As more EVs enter the market, a growing number of batteries will reach the end of their primary automotive life. While unsuitable for vehicles, they often retain substantial capacity and can be repurposed for energy storage applications [8—9]. This supports environmental sustainability by reducing waste and promoting circular economy principles.

Ukraine has been shifting towards sustainable energy practices, with increasing EV adoption leading to an influx of used EV batteries [10]. These can be repurposed into various energy storage systems, providing flexible, cost-effective storage solutions ahead of the 2030 target. This research evaluates the feasibility of transforming used EV batteries into sustainable storage solutions across residential, commercial, and grid-scale applications, significantly extending their lifespan (Fig. 1) [11—12].

By integrating repurposed EV batteries into renewable energy infrastructure, these systems can help stabilize the grid, reduce dependence on fossil fuels, and enhance energy resilience. Successful large-scale deployment of second-life batteries in Ukraine will require collaboration among policymakers, industry, and researchers to develop standardized regulations, investment incentives, and technology adaptation strategies for repurposed batteries.

Numerous studies have explored the potential of second-life EV batteries within the framework of the circular economy, emphasizing their role in extending battery lifespans, reducing waste, and decreasing reliance on raw material extraction through sustainable reuse models [13—17]. Research on the economic feasibility of second-life battery applications has highlighted cost reductions compared to new energy storage systems, particularly in terms of levelized cost of storage (LCOS) and potential financial benefits for both businesses and consumers [18—21]. Environmental assessments have demonstrated that repurpo-

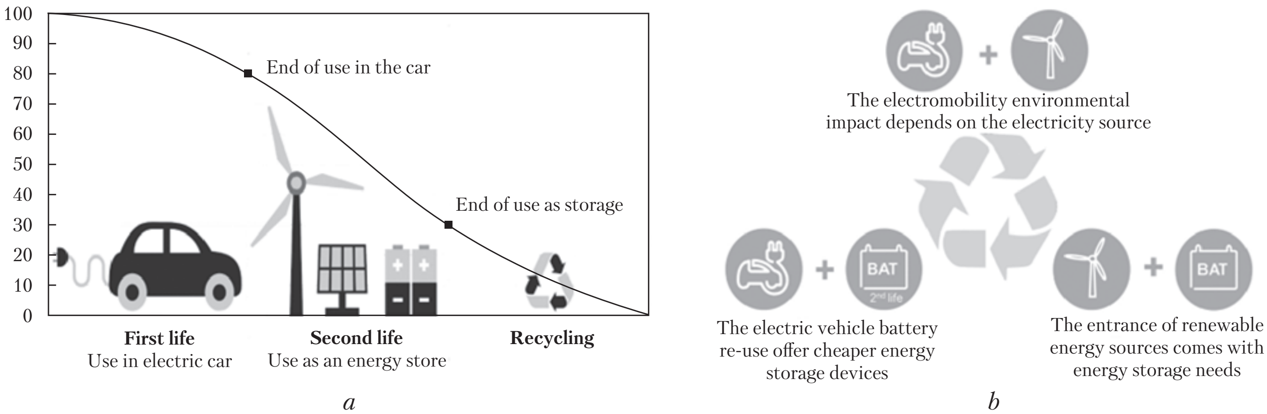

Fig. 1. The role of second-life EV batteries in the circular economy and sustainable energy transition: lifecycle of EV batteries: *a* — from primary use to recycling; *b* — second-life battery applications in the context of sustainability

sing EV batteries significantly reduces carbon emissions by delaying recycling processes and minimizing the environmental impact associated with new battery production [22—24]. Additionally, numerous studies have focused on battery degradation, analyzing capacity fade, cycle life variations, and predictive models for assessing the remaining useful life (RUL) of second-life batteries [25—27]. Investigations into different application scenarios have covered both grid-scale integration — including frequency regulation, load balancing, and renewable energy storage — and household-level solutions, such as residential solar energy storage and backup power systems [28—31]. Furthermore, life cycle assessments (LCA) of second-life batteries have provided a comprehensive perspective on their overall sustainability, comparing energy efficiency, material recovery rates, and long-term environmental impact against conventional storage technologies [32—36].

Despite extensive global studies, research on second-life EV batteries in Ukraine remains scarce. Apart from the authors' recent studies [37—40], no comprehensive analyses address the technical, economic, or regulatory feasibility of their integration into Ukraine's energy system. The absence of local case studies, experimental projects, and regulatory policies highlights the novelty and significance of this research in filling a critical knowledge gap.

This study is the first to explore the potential of second-life EV batteries for energy storage and backup power in Ukraine. As renewable energy adoption grows and the need for effective storage solutions increases, this research provides strategic insights into how repurposed batteries can enhance energy resilience. Additionally, it contributes to international discussions by offering a comparative perspective on the adoption challenges and opportunities of second-life batteries in Ukraine.

This paper assesses the feasibility and prospects of secondary EV battery use for energy storage, supporting the transition to sustainable energy, efficient battery end-of-life management, and the development of a circular economy.

DYNAMICS OF EVS FLEET DEVELOPMENT IN UKRAINE

In recent years, Ukraine has experienced a rapid expansion of the electric vehicle (EV) fleet, reflecting global trends. The number of EVs on Ukrainian roads has grown exponentially, increasing from a few dozen units in 2013 to tens of thousands by 2023 [41]. This surge has been driven by both growing environmental awareness and economic factors, as EVs offer lower operational costs as compared with internal combustion engine vehicles. The growth dynamics of the EV fleet are illustrated in Fig. 2.

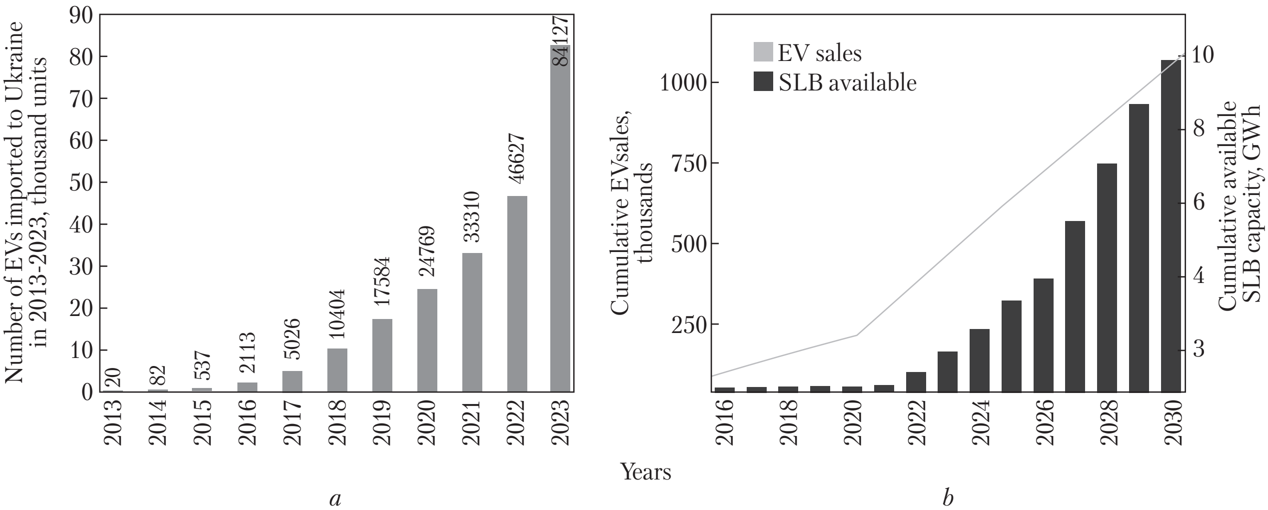

Fig. 2. Growth of the Electric Vehicle Fleet in Ukraine and Forecasted Availability of Second-Life Batteries: *a* — dynamics of EV fleet growth in Ukraine; *b* — forecast of available second-life batteries

Looking ahead to 2030, projections based on state programs suggest that EVs will comprise at least 15% of Ukraine's total vehicle fleet, reaching approximately 1.5 million units [42]. Notably, 75—80% of EVs entering the Ukrainian market are used, with an average service life of 4—5 years. This significantly reduces the remaining lifespan of EV batteries in primary transportation applications, accelerating their transition to secondary use in energy storage. Battery degradation not only limits vehicle range but also increases charging time and reduces efficiency, reinforcing the urgent need for battery repurposing strategies.

Among the electric vehicle models in Ukraine, the Nissan LEAF remains the most widely used, with 22.7 thousand registered units, accounting for 28.5% of the total EV fleet [43—44]. However, since 2021, Ukraine has seen an influx of Chinese EV brands, including MG, JAC, MAXUS, CENNTRO, SKYWELL, and ORA, which together captured 30% of the market by 2023. As these vehicles age, their batteries will progressively reach the end of their first-life automotive use, necessitating sustainable management solutions (Fig. 2).

The forecast presented in Fig. 2 is based on an analysis of the expected growth of the Ukrainian EV fleet by 2030, considering market trends, battery lifespan, and the prevalence of used EV imports. The projections take into account several key factors:

- EV fleet expansion — Official targets aim for 15% EV penetration by 2030, aligning with global electrification strategies [5];
- Battery degradation patterns — The typical lifespan of an EV battery is 8—10 years, after which its capacity declines to levels unsuitable for vehicle propulsion but still viable for stationary energy storage. Given that most imported used EVs in Ukraine are 4—5 years old, a substantial volume of decommissioned batteries will become available by 2030;
- Potential for secondary applications — Batteries that degrade to 70—80% of their original capacity can still provide effective storage solutions for renewable energy integration, grid stabilization, and commercial backup power.

These estimates also account for global trends in battery repurposing and recycling, aligning with Ukraine's shift toward a sustainable, circular economy and the increasing demand for decentralized energy storage solutions.

Given these developments, a comprehensive assessment of second-life EV battery applications is essential. This study employs SWOT-analysis to systematically evaluate the strengths, weaknesses, opportunities, and threats associated with large-scale battery repurposing. The SWOT approach is critical for developing effective strategies that integrate technical, economic, environmental, and regulatory considerations, paving the way for innovative and sustainable energy storage solutions in Ukraine's evolving energy landscape.

ELECTRIC VEHICLE BATTERIES AND THEIR SECOND-LIFE APPLICATIONS

With the increasing adoption of EVs, the rechargeable battery market is expanding rapidly. Lithium-ion batteries have become the dominant storage technology due to their high energy density, efficiency, and ability to be repurposed [45—55]. However, their performance and suitability for second-life applications largely depend on the specific chemical composition of the battery.

Among the most common chemistries, lithium cobalt oxide (LCO) offers high energy density but suffers from low thermal stability, making it more prevalent in consumer electronics than in EVs [47—48]. Lithium manganese oxide (LMO), widely used in early-generation Nissan LEAF and Mitsubishi i-MiEV models, provides better thermal stability and power output, though at the cost of lower energy density. More advanced lithium nickel manganese cobalt oxide (NMC) batteries [52], found in Tesla Model 3, Nissan LEAF 30 + kWh, and VW e-Golf, strike a balance between energy capacity, safety, and lifespan, making them the preferred choice for long-range EVs.

In contrast, lithium nickel cobalt aluminum oxide (NCA) batteries, primarily used in premium EVs like Tesla Model S and Model X, maximize energy density and longevity, though at a higher cost [52]. Meanwhile, lithium iron phosphate (LFP) batteries, which dominate mass-market and commercial EVs such as BYD e6 and Chevrolet Spark EV, offer exceptional cycle life and thermal stability, albeit with lower energy density [56—57]. Lastly, lithium titanate (LTO) batteries, while uncommon in passenger EVs, are valued for their ultra-fast charging capability and extreme cycle stability, making them ideal for specialized applications such as Honda Fit EV.

Each chemistry impacts not only vehicle performance but also the battery's potential for second-life use. Among them, NMC and LFP stand out as the most suitable for stationary energy storage, balancing stability, durability, and remaining energy capacity [58—59]. LMO batteries, despite their lower energy density, remain viable for short-duration storage and backup power applications, while LTO batteries, with their robust cycle stability, are ideal for high-frequency charge-discharge scenarios in grid applications.

Batteries used in EVs experience gradual degradation, which affects their capacity, charging efficiency, and operational stability over time. While a battery may no longer be suitable for propulsion after 8—10 years, it often retains 70—80% of its original capacity, making it viable for stationary energy storage before reaching the recycling phase [59]. The transition from automotive use to repurposing and final disposal plays a key role in sustainable resource management and aligns with circular economy principles.

As concerns over the sustainability of battery production and disposal grow, the circular economy model promotes material recovery, repurposing, and recycling as alternatives to premature disposal. Rather than discarding EV batteries after their primary use, second-life applications allow them to be integrated into stationary energy storage systems, extending their service life and reducing waste [58—59].

For Ukraine, where used batteries dominate the EV market, the need for second-life applications is particularly urgent. Integrating repurposed EV batteries into the energy system offers multiple benefits: reducing dependence on expensive new storage solutions, enhancing decentralized RES integration, and providing cost-effective backup power in areas with grid instability. By prioritizing repurposing over premature recycling, Ukraine can strengthen energy security, advance environmental sustainability, and align with global circular economy trends.

THE LIFECYCLE OF ELECTRIC VEHICLE BATTERY

The lifecycle of an EV battery is a multi-stage process that determines its total economic value, environmental footprint, and technological feasibility for secondary applications [60—61]. Understanding this lifecycle is crucial for optimizing battery performance, repurposing strategies, and end-of-life management.

Figure 3 illustrates the key lifecycle stages of an EV battery, from manufacturing and primary automotive use to assessment, repurposing, secondary applications, and final recycling. Each phase presents unique challenges and opportunities, requiring well-defined technical solutions, regulatory policies, and investment strategies to maximize the economic and environmental benefits of second-life batteries.

The lifecycle of an EV battery consists of five key stages, each determining its economic value, environmental footprint, and potential for secondary applications.

1. Manufacturing Stage: EV batteries are produced using lithium, cobalt, nickel, and manganese, requiring resource-intensive extraction and processing. This phase has a high environmental impact, making material recovery and second-life applications crucial for sustainability.

2. Primary Use in Electric Vehicles: During operation, EV batteries undergo charge-discharge cycles, thermal stress, and gradual degradation. After 8—10 years, they typically retain 70—80% of their capacity, becoming unsuitable for propulsion but still viable for stationary energy storage.

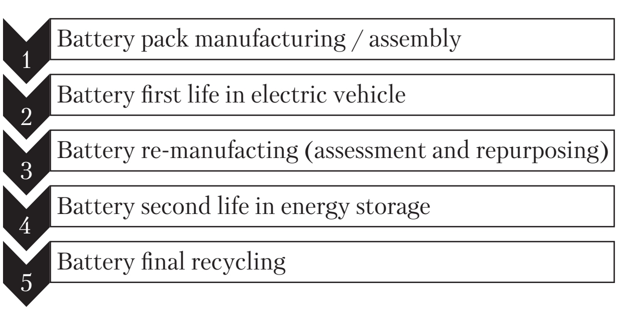

Fig. 3. Key Lifecycle Stages of an Electric Vehicle Battery

- End of Primary Use: Once decommissioned, batteries undergo diagnostic testing to determine whether they should be repurposed or directly recycled based on remaining energy capacity and stability.

3. Battery Assessment and Repurposing: Instead of disposal, viable batteries are refurbished and adapted for secondary use through:

- Testing and sorting — Assessing capacity and safety.
- Reconfiguration — Adjusting for energy storage applications.
- System integration — Deploying in grid or backup power solutions.

In Ukraine, where renewable energy adoption is growing, second-life batteries offer an opportunity to stabilize the grid and enhance energy flexibility. However, the lack of standardized repurposing protocols remains a major challenge.

4. Battery Second Life in Energy Storage: Successfully repurposed batteries support various applications, such as grid storage (smoothing fluctuations from renewables), backup power (enhancing resilience in critical infrastructure), microgrids (expanding off-grid energy access).

5. Final Recycling and Material Recovery

At the end of the second-life phase, batteries that are no longer viable undergo recycling, where valuable materials are recovered. Given that Ukraine's battery recycling infrastructure is still developing, second-life applications serve as a cost-effective, short-term alternative to delay disposal and maximize value.

PREDOMINANT EV MODEL IN UKRAINE: NISSAN LEAF AND ITS SUITABILITY FOR SECOND-LIFE APPLICATIONS

The Nissan LEAF is the most widely used electric vehicle (EV) model in Ukraine, comprising nearly 30% of the total EV fleet [43—44]. This makes it a central figure in discussions on second-life battery applications, particularly for stationary energy storage and grid stabilization. Given the large number of imported used LEAF vehicles, battery repurposing is an essential strategy for maximizing their lifespan beyond automotive use.

Since its introduction in 2010, the Nissan LEAF's battery technology has undergone significant improvements. The first-generation models utilized Lithium Manganese Oxide (LMO) chemistry, while later models transitioned to Nickel Manganese Cobalt (NMC), offering higher energy density and longevity [62]. These advancements directly impact battery suitability for second-life applications, with newer NMC batteries demonstrating greater efficiency in renewable energy storage and backup power systems.

Table 1 presents an evaluation of Nissan LEAF batteries, assessing their capacity, chemistry, and repurposing potential for secondary applications.

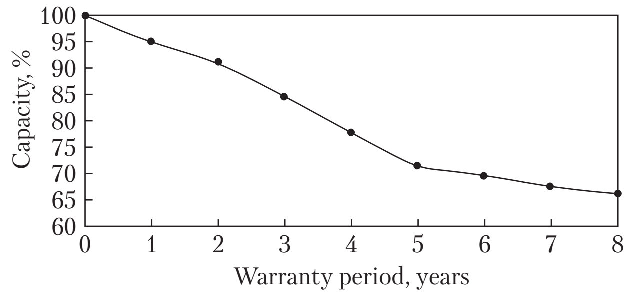

Fig. 4. Dynamics of Nissan LEAF battery aging/degradation during the warranty period

The degradation of Nissan LEAF batteries over time further supports their secondary use potential. For instance, the 2015 LEAF (30 kWh battery) comes with an 8-year warranty or 160,000 km,

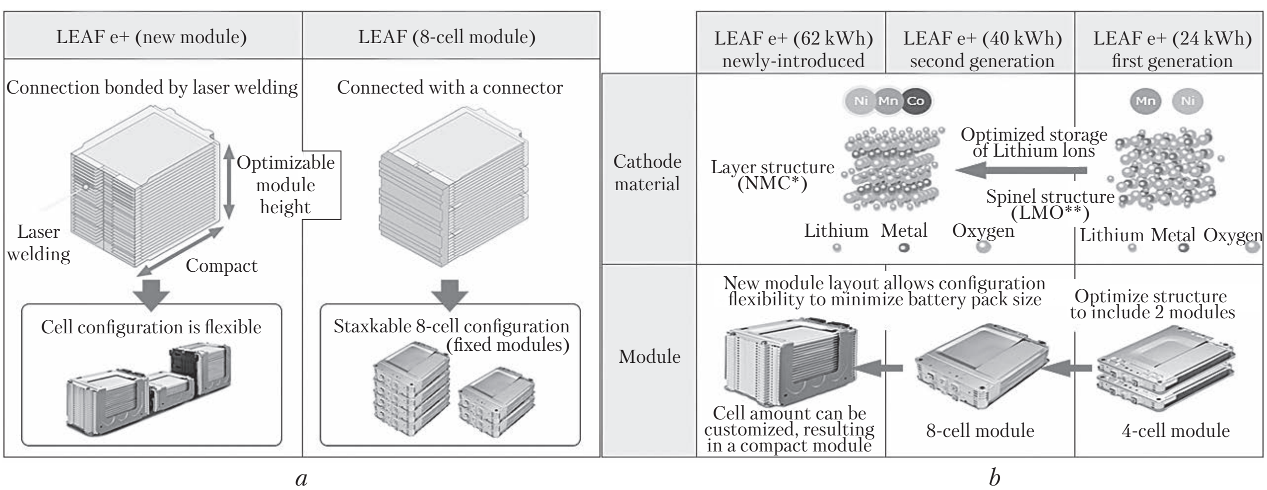

Fig. 5. Evolution of Nissan LEAF Battery Configurations for Secondary Use: *a* — New LEAF e+ Module; *b* — Comparison of Battery Structures Across LEAF Generations; * — Lithium Nickel Cobalt Manganese Oxide; ** — Lithium Manganese Oxide

Table 1. **Evaluation of Nissan LEAF Batteries' Suitability for Second-Life Use**

Battery Capacity, kWh	Year Released	Battery Chemistry	Suitability for Second-Life Use
24	2010	LMO	Moderate (suitable for stationary energy systems with less stringent power requirements)
24	2012	LMO	Moderate (requires additional testing for longevity in second-life use)
30	2015	NMC	High (better suited for integration with renewable energy sources due to higher energy density)
40	2017	NMC	High (higher energy density, more charge/discharge cycles, high efficiency for energy storage)
62	2019	NMC	High (optimal choice for large-scale energy storage and grid stabilization)

after which battery capacity typically decreases to around 66%. This reduction limits its automotive efficiency but leaves substantial energy storage capacity for stationary applications. The aging process of Nissan LEAF batteries is illustrated in Fig. 4, showing the decline in capacity over time and its implications for secondary use.

Beyond capacity retention, the modular design of LEAF batteries enhances their suitability for secondary use. Early models featured a 4-cell module structure, while newer 40 kWh and 62 kWh versions adopted an 8-cell configuration, allowing for more efficient repurposing in stationary storage applications. The LEAF e+ model introduced laser welding for compact, customizable modules, improving their adaptability for energy storage and grid applications [60]. These advancements are depicted in Fig. 5, which illustrates the evolution of Nissan LEAF battery configurations and their relevance to second-life applications.

The standardization of LEAF battery designs simplifies their integration into large-scale storage systems, ensuring consistent performance and optimized management. This modularity, combi-

Table 2. **SWOT-Analysis of the Secondary Use of EV Batteries in Ukraine**

STRENGTHS	WEAKNESSES
Cost savings: Using repurposed batteries significantly reduces the cost of energy storage systems as compared with new batteries; **Resource efficiency & circular economy:** Extends battery life, reduces waste, and decreases demand for raw materials (e.g., lithium, cobalt, nickel); **Improved grid stability & peak shaving:** Enhances energy system flexibility, reduces reliance on fossil-fuel-based peaking plants, and supports frequency regulation; **Supports renewable energy expansion:** Helps address the intermittency of solar and wind power, making renewables more viable; **Enhances power system resilience:** Serves as backup power for critical infrastructure, emergency response, and military applications.	**Performance limitations:** Second-life batteries have reduced capacity, efficiency, and energy density, affecting performance over time; **Lack of standardization:** Absence of universal safety, testing, and classification standards complicates integration into grid and storage applications; **Additional refurbishment costs:** costs for testing, sorting, and repurposing make the economic case dependent on subsidies or economies of scale; **Uncertain longevity & degradation variability:** Difficulty in predicting remaining useful life of each repurposed battery, impacting investment decisions; **Safety concerns:** Risks related to fire hazards, thermal runaway, and chemical leakage require robust safety protocols and monitoring systems.
OPPORTUNITIES	THREATS
Growing demand for energy storage solutions: Rising electricity demand and renewable energy deployment create a large market for second-life batteries; **Government incentives & regulatory support:** Potential for tax benefits, subsidies, and market regulations encouraging battery reuse; **Emerging business models & partnerships:** Collaborations between EV manufacturers, energy companies, and grid operators can accelerate deployment; **Development of advanced diagnostics & AI-based predictive maintenance:** Data-driven models can improve battery life prediction, boosting investor confidence and system reliability; **Applications in decentralized grids & microgrids:** Second-life batteries are ideal for off-grid solutions, rural electrification, and military bases.	**Technological advances in new batteries:** The emergence of cheaper, high-energy-density solid-state or next-generation batteries may reduce demand for second-life batteries; **Regulatory and legal uncertainties:** Complex permitting processes and lack of a legal framework for second-life battery certification can hinder market adoption; **Fluctuating raw material prices & recycling costs:** Economic viability depends on global lithium and cobalt prices, which affect both battery refurbishment and disposal economics; **Cybersecurity risks:** Increased reliance on digitally connected battery storage systems introduces risks of cyberattacks on energy infrastructure; **Consumer skepticism & perception barriers:** Public concerns over safety, efficiency, and trust in used battery solutions may slow adoption.

ned with improvements in cycle life and energy density, makes LEAF batteries a viable resource for stabilizing the power grid, integrating renewable energy sources, and enhancing energy security in Ukraine. By strategically repurposing Nissan LEAF batteries, Ukraine can reduce energy storage costs, extend the usability of EV batteries, and support the country's transition toward a sustainable energy infrastructure.

SWOT-ANALYSIS OF SECOND-LIFE EV BATTERY APPLICATION IN UKRAINE

The integration of second-life EV batteries into Ukraine's energy infrastructure presents both challenges and opportunities. A SWOT-analysis provides a structured evaluation of strengths, weaknesses, opportunities, and threats, allowing policymakers, investors, and energy stakeholders to assess feasibility and mitigate risks.

From an environmental perspective, while EV adoption reduces direct emissions, Ukraine's electricity mix — still heavily reliant on coal and gas — limits its overall impact. Additionally, the lack of effective battery disposal management remains a key challenge [63]. Repurposing EV batteries presents a viable solution within the circular economy framework, extending battery lifespan, reducing waste, and improving energy security.

Beyond environmental benefits, the secondary use of EV batteries significantly reduces costs for both consumers and manufacturers, offering affordable energy storage solutions and supporting the expansion of renewable energy [64]. These repurposed batteries play a critical role in grid stability, backup power, and decentralized energy systems. Given Ukraine's energy vulnerabilities, including infrastructure disruptions due to war and geopolitical risks, leveraging second-life batteries can enhance energy resilience and disaster recovery efforts [40].

A structured approach, supported by government policies, private sector engagement, and research initiatives, is essential for the successful deployment of second-life batteries. Table 2 provides a detailed SWOT-analysis of second-life battery applications in Ukraine.

The SWOT-analysis of the secondary use of EV batteries in Ukraine highlights key strengths, weaknesses, opportunities, and threats, allowing stakeholders to develop targeted strategies that enhance benefits and mitigate risks. The practical application of this analysis provides a roadmap for decision-making in government, energy, automotive, and investment sectors.

STRATEGIC RECOMMENDATIONS BASED ON SWOT-ANALYSIS

The SWOT-analysis identifies key strategic actions required to overcome challenges and maximize opportunities for second-life EV battery applications in Ukraine. The Table 3 summarizes targeted recommendations for key stakeholders.

The SWOT-analysis of second-life EV batteries in Ukraine highlights significant opportunities for energy storage expansion, grid stability, and circular economy integration. However, challenges such as regulatory gaps, uncertain lifespan, and safety concerns must be addressed. By implementing targeted policies, advancing technical solutions, and fostering industry collaboration, Ukraine can establish a sustainable market for second-life battery storage, enhancing both energy security and economic viability.

EVALUATION OF SECOND-LIFE EV BATTERY POTENTIAL MARKET IN UKRAINE

As Ukraine transitions toward a more sustainable energy system, the expanding EV market presents a significant opportunity for energy storage solutions. According to the national transport strategy, EVs are projected to comprise at least 15% of the total vehicle fleet by 2030, with the total number of EVs expected to reach 1.5—2 million by 2040. This increase directly correlates with a growing stock of decommissioned EV batteries, making secondary use an essential component of

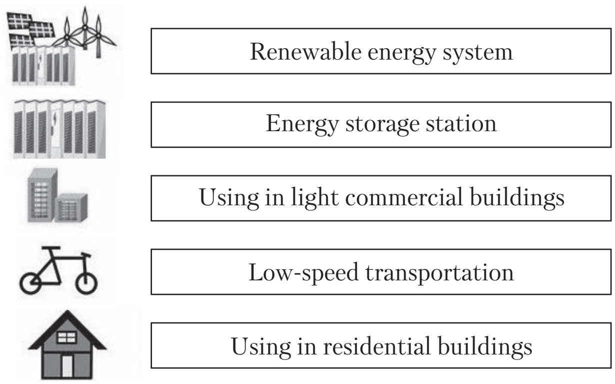

Fig. 6. Key Applications of Second-Life EV Batteries in Ukraine

energy system stability and renewable energy integration [66].

One of the key challenges in Ukraine's energy transition is ensuring cost-effective and flexible storage solutions to balance renewable energy generation and grid demand fluctuations. The repurposing of used EV batteries into stationary storage systems provides a scalable and economically viable alternative to new storage technologies (Fig. 6).

Figure 7 presents a conceptual framework for integrating second-life EV batteries into Ukraine's power system, outlining their technical components, connectivity layers, and grid applications in renewable energy support, backup power, and grid resilience.

With Ukraine's rapidly growing EV fleet, secondary battery applications are becoming increasingly relevant across multiple energy sectors. A detailed market evaluation identifies several key segments for battery repurposing:

Households: As residential adoption of solar and wind energy increases, reliable and affordable storage solutions will be essential. Second-life batteries can help homeowners store excess renewable energy and ensure energy independence.

Table 3. **SWOT-Analysis Based Recommendations**

Stakeholder Group	Key Focus Areas	Recommended Actions
Government & Policy Makers	Regulatory clarity, financial incentives, safety standards	Establish regulatory frameworks for testing, certification, and deployment of second-life batteries Introduce tax incentives and subsidies for repurposed battery storage Mandate battery collection and repurposing programs to support the circular economy Implement safety protocols to mitigate risks associated with aging battery cells
Energy Sector & Grid Operators	Grid resilience, storage integration, cybersecurity	Invest in advanced battery management systems (BMS) to monitor degradation and optimize lifespan Conduct pilot projects for integrating second-life batteries into grid storage, backup power, and microgrids Strengthen cybersecurity measures for battery storage systems
EV & Battery Manufacturers	Sustainability, cost-effective refurbishment, repurposing logistics	Develop modular battery designs to simplify repurposing and energy storage integration Partner with energy companies to create buyback and reuse programs Enhance battery tracking systems using AI and blockchain to streamline repurposing logistics
Investors & Startups	Market scalability, economic viability, risk mitigation	Support scaling up refurbishment facilities to achieve economies of scale Develop battery-as-a-service (BaaS) and energy-as-a-service (EaaS) models for flexible financing options Invest in AI-driven battery degradation forecasting to improve valuation models.
Research Institutions & Labs	Degradation modeling, predictive maintenance, industry collaboration	Conduct longitudinal studies on battery aging to refine degradation models Develop standardized testing protocols for evaluating second-life battery performance Foster collaborations between academia and industry to accelerate technology transfer and implementation

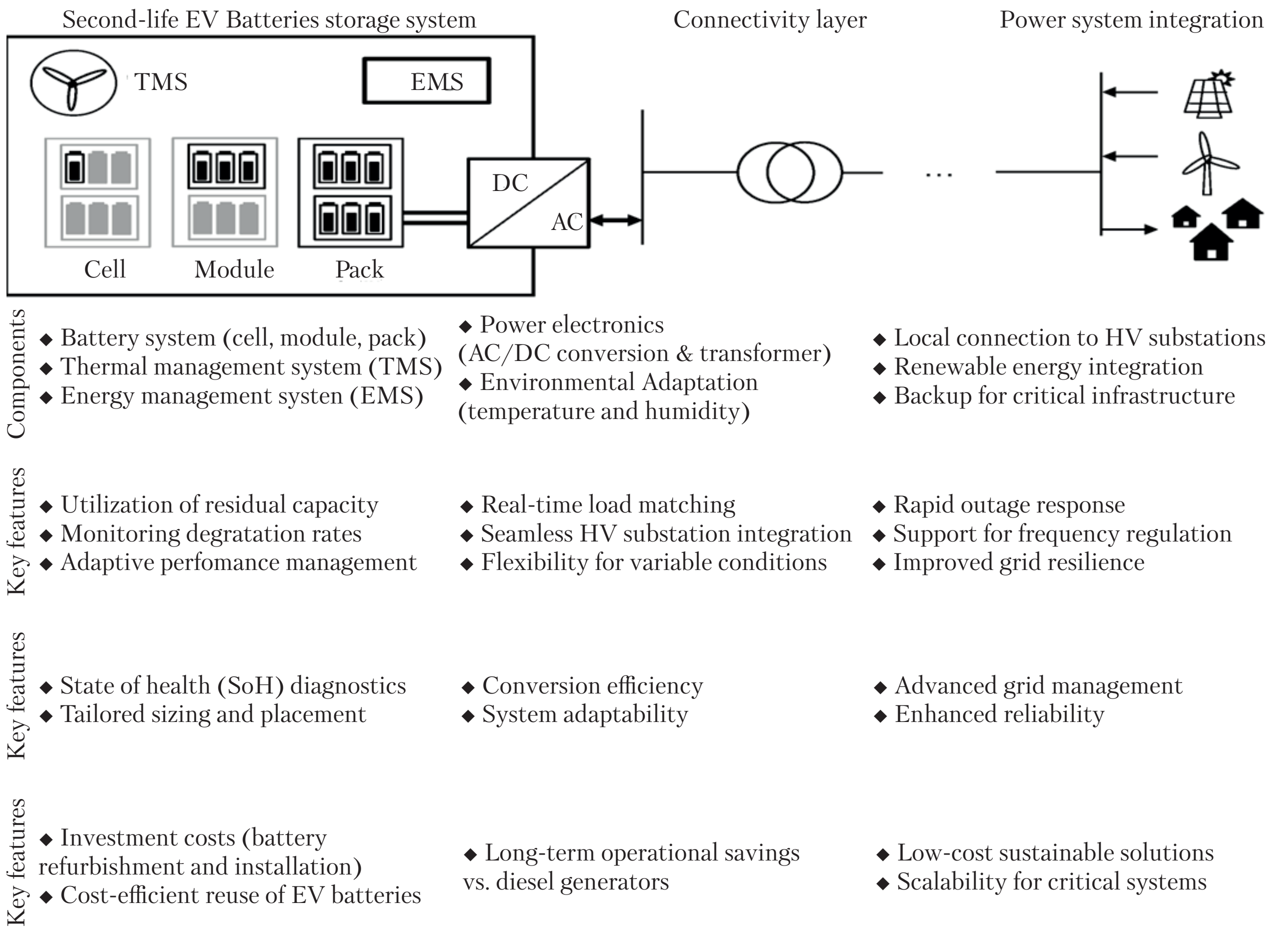

Fig. 7. Framework for Integrating Second-Life EV Batteries into the Power System

Commercial and Municipal Consumers: Businesses and public infrastructure require large-scale energy storage systems for uninterrupted operations and peak demand management. Repurposed EV batteries provide a sustainable and cost-effective alternative to new battery storage.

Renewable Energy Support: With increasing investments in solar and wind power, secondary-use EV batteries can address intermittency issues by storing surplus electricity during peak generation periods.

Grid Support Services: As renewable energy penetration grows, grid fluctuations become more frequent. Repurposed batteries can enhance grid stability, provide load leveling, and support frequency regulation.

EV Charging Stations: Fast-charging infrastructure places high demands on the power grid, often leading to peak load stress. Second-life batteries can serve as buffer storage, optimizing charging time and alleviating grid strain.

To assess the market potential for second-life lithium-ion batteries in Ukraine, a detailed evaluation was conducted. The analysis considers key factors such as battery availability, total market size, required power and energy capacity, and operational requirements across different sectors. The findings summarized in Table 4 provide a structured assessment of the most viable applications for repurposed EV batteries.

These findings confirm the significant market for second-life EV battery applications in Ukraine.

Additionally, repurposed EV batteries can help reduce energy costs and enhance the resilience of local communities and the national power grid, especially as renewable energy penetration increases.

ENSURING THE DURABILITY OF BATTERIES FOR SECOND-LIFE APPLICATIONS

As repurposed EV batteries transition to secondary applications, ensuring their longevity is critical. Factors such as depth of discharge (DoD), temperature, charge/discharge cycles, and operational conditions significantly influence battery lifespan in stationary storage systems [67—73].

Table 5 presents an assessment of the projected lifespan of second-life EV batteries across different applications, factoring in economic savings and carbon footprint reductions.

The longevity of second-life batteries varies based on usage patterns and battery management systems. With optimal management, residential battery systems could last 7—10 years, while grid-level applications may extend beyond 10 years due to lower cycling demand

DIRECTIONS OF FUTURE RESEARCHES FOR UKRAINE

Over the past few years, in accordance with global trends, there has been an annual increase in the fleet of electric vehicles tenfold in Ukraine — from several units in 2013 to tens of thousands of

Table 4. **Evaluated Markets for Second-Life Li-ion Batteries in Ukraine**

Application	Number of Packs	Market Size	Power, kW/MW	Energy, min	Energy, Max	Time of Use, h	Frequency of Use
Residential	1—2	>250,000	1—10 kW	3.5—35 kWh	10—100 kWh	3.5 h	Daily
Municipal/ Communities	10—15	10,000—50,000	25—200 kW	100—800 kWh	100—1000 kWh	4 h	Daily
Office Buildings	30—40	>50,000	200—2000 kW	1000—10,000 kWh	1000—10,000 kWh	5 h	Daily
Trade Outlets	30—40	>100,000	200—250 kW	1400—1750 kWh	1400—1750 kWh	7 h	Daily
Renewables Support	500—700	>100	0.5—2.5 MW	2.75—13.75 MWh	2.75—13.75 MWh	5.5 h	10—20/month
Grid Support	1000s	>10	1—100 MW	0.25—25 MWh	0.25—25 MWh	0.25 h	5—10/month
EV Charging Stations	10—50	>500	50—500 kW	300—3000 kWh	300—3000 kWh	6 h	Daily

Table 5. **Secondary EV Battery Application Lifespan**

Application	Second-Life Scheduling	Estimated 2nd Life Duration, years	Economic Savings, %	CO_2 Emissions Reduction, kg/year
Residential Energy Storage	Daily cycling with PV	7—10	30—50	400—800
Commercial/Industrial Backup	Peak shaving, load shifting	5—8	25—40	600—1200
Grid Energy Storage	Frequency regulation	6—9	35—55	800—1500
EV Charging Stations	Fast charge buffering	4—6	20—35	500—1000
Residential Energy Storage	Daily cycling with PV	7—10	30—50	400—800

units in 2022/2023 [5]. It can be predicted that such development dynamics will inevitably lead to a large number of degraded batteries by 2030.

Numerous studies in Ukraine have addressed electric transportation [74—77], energy generation and consumption patterns [78—82], energy storage systems [83—86], operational aspects such as resilience, control modes, and consumer–regulator dynamics [87—93], as well as modeling approaches for energy transitions and system behavior under uncertainty [94—98]. While these topics intersect with our research, the specific issue of electric vehicle batteries and their secondary use potential remains largely underexplored.

Moving forward, research should focus on optimizing the integration of second-life batteries into Ukraine's power system, particularly in grid support services, renewable energy balancing, and frequency regulation. Given the increasing share of solar and wind power, understanding how repurposed batteries can mitigate power fluctuations is crucial for long-term grid stability. Another key research area is the economic and environmental assessment of second-life battery applications. Comparative analyses of Levelized Cost of Storage (LCOS) and CO_2 reduction potential will provide essential insights into the feasibility of repurposed batteries relative to newly manufactured energy storage solutions.

As well, research should explore grid integration strategies, including the role of second-life batteries in frequency regulation, load balancing, and energy arbitrage. The development of market mechanisms for battery energy storage participation in electricity markets should also be addressed. Another critical research direction involves techno-economic assessments of different repurposing strategies, evaluating the cost-benefit trade-offs of battery refurbishment, hybrid energy storage solutions, and potential business models such as battery-as-a-service. These insights will help identify the most effective pathways for commercial adoption. A final research direction involves scaling up circular economy principles in Ukraine's battery sector, including strategies for effective recycling at the end of the second-life phase.

By addressing these research gaps, Ukraine can accelerate the deployment of second-life EV batteries, strengthening its energy security, sustainability, and economic resilience in the transition to a low-carbon future.

CONCLUSIONS

1. **This study has assessed the feasibility, market potential, and technical viability of integrating second-life EV batteries into Ukraine's energy system.** The analysis of degradation patterns, repurposing strategies, and secondary applications has confirmed that these batteries can effectively enhance grid stability, facilitate renewable energy integration, and strengthen backup power resilience.

2. **The forecast of second-life battery availability has been developed**, based on EV market growth and projected volumes of decommissioned batteries by 2040. The scenario-based assessment has demonstrated economic and environmental benefits, including cost savings and emissions reductions compared to new storage systems, thereby supporting strategic planning for residential and grid-scale deployment.

3. **The SWOT-analysis has identified strengths, weaknesses, opportunities, and threats** associated with second-life battery adoption in Ukraine. The findings have informed policy and investment recommendations, emphasizing the need to close regulatory gaps, standardize testing procedures, and foster industry collaboration. A well-defined framework is essential for supporting large-scale repurposing.

4. **The key prerequisites for successful second-life battery deployment have been evaluated,** including regulatory, technological, and market-driven factors. The study has underscored the importance of advanced diagnostic tools, optimized operational strategies, and improved energy management systems to enhance efficiency, reliability, and safety.

5. **The practical recommendations have been formulated for policymakers, industry stakeholders, and research institutions.** Successful deployment requires regulatory harmonization, financial incentives, and the development of refurbishment infrastructure. Raising awareness among consumers and businesses has been recognized as critical for accelerating adoption. While the market potential has been demonstrated, fully unlocking the benefits requires coordinated actions across policy, industry, and research sectors.

REFERENCES

1. European Environment Agency. (2023). EEA greenhouse gas — data viewer. URL: https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer (Last accessed: 10.02.2024).
2. Kostenko, G. (2022). Overview of European trends in electric vehicle implementation and the influence on the power system. *System Research in Energy,* 1(70), 62—71. https://doi.org/10.15407/srenergy2022.01.062
3. Ivanenko, N. (2022). Overview of trends and prospects of electric transport development in the EU and assessment of economic/climate efficiency of electromob operation. *System Research in Energy,* 2(71), 13—21. https://doi.org/10.15407/srenergy2022.02.013
4. European Environment Agency. (2023). Trends and projections in Europe 2023 (83 pp.). URL: https://www.eea.europa.eu/publications/trends-and-projections-in-europe-2023 (Last accessed: 10.02.2024).
5. National Transport Strategy of Ukraine up to 2030. (2017). URL: http://publications.chamber.ua/2017/Infrastructure/UDD/National_Transport_Strategy_2030.pdf (Last accessed: 10.02.2024).
6. Shirokun, I. How many cars are there in Ukraine? URL: https://auto.24tv.ua/skilky_naspravdi_mashyn_v_ukraini_bahato_chy_malo_n43694 (Last accessed: 10.02.2024).
7. Pagliaro, M., Meneguzzo, F. (2019). Lithium battery reusing and recycling: A circular economy insight. *Heliyon,* 5, e01866. https://doi.org/10.1016/j.heliyon.2019.e01866
8. Haram, M. H. S. M., Sarker, M. T., Ramasamy, G., Ngu, E. E. (2023). Second life EV batteries: Technical evaluation, design framework, and case analysis. *IEEE Access,* 11, 138799—138812. https://doi.org/10.1109/ACCESS.2023.3340044
9. Martinez-Laserna, E., Gandiaga, I., Sarasketa-Zabala, E., Badeda, J., Stroe, D.-I., Swierczynski, M., Goikoetxea, A. (2018). Battery second life: Hype hope or reality? A critical review of the state of the art. *Renewable and Sustainable Energy Reviews,* 93, 701—718. https://doi.org/10.1016/j.rser.2018.04.035
10. Martinez-Laserna, E., Sarasketa-Zabala, E., Villarreal Sarria, I., Stroe, D.-I., Swierczynski, M., Warnecke, A., ..., Rodriguez, P. (2018). Technical viability of battery second life: A study from the ageing perspective. *IEEE Transactions on Industrial Applications,* 54(3), 2703—2713. https://doi.org/10.1109/TIA.2018.2801262
11. Elis, S. (2023). Second life applications for degraded EV batteries: Evaluating benefits based on remaining useful life and battery configurations [Master's thesis]. URL: https://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-196013 (Last accessed: 10.03.2024).
12. Kurland, S. D. (2020). Energy use for GWh-scale lithium-ion battery production. *Environmental Research Communications,* 2(1), Article 012001. https://doi.org/10.1088/2515-7620/ab5e1e
13. Gohla-Neudecker, M., Bowler, J., Mohr, S. (2015, June). Battery 2nd life: Leveraging the sustainability potential of EVs and renewable energy grid integration. *In Proceedings of the International Conference on Clean Electrical Power (ICCEP),* 311—318.
14. Katwala, A. The spiralling environmental cost of our lithium battery addiction. WIRED U.K. URL: https://www.wired.co.uk/article/lithium-batteries-environment-impact (Last accessed: 10.03.2024).
15. Illa Font, C. H., Siqueira, H. V., Machado Neto, J. E., Santos, J. L. F. d., Stevan, S. L. Jr., Converti, A., Corrêa, F. C. (2023). Second life of lithium-ion batteries of electric vehicles: A short review and perspectives. *Energies,* 16(2), 953. https://doi.org/10.3390/en16020953
16. Haram, M. H. S. M., Lee, J. W., Ramasamy, G., Ngu, E. E., Thiagarajah, S. P., Lee, Y. H. (2021). Feasibility of utilising second life EV batteries: Applications, lifespan, economics, environmental impact assessment and challenges. *Alexandria Engineering Journal,* 60(5), 4517—4536. https://doi.org/10.1016/j.aej.2021.03.021
17. Assunção, A., Moura, P. S., de Almeida, A. T. (2016). Technical and economic assessment of the secondary use of repurposed electric vehicle batteries in the residential sector to support solar energy. *Applied Energy,* 181, 120—131. https://doi.org/10.1016/j.apenergy.2016.08.056

18. Tong, S., Fung, T., Klein, M. P., Weisbach, D. A., Park, J. W. (2017). Demonstration of reusing electric vehicle battery for solar energy storage and demand side management. *Journal of Energy Storage,* 11, 200—210. https://doi.org/10.1016/j.est.2017.03.003
19. Li, J., Wang, Y., Tan, X. (2017). Research on the classification method for the secondary uses of retired lithium-ion traction batteries. *Energy Procedia,* 105, 2843—2849.
20. Han, X., Liang, Y., Ai, Y., Li, J. (2018). Economic evaluation of a PV combined energy storage charging station based on cost estimation of second-use batteries. *Energy,* 165, 326—339. https://doi.org/10.1016/j.energy.2018.09.022
21. Wang, L., Pan, C., Liu, L., Cheng, Y., Zhao, X. (2016). On-board state of health estimation of LiFePO4 battery pack through differential voltage analysis. *Applied Energy,* 168, 465—472. https://doi.org/10.1016/j.apenergy.2016.01.125
22. Baghadadi, I., Briat, O., Hyan, P., Vinassa, J. M. (2016). State of health assessment for lithium batteries based on voltage-time relaxation measure. *Electrochimica Acta,* 194, 461—472. https://doi.org/10.1016/j.electacta.2016.02.109
23. Hu, X., Feng, F., Liu, K., Zhang, L. (2019). State estimation for advanced battery management: Key challenges and future trends. *Renewable and Sustainable Energy Reviews,* 114, 109334. https://doi.org/10.1016/j.rser.2019.109334
24. Waag, W., Kabitz, S., Sauer, D. U. (2013). Experimental investigation of the lithium-ion battery impedance characteristic at various conditions and aging states and its influence on the application. *Applied Energy,* 102, 885—897. https://doi.org/10.1016/j.apenergy.2012.09.030
25. Li, X., Wang, Z., Yan, J. (2019). Prognostic health condition for lithium battery using the partial incremental capacity and Gaussian process regression. *Journal of Power Sources,* 421, 56—67. https://doi.org/10.1016/j.jpowsour.2019.03.008
26. Bai, B., Xiong, S., Song, B., Xiaoming, M. (2019). Economic analysis of distributed solar photovoltaics with reused electric vehicle batteries as energy storage systems in China. *Renewable and Sustainable Energy Reviews,* 109, 213—229. https://doi.org/10.1016/j.rser.2019.03.048
27. Madlener, R., Kirmas, A. (2017). Economic viability of second use electric vehicle batteries for energy storage in residential applications. *Energy Procedia,* 105, 3806—3815. https://doi.org/10.1016/j.egypro.2017.03.890
28. Sun, S. I., Chipperfield, A. J., Kiaee, M., Wills, R. G. A. (2018). Effects of market dynamics on the time-evolving price of second-life electric vehicle batteries. *Journal of Energy Storage,* 19, 41—51. https://doi.org/10.1016/j.est.2018.06.012
29. Song, Z., Feng, S., Zhang, L., Hu, Z., Hu, X., Yao, R. (2019). Economy analysis of second-life battery in wind power systems considering battery degradation in dynamic processes: Real case scenarios. *Applied Energy,* 251, 113411. https://doi.org/10.1016/j.apenergy.2019.113411
30. Kuki, Á., Lakatos, C., Nagy, L., Nagy, T., Kéki, S. (2025). Energy use and environmental impact of three lithium-ion battery factories with a total annual capacity of 100 GWh. *Environments,* 12, 24. https://doi.org/10.3390/environments12010024
31. Kim, H. C., Wallington, T. J., Arsenault, R., Bae, C., Ahn, S., Lee, J. (2016). Cradle-to-Gate Emissions from a Commercial Electric Vehicle Li-Ion Battery: A Comparative Analysis. *Environmental Science & Technology,* 50(14), 7715—7722. https://doi.org/10.1021/acs.est.6b00830
32. Lyu, W., Hu, Y., Liu, J., Chen, K., Liu, P., Deng, J., Zhang, S. (2024). Impact of battery electric vehicle usage on air quality in three Chinese first-tier cities. *Scientific Reports,* 14(1). https://doi.org/10.1038/s41598-023-50745-6
33. Rossi, F., Tosti, L., Basosi, R., Cusenza, M. A., Parisi, M. L., Sinicropi, A. (2023). Environmental optimization model for the European batteries industry based on prospective life cycle assessment and material flow analysis. *Renewable and Sustainable Energy Reviews,* 183, 113485. https://doi.org/10.1016/j.rser.2023.113485
34. Cox, B., Mutel, C. L., Bauer, C., Mendoza Beltran, A., van Vuuren, D. P. (2018). Uncertain environmental footprint of current and future battery electric vehicles. *Environmental Science & Technology,* 52, 4989—4995. https://doi.org/10.1021/acs.est.8b00261
35. Dunn, J. B., Gaines, L., Kelly, J. C., James, C., Gallagher, K. G. (2014). The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction. *Energy & Environmental Science,* 8, 158—168. https://doi.org/10.1039/C4EE03029J
36. Picatoste, A., Justel, D., Mendoza, J. M. (2023). Analysing repurposing solutions for electric vehicle batteries: Circularity indicators, LCA and methodological guidelines. The 11th International Conference on Life Cycle Management (September, 2023). URL: https://www.researchgate.net/publication/373993858_Analysing_repurposing_solutions_for_electric_vehicle_batteries_circularity_indicators_LCA_and_methodological_guidelines (Last accessed: 10.02.2024).
37. Kostenko, G., Zaporozhets, A. (2024). World experience of legislative regulation for lithium-ion electric vehicle batteries considering their second-life application in power sector. *System Research in Energy,* 2(77), 97—114. https://doi.org/10.15407/srenergy2024.02.097
38. Kostenko, G., Zaporozhets, A. (2024). Transition from electric vehicles to energy storage: Review on targeted lithium-ion battery diagnostics. *Energies,* 17(20), 5132. https://doi.org/10.3390/en17205132

39. Kostenko, G. (2024). Accounting calendar and cyclic ageing factors in diagnostic and prognostic models of second-life EV batteries application in energy storage systems. *System Research in Energy,* 3(79), 21—34. https://doi.org/10.15407/srenergy2024.03.021
40. Kostenko, G. (2025). Cluster-based deployment of second-life EV batteries for reliable and sustainable backup power solution in power systems. *System Research in Energy,* 1(81), 40—60. https://doi.org/10.15407/srenergy2025.01.040
41. Zahoor, A., Kun, R., Mao, G., Farkas, F., Sápi, A., Kónya, Z. (2024). Urgent needs for second life using and recycling design of wasted electric vehicles (EVs) lithium-ion battery: A scientometric analysis. *Environmental Science and Pollution Research,* 31, 43152—43173. https://doi.org/10.1007/s11356-024-33979-3
42. Bekaert, E. Second life batteries for a sustainable energy transition. CIC energiGUNE. URL: https://cicenergigune.com/en/blog/second-life-batteries-sustainable-energy-transition (Last accessed: 30.12.2023).
43. Bukatyuk, U. In 2023, the market of electric cars in Ukraine will almost double. Is the charging infrastructure keeping up with the boom? Forbes Ukraine. URL: https://forbes.ua/innovations/supermarzhinalniy-rinok-za-rik-svitovi-prodazhi-elektrokariv-zrosli-na-20-30-a-v-ukraini-mayzhe-vdvichi-chi-vstigae-za-bumom-zaryadna-infrastruktura-03012024-18288 (Last accessed: 29.02.2024).
44. Tarasovskyi, Y. A record number of electric cars were imported to Ukraine in 2023. Forbes Ukraine. URL: https://forbes.ua/news/v-ukrainu-vvezli-rekordnu-kilkist-elektromobiliv-u-2023-rotsi-pokaznik-u-chotiri-razi-perevishchiv-dovoenniy-2021-rik-24012024-18735 (Last accessed: 29.02.2024).
45. Miao, Y., Hynan, P., von Jouanne, A., Yokochi, A. (2019). Current Li-Ion battery technologies in electric vehicles and opportunities for advancements. *Energies,* 12(6), 1074. https://doi.org/10.3390/en12061074
46. Fichtner, M. (2022). Recent research and progress in batteries for electric vehicles. *Batteries & Supercaps,* 5(2), e202100224. https://doi.org/10.1002/batt.202100224
47. Hasselwander, S., Meyer, M., Österle, I. (2023). Techno-economic analysis of different battery cell chemistries for the passenger vehicle market. *Batteries,* 9(7), 379. https://doi.org/10.3390/batteries9070379
48. Ma, J., Li, Yu., Grundish, N. S., Goodenough, J. B., Chen, Yu., Guo, L., Peng, Zh., ..., Wan, L.-J. (2021). The 2021 battery technology roadmap. *Journal of Physics D: Applied Physics,* 54(18), 183001. https://doi.org/10.1088/1361-6463/abd353
49. Tsiropoulos, I., Tarvydas, D., Lebedeva, N. (2018). Li-ion batteries for mobility and stationary storage applications — Scenarios for costs and market growth (EUR 29440 EN). https://doi.org/10.2760/87175.
50. BNEF. (2021, November). Battery pack prices fall to an average of $132/kWh, but rising commodity prices start to bite. URL: https://about.bnef.com/blog/battery-pack-prices-fall-to-an-average-of-132-kwh-but-rising-commodity-prices-start-to-bite/ (Last accessed: 30.12.2023).
51. Halimah, P. N., Rahardian, S., Budiman, B. A. (2019). Battery cells for electric vehicles. *International Journal of Sustainable Transportation Technology,* 2(2), 54—57.
52. Zubi, G., Dufo-López, R., Carvalho, M., Pasaoglu, G. (2018). The lithium-ion battery: State of the art and future perspectives. *Renewable and Sustainable Energy Reviews,* 89, 292—308. https://doi.org/10.1016/j.rser.2018.03.002
53. Rahimi-Eichi, H., Ojha, U., Baronti, F., Chow, M.-Y. (2013). Battery management system: An overview of its application in the smart grid and electric vehicles. *IEEE Industrial Electronics Magazine,* 7(2), 4—16. https://doi.org/10.1109/MIE.2013.2250351
54. Kovtun, S., Ponomarenko, O., Nazarenko, O. (2023). Quality of the information flow management at stochastic energy consumption conditions. *System Research in Energy,* 3(74), 78—84. https://doi.org/10.15407/srenergy2023.03.078
55. Zhong, S., Yuan, B., Guang, Z., Chen, D., Li, Q., Dong, L., Ji, Y., Dong, Y., Han, J., He, W. (2021). Recent progress in thin separators for upgraded lithium-ion batteries. *Energy Storage Materials,* 41, 805—841.
56. Chirumalla, K., Kulkov, I., Parida, V., Dahlquist, E., Johansson, G., Stefan, I. (2024). Enabling battery circularity: Unlocking circular business model archetypes and collaboration forms in the electric vehicle battery ecosystem. *Technological Forecasting and Social Change,* 199. https://doi.org/10.1016/j.techfore.2023.123044
57. Vu, F., Rahic, M., Chirumalla, K. (2020). Exploring second life applications for electric vehicle batteries. In *SPS2020: Advances in Transdisciplinary Engineering* (Eds. K. Säfsten, F. Elgh.). *IOS Press,* 13, 273—284. https://doi.org/10.3233/ATDE200165
58. Hossain, E., Murtaugh, D., Mody, J., Faruque, H. M. R., Sunny, M. S., Sami, N. M. (2019). A comprehensive review on second-life batteries: Current state, manufacturing considerations, applications, impacts, barriers & potential solutions, business strategies, and policies. *IEEE Access,* 7, 73215—73252. https://doi.org/10.1109/ACCESS.2019.2917859
59. Kotak, Y., Marchante Fernandez, C., Canals Casals, L., Kotak, B. S., Koch, D., Geisbauer, C., Trilla, L., Gomez-Nunez, A., Schweiger, H.-G. (2021). End of electric vehicle batteries: Reuse vs. recycle. *Energies,* 14(8), 2217. https://doi.org/10.3390/en14082217

60. Bobba, S., Mathieux, F., Ardente, F., Blengini, G. A., Cusenza, M. A., Podias, A., Pfrang, A. (2018). Life cycle assessment of repurposed electric vehicle batteries: An adapted method based on modelling energy flows. *Journal of Energy Storage,* 19, 213—225. https://doi.org/10.1016/j.est.2018.07.008
61. Canals Casals, L. L., Amante García, B., Camille Canal, C. (2019). Second life batteries lifespan: Rest of useful life and environmental analysis. *Journal of Environmental Management,* 232, 354—363. https://doi.org/10.1016/j.jenvman.2018.11.046
62. Nissan Motor Corporation. (n.d.). Electric vehicle lithium-ion battery. URL: https://www.nissan-global.com/EN/INNOVATION/TECHNOLOGY/ARCHIVE/LI_ION_EV/ (Last accessed: 30.01.2024).
63. InsideEVs Editorial Team. (n.d.). Battery capacity loss warranty chart for 30 kWh Nissan LEAF. URL: https://insideevs.com/news/326563/battery-capacity-loss-warranty-chart-for-2016-30-kwh-nissan-leaf/ (Last accessed: 30.01.2024).
64. Koroma, M. S., Costa, D., Philippot, M., Cardellini, G., Hosen, M. S., Coosemans, T., Messagie, M. (2022). Life cycle assessment of battery electric vehicles: Implications of future electricity mix and different battery end-of-life management. *Science of the Total Environment,* 831, 154859. https://doi.org/10.1016/j.scitotenv.2022.154859
65. Tao, Y., Rahn, C. D., Archer, L. A., You, F. (2021). Second life and recycling: Energy and environmental sustainability perspectives for high-performance lithium-ion batteries. *Science Advances,* 7(45), eabi7633. https://doi.org/10.1126/sciadv.abi7633
66. Dong, Q., Liang, S., Li, J., Kim, H. C., Shen, W., Wallington, T. J. (2023). Cost, energy, and carbon footprint benefits of second-life electric vehicle battery use. *iScience,* 26(7), 107195. https://doi.org/10.1016/j.isci.2023.107195
67. Reinhardt, R., Christodoulou, I., Gassó-Domingo, S., Amante García, B. (2019). Towards sustainable business models for electric vehicle battery second use: A critical review. *Journal of Environmental Management,* 245, 432—446. https://doi.org/10.1016/j.jenvman.2019.05.095
68. Neubauer, J., Smith, K., Wood, E., Pesaran, A. (2015). Identifying and overcoming critical barriers to widespread second use of PEV batteries (NREL/TP-6300-63332). National Renewable Energy Laboratory. URL: https://www.nrel.gov/docs/fy15osti/63332.pdf (Last accessed: 30.01.2024).
69. Faria, R., Marques P., Garcia, R., Moura, P., Freire, F., Delgado, J., de Almeida, A. T. (2014). Primary and secondary use of electric mobility batteries from a life cycle perspective. *Journal of Power Sources,* 262, 169—177. https://doi.org/10.1016/j.jpowsour.2014.03.092
70. Wang, D., Coignard, J., Zeng, T., Zhang, C., Saxena, S. (2016). Quantifying electric vehicle battery degradation from driving vs. vehicle-to-grid services. *Journal of Power Sources,* 332, 193—203. https://doi.org/10.1016/j.jpowsour.2016.09.116
71. Dubarry, M., Baure, G., Devie, A. (2018). Durability and reliability of EV batteries under electric utility grid operations: Path dependence of battery degradation. *Journal of The Electrochemical Society,* 165, A773. https://doi.org/10.1149/2.0421805jes
72. Eddahech, A., Briat, O., Woirgard, E., Vinassa, J. M. (2012). Remaining useful life prediction of lithium batteries in calendar ageing for automotive applications. *Microelectronics Reliability,* 52(9—10), 2438—2442. https://doi.org/10.1016/j.microrel.2012.06.085
73. Neubauer, J., Wood, E., Pesaran, A. (2015). A second life for electric vehicle batteries: Answering questions on battery degradation and value. *SAE International Journal of Materials and Manufacturing,* 8(2), 544—553. https://doi.org/10.4271/2015-01-1306
74. Kostenko, G. P. (2023). Situation analysis of electric transport development prospects and its integration into Ukrainian power system. *Power Engineering: Economics, Technique, Ecology,* 1, 71. https://doi.org/10.20535/1813-5420.1.2023.276185
75. Ivanenko, N. (2023). The impact of the implementation of electric transportation on Ukraine's integrated power system functioning. *System Research in Energy,* 1(72), 4—11. https://doi.org/10.15407/srenergy2023.01.004
76. Kostenko, G. P., Zgurovets, O. V., Tovstenko, M. M. (2023). SWOT-analysis of electric transport and V2G implementation for power system sustainable development in the terms of Ukraine. *IOP Conf. Ser.: Earth Environ. Sci.,* 1254, 012030. https://doi.org/10.1088/1755-1315/1254/1/012030
77. Zaporozhets, A., Kostenko, G., Zgurovets, O. (2023). Preconditions and main features of electric vehicles application for frequency regulation in the power system. *CEUR Workshop Proc.,* 3628, 43—54.
78. Zaporozhets, A., Kulyk, M., Babak, V., Denysov, V. (2025). Current trends in modeling and updating the dissemination processes of energy conversion and utilization technologies in the energy sector of Ukraine. In: *Structure Optimization of Power Systems with Renewable Energy Sources* (Studies in Systems, Decision and Control, Vol. 583). Springer. https://doi.org/10.1007/978-3-031-83697-8_1
79. Babak, V., Nikitin, Y., Teslenko, O. (2024). Holistic approach to the systemic transformation of the electric power industry, district heating and municipal infrastructure. *System Research in Energy,* 4(80), 6—25. https://doi.org/10.15407/srenergy2024.04.006

80. Kostenko, G. P., Zaporozhets, A. O., Zaporozhets, N. V., Verpeta, V. O. (2024). Aspects of integrating renewable distributed generation into the energy supply system of Ukraine. *The Problems of Economy*, 2, 83—93. https://doi.org/10.32983/2222-0712-2024-2-83-93
81. Kostenko, G., Zgurovets, O. (2023). Current state and prospects for development of renewable distributed generation in Ukraine. *System Research in Energy,* 2(73), 4—17. https://doi.org/10.15407/srenergy2023.02.004
82. Babak, V., Kulyk, M. (2023). Increasing the efficiency and security of integrated power system operation through heat supply electrification in Ukraine. *Science and Innovation,* 19(5), 100—116. https://doi.org/10.15407/scine19.05.100
83. Zaporozhets, A., Kostenko, G., Zgurovets, O., Deriy, V. (2024). Analysis of global trends in the development of energy storage systems and prospects for their implementation in Ukraine. In: *Studies in Systems, Decision and Control* (Eds. O. Kyrylenko, S. Denysiuk, R. Strzelecki, I. Blinov, I. Zaitsev, A. Zaporozhets), 512. https://doi.org/10.1007/978-3-031-44772-3_4
84. Hotra, O., Kulyk, M., Babak, V., Kovtun, S., Zgurovets, O., Mroczka, J., Kisała, P. (2024). Organisation of the structure and functioning of self-sufficient distributed power generation. *Energies,* 17(1), 27. https://doi.org/10.3390/en1701002
85. Derii, V. (2023). Electric energy storages. *System Research in Energy,* 1(72), 12—24. https://doi.org/10.15407/srenergy2023.01.012
86. Zgurovets, O. V., Kulyk, M. M. (2022). Possibilities to form a modern reserve of frequency support in integrated power systems based on storage batteries for automatic adjustment of frequency and power. *System Research in Energy,* 1—2(68—69), 20—29. https://doi.org/10.15407/pge2022.01-02.020
87. Zaporozhets, A., Babak, V., Kostenko, G., Zgurovets, O., Denisov, V., Nechaieva, T. (2024). Power system resilience: An overview of current metrics and assessment criteria. In: *Studies in Systems, Decision and Control* (Eds. V. Babak, A. Zaporozhets), 561. https://doi.org/10.1007/978-3-031-68372-5_2
88. Kostenko, G., Zaporozhets, A. (2023). Enhancing of the power system resilience through the application of micro power systems (microgrid) with renewable distributed generation. *System Research in Energy,* 3(74), 25—38. https://doi.org/10.15407/srenergy2023.03.025
89. Denysov, V., Babak, V., Zaporozhets, A., Nechaieva, T., Kostenko, G. (2024). Energy system optimization potential with consideration of technological limitations. In: *Studies in Systems, Decision and Control* (Eds. A. Zagorodny, V. Bogdanov, A. Zaporozhets), 559. https://doi.org/10.1007/978-3-031-66764-0_5
90. Denysov, V., Babak, V., Zaporozhets, A., Nechaieva, T., Kostenko, G. (2024). Quasi-dynamic energy complexes optimal use on the forecasting horizon. In: *Studies in Systems, Decision and Control* (Eds. V. Babak, A. Zaporozhets), 561. https://doi.org/10.1007/978-3-031-68372-5_4
91. Zaporozhets, A., Babak, V., Kostenko, G., Sverdlova, A., Dekusha, O., Kornienko, S. (2023). Some features of air pollution monitoring as a component of the microclimate of the premises. *System Research in Energy,* 4(75), 65—73. https://doi.org/10.15407/srenergy2023.04.065
92. Derii, V., Nechaieva, T., Leshchenko, I. (2023). Assessment of the effect of structural changes in Ukraine's district heating on greenhouse gas emissions. *Science and Innovation,* 19(4), 57—65. https://doi.org/10.15407/scine19.04.057
93. Babak, V. P., Kulyk, M. M. (2023). Possibilities and perspectives of the consumers-regulators application in systems of frequency and power automatic regulation. *Technical Electrodynamics,* 4, 72—80. https://doi.org/10.15470/techned2023.04.072
94. Denysov, V., Kulyk, M., Babak, V., Zaporozhets, A., Kostenko, G. (2024). Modeling nuclear-centric scenarios for Ukraine's low-carbon energy transition using diffusion and regression techniques. *Energies,* 17(20), 5229. https://doi.org/10.3390/en17205229
95. Maistrenko, N., Horskyi, V. (2024). Assessment of the energy saving potential by regions of Ukraine (methodology and predictive assessment). *System Research in Energy,* 1(76), 4—16. https://doi.org/10.15407/srenergy2024.01.004
96. Maistrenko, N. (2023). Taking into account environmental constraints on emissions in economic models: Long-term forecasting of energy consumption (review of publications). *System Research in Energy,* 3(74), 85—94. https://doi.org/10.15407/srenergy2023.03.085
97. Denysov, V., Kostenko, G., Babak, V., Shulzhenko, S., Zaporozhets, A. (2023). Accounting the forecasting stochasticity at the power system modes optimization. In: *Studies in Systems, Decision and Control* (Ed. A. Zaporozhets), 481. https://doi.org/10.1007/978-3-031-35088-7_3
98. Babak, V., Babak, S., Zaporozhets, A. (2025). Tasks for creating the environmental monitoring systems for energy objects. In: *Statistical Diagnostics of Electric Power Equipment. Studies in Systems, Decision and Control,* 573). https://doi.org/10.1007/978-3-031-76253-6_9

Received 11.03.2024
Revised 18.03.2025
Accepted 11.04.2025

А.О. Запорожець[1, 2, 3] (https://orcid.org/0000-0002-0704-4116),
Г.П. Костенко[1] (https://orcid.org/0000-0002-8839-7633)

[1] Інститут загальної енергетики НАН України,
вул. Антоновича, 172, Київ, 03150, Україна
+380 44 294 6701, info@ienergy.kyiv.ua
[2] Університет Юань Же,
Юандонг Роад, 320, Таоюань, Тайвань,
+886 3 463 8800, iadept@saturn.yzu.edu.tw
[3] Центр інформаційно-аналітичного та технічного забезпечення
моніторингу об'єктів атомної енергетики Національної академії наук України,
просп. Академіка Палладіна, 34 А, Київ, 03142, Україна,
+380 44 502 1233, cnpfm.info@gmail.com

ВТОРИННЕ ВИКОРИСТАННЯ АКУМУЛЯТОРНИХ БАТАРЕЙ ЕЛЕКТРОМОБІЛІВ У ЕНЕРГЕТИЧНОМУ СЕКТОРІ УКРАЇНИ: *SWOT*-АНАЛІЗ ТА ОЦІНКА РИНКОВИХ ПЕРСПЕКТИВ

Вступ. Розширення використання електромобілів (*EV*) посилює питання утилізації літій-іонних батарей. Їх повторне використання є економічно вигідним та екологічно безпечним рішенням, що підтримує стабільність мережі та циркулярну економіку. В Україні вторинне застосування батарей може сприяти енергетичній безпеці та інтеграції відновлюваних джерел.

Проблематика. Попри переваги широке впровадження батарей *EV* в Україні зіштовхується з технічними, економічними та регуляторними бар'єрами. Відсутність стандартів оцінки стану батарей, стратегій інтеграції та ринкового аналізу потребує комплексного *SWOT*-аналізу.

Мета. Оцінювання ринкового потенціалу вторинного використання батарей *EV* в Україні за допомогою *SWOT*-аналізу, визначення доцільності їх інтеграції в енергосистему та використання у системах накопичення енергії.

Матеріали й методи. Використано *SWOT*-аналіз як основний підхід, доповнений оцінкою ринку, аналізом регуляторного середовища та економічної доцільності. Робота ґрунтується на глобальних кейсах, політичних документах і емпіричних даних щодо деградації батарей, їх продуктивності та продовження життєвого циклу.

Результати. *SWOT*-аналіз підтверджує, що вторинне застосування батарей *EV* є вигідним рішенням для накопичення енергії, підтримки стабільності мережі та циркулярної економіки. Викликами є відсутність стандартів, невизначена тривалість експлуатації та регуляторні прогалини. Можливості включають державні стимули, нові бізнес-моделі та зростаючий попит на гнучкі системи зберігання. Загрози пов'язані з конкуренцією з новітніми батареями, кіберризиками та ринковою нестабільністю. Запропоновано стратегічні заходи для подолання цих бар'єрів.

Висновки. Вторинне застосування батарей *EV* може підвищити енергетичну безпеку України та розширити використання відновлювальних джерел енергії. Для впровадження потрібні регуляторні механізми, фінансові стимули та ефективне управління. Подальші дослідження мають зосередитися на моделюванні деградації, ринкових механізмах та інтеграції в енергосистему.

Ключові слова: вторинні батареї електромобілів, накопичення енергії, інтеграція в мережу, циркулярна економіка, енергетична безпека, відновлювана енергія, сталий розвиток.