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CLUSTER-BASED DEPLOYMENT OF SECOND-LIFE EV BATTERIES FOR RELIABLE AND SUSTAINABLE BACKUP POWER SOLUTION IN POWER SYSTEMS

Abstract. *In emergency situations, ensuring reliable backup power sources for the power system is critically important for maintaining the stability and uninterrupted operation of energy infrastructure. The challenges posed by wartime conditions and the growing vulnerability of energy infrastructure, particularly HVsubstations, demand innovative approaches that combine economic efficiency, technical reliability, and environmental sustainability. The aim of this study is to develop comprehensive solutions for providing reliable and sustainable backup power to Ukraine's HVsubstations, addressing contemporary challenges in energy security and environmental resilience. The paper examines the potential of second-life electric vehicle (EV) batteries as a promising alternative to traditional solutions, such as diesel generators. The use of second-life batteries offers a novel approach that meets modern requirements for energy efficiency and sustainable development. The clustering methodology employed in the study enables the optimization of resource allocation among substations, considering factors such as load levels, outage frequency, and required reserve capacity. This approach ensures tailored solutions for the specific operational needs of each cluster, enhancing resource utilization efficiency. The study includes a detailed evaluation of the economic, technical, and environmental characteristics of various solutions, including diesel generators, new batteries, and second-life batteries, both independently and in combination with renewable energy sources such as photovoltaic modules. The results demonstrate that second-life batteries, particularly when integrated with renewable energy sources, offer substantial advantages, including cost reductions, decreased CO_2 emissions, and enhanced energy resilience. The proposed recommendations for implementing second-life batteries are supported by a comprehensive analysis of legislative, technical, and economic aspects. This study provides a roadmap for integrating second-life EV batteries as a sustainable and scalable solution to strengthen energy security, facilitate the transition to a low-carbon economy, and enhance the resilience of Ukraine's power system.*
Keywords: second-life batteries integration, backup power, resilience, HV substations, clustering methodology, sustainable development.

1. Introduction

Ukraine’s energy sector is at a critical juncture, balancing the demands of modernization, resilience, and sustainability. The Energy Strategy of Ukraine until 2050 outlines ambitious goals to enhance energy independence, integrate renewables, and improve efficiency [1–2]. These efforts align with the EU strategy on power system integration, which emphasizes innovative and sustainable energy solutions [3]. However, significant challenges remain, including the restoration of decimated infrastructure caused by ongoing hostilities [4]. Some initiatives are pivotal in stabilizing the energy network while promoting sustainable recovery [5]. Meanwhile, research highlights opportunities for innovation, including nuclear-centric scenarios, regional energy efficiency programs, and advanced electro-thermal system structures [6–10]. These frameworks emphasize the need for resilient and cost-effective solutions to ensure reliability and sustainability.

The ongoing war in Ukraine has significantly impacted the nation’s energy infrastructure, revealing vulnerabilities that demand immediate attention. High-voltage (HV) substations, essential for maintaining the stability and functionality of the power grid [11–13], have become frequent targets of attacks, disrupting electricity supply to critical facilities. These interruptions underscore the urgent need for innovative, reliable, and resilient backup power systems capable of maintaining continuity under adverse conditions, particularly for the internal power needs of these substations, which are critical to their operation.

Traditional backup power solutions, such as diesel generators, have long been the standard choice for ensuring uninterrupted energy supply. However, these systems are increasingly inadequate due to their dependency on fuel supply chains, high operational costs, and substantial greenhouse gas emissions. While new battery technologies offer a cleaner alternative, their high capital costs make them less accessible for large-scale applications. These limitations necessitate the exploration of alternative solutions that balance technical feasibility, economic viability, and environmental sustainability.

Second-life electric vehicle (EV) batteries present a promising alternative for addressing these challenges [14–17]. After their primary use in EVs, these batteries retain significant capacity for energy storage applications, making them suitable for backup power systems [18–20]. Their cost-effectiveness, alignment with circular economy principles, and ability to provide rapid response and stable output make them particularly well-suited for critical infrastructure such as HV substations and for enhancing power system resilience in general [21–29]. Furthermore, their integration into power systems offers a sustainable approach to enhancing resilience, reducing environmental impact, and optimizing resource use.

Despite the demonstrated potential of second-life batteries (SLBs) in various applications [30–36], their use in HV substations, specifically for internal operational needs, remains an underexplored concept. Substations, while standardized in equipment, operate under diverse conditions based on load profiles, outage frequencies, and the criticality of the infrastructure they support. These variations demand tailored solutions, underscoring the need for a granular, cluster-based approach to deploying SLBs. Categorizing substations into operational clusters and customizing backup power strategies can enhance energy resilience while optimizing resource allocation.

This study focuses on evaluating the feasibility of SLBs as a sustainable and reliable solution for backup power at HV substations in Ukraine, with an emphasis on addressing their internal operational requirements. By analyzing technical, economic, and environmental aspects, the paper aims to propose operational models and recommendations tailored to the unique conditions of Ukraine's power system. The objective is to establish SLBs as a cornerstone of energy resilience, offering cost-effective and environmentally sustainable solutions for critical nodes in the power grid.

2. Methods and Materials

2.1. Power Supply Reliability and Sufficient Ensuring of Backup Power

The electrical power system is a complex, branched network (Fig. 1) that connects various power generation sources, transmission and distribution grids, ensuring reliable electricity delivery to industrial, urban, and rural consumers.

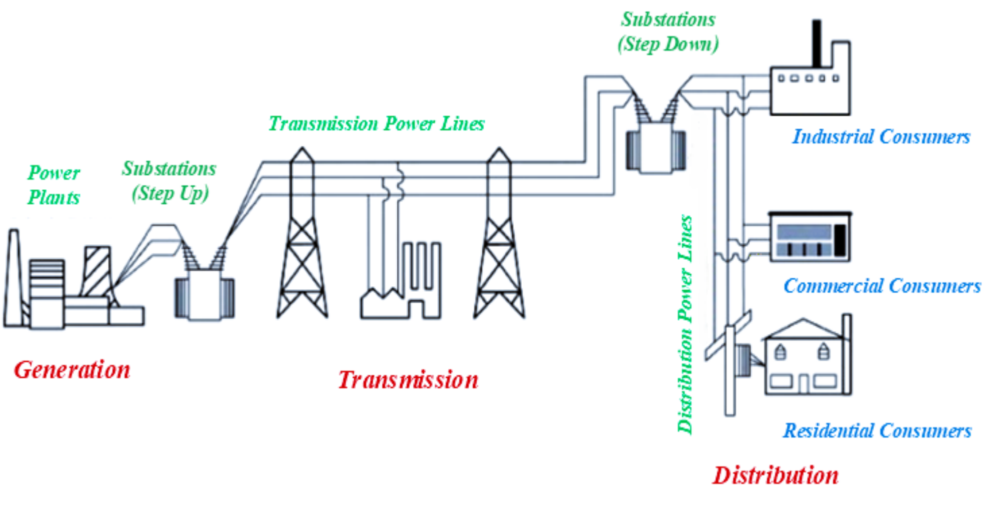

Figure 1. Electricity Supply Chain: From Generation to Consumers [37]

The ongoing war in Ukraine has profoundly impacted the country's energy system, creating significant challenges in electricity generation and consumption. Figure 2 illustrates the shifts in key energy indicators before and after the start of the conflict. Subplot (a) depicts the changes in electricity generation capacity by energy source, highlighting the decline in natural gas and coal use. Subplot (b) shows daily electricity demand trends, capturing the abrupt drop and subsequent stabilization. Subplots (c) and (d) present average monthly electricity demand and generation capacity in 2021 and 2022, providing a comparative perspective on seasonal variations and the resilience of the energy system. This analysis underscores the urgency of implementing reliable and sustainable backup power solutions to address these disruptions.[37, 55].

Figure 2. Key Energy Indicators of Ukraine's Power System Before and After War Beginning
(a) Electricity generation capacity in 2021–2022; (b) Daily electricity demand in 2021/2022; (c) Average daily electricity demand by month for 2021/2022; (d) Average daily electricity generation capacity by month for 2021/2022.

The data presented in Fig. highlight the critical challenges facing Ukraine's energy system and emphasize the need for innovative solutions. The significant reduction in electricity generation capacity and demand underscores the vulnerability of the current energy infrastructure. These disruptions reinforce the importance of clustering substations and integrating second-life EV batteries as a means to enhance grid resilience, reduce dependence on fossil fuels, and ensure reliable power supply for critical infrastructure during crises.

Traditional backup power solutions, such as diesel generators and new battery systems, while effective in the past, present significant limitations. Diesel generators, though reliable, emit substantial greenhouse gases, contribute to climate change, and depend heavily on secure fuel supply chains, which are vulnerable during crises. Similarly, new battery systems offer cleaner and more efficient alternatives but involve high upfront costs, making widespread adoption economically challenging. These shortcomings necessitate exploring innovative and sustainable solutions tailored to the specific demands of critical infrastructure like HV substations. By integrating SLBs into HV substations, the power system can reduce reliance on fossil fuels, mitigate greenhouse gas emissions, and ensure continuous operation of critical infrastructure even during extended outages.

2.2. Traditional Solutions for Backup Power

In power systems, ensuring a reliable level of backup power is critical, especially for infrastructure that plays a vital role in the stability of the grid or the functioning of essential services. The most common approaches [37-38] for achieving this include the following:

Installation of an Additional Local Transformer Substation. This approach involves setting up an auxiliary transformer substation to provide an independent backup power source. By directly connecting to the primary grid, these substations ensure a stable and redundant power supply. They are particularly effective for facilities with high energy demands or critical operations. However, this method requires significant capital investment and long installation timelines, making it less feasible for smaller applications.

Deployment of a High-Capacity Diesel Generator with a Dedicated Connection to the Grid. Diesel generators are widely used as backup power sources due to their ability to provide reliable and immediate energy during outages. These systems are typically installed with a stationary connection to the grid through a separate channel, ensuring they can operate autonomously when required. While diesel generators are effective for short- to medium-duration outages, their reliance on fossil fuels leads to high operational costs and environmental concerns, including significant CO_2 emissions.

Implementation of a High-Capacity Battery System. Establishing a sufficiently powerful battery system is an increasingly popular method for backup power. Such systems are capable of maintaining the operational functionality of a facility for extended periods during outages. Unlike diesel generators, battery systems offer a cleaner and quieter alternative, with zero operational emissions. Advances in battery technology, including the use of second-life batteries, have made this approach more economically viable. Battery systems also integrate seamlessly with RES, such as solar panels, further enhancing their sustainability and cost-effectiveness.

These methods vary in terms of cost, environmental impact, and suitability for specific applications. The choice of solution often depends on the criticality of the infrastructure, the frequency and duration of potential outages, and the economic considerations of the facility operator. Increasingly, a shift towards battery systems is observed due to their alignment with global sustainability and energy resilience goals.

Diesel generators are a longstanding solution for backup power, valued for their ability to deliver immediate and reliable energy during outages [56]. Their robustness makes them particularly suitable for facilities with high energy demands, ensuring long durations of uninterrupted operation. Despite their widespread use, diesel generators face several critical limitations that undermine their viability in modern power systems. High operational costs, driven by significant fuel consumption and ongoing maintenance requirements, present a substantial financial burden over time. Additionally, the environmental impact of diesel generators is considerable, with significant CO_2 emissions contributing to climate change and air pollution. Another major drawback is their dependency on consistent fuel supply, which exposes these systems to vulnerabilities during logistical disruptions, particularly in crisis situations. These challenges highlight the need for more sustainable and cost-effective alternatives in backup power solutions.є

Modern battery energy storage systems (BESS) have emerged as a promising alternative to traditional generators, offering numerous advantages in terms of efficiency, environmental impact, and responsiveness [54–56]. These systems boast efficiency levels exceeding 90%, making them significantly more energy-efficient than their diesel counterparts. Furthermore, batteries produce no direct emissions during operation, aligning with global sustainability goals and reducing the carbon footprint of power systems. Their ability to deliver near-instantaneous power makes them particularly well-suited for sensitive applications, where even brief interruptions in power supply can have critical consequences. Despite these benefits, the high upfront costs associated with new battery systems remain a significant barrier to their widespread adoption, particularly in resource-constrained environments where financial limitations restrict large-scale implementation.

Ensuring reliable backup power for critical infrastructure requires a careful assessment of cost, efficiency, and environmental impact. Two primary solutions—diesel generators and lithium-ion batteries—are widely used, each offering distinct advantages and trade-offs. Diesel generators provide a stable power supply with relatively low upfront costs but suffer from high operational expenses and significant CO_2 emissions (500 g/kWh) [37]. Their efficiency is around 30%, and their average operational lifespan is approximately 5 years with regular maintenance. They are typically deployed in 10–500 kW configurations, depending on the scale of the facility. Lithium-ion batteries, on the other hand, offer a significantly higher efficiency of 90 %, rapid response times (less than 1 second), and zero direct emissions.

In this study, second-life batteries from Nissan LEAF vehicles were considered, specifically focusing on the 40 kWh NMC battery pack widely used in second-generation models. After primary use in electric vehicles, these batteries typically retain 75–80% of their initial capacity, making them viable for secondary applications in energy storage. With a cycle life ranging between 2000 and 3000 cycles, their operational longevity is largely dependent on depth-of-discharge (DOD), thermal conditions, and charging strategies. Under controlled operational settings, these batteries can provide an additional 7–10 years of service in stationary storage systems before reaching the end-of-life threshold. Their modular 8-cell configuration allows for efficient scaling in backup power applications, ensuring adaptability across different system requirements. By leveraging these characteristics, Nissan LEAF second-life batteries offer a cost-effective, scalable, and environmentally sustainable solution for enhancing energy resilience in power infrastructure. The rated power capacity of the battery systems ranges from 50 kW to several MW, depending on system configuration and the number of modules deployed. These batteries provide a cost-effective alternative with lower long-term operational costs compared to diesel generators, making them an attractive option for backup power solutions.

The following comparison (Tab. 1) summarizes the key characteristics of these backup power technologies.

Table 1. Comparison of Diesel Generators and Li-ion Batteries for Backup Power Solutions

Parameter	**Diesel Generators**	**Li-ion Batteries**
Equipment Cost (₴/unit)	40000	115000
Operational Costs (₴/year)	60668	33227
CO_2 Emissions (g/kWh)	500	0
Lifespan (years)	5	10
Cost of Electricity (₴/kWh)	22.1	6.7
Efficiency (%)	30-40	85-90
Backup Duration (hours)	10	4-12 (depending on capacity and load)
Response Time (seconds)	10-60	1
Cyclic Durability (cycles)	N/A	1000+

The data presented in Table 1 highlights the fundamental economic and environmental differences between diesel generators and lithium-ion batteries as backup power solutions. While diesel generators require a lower initial investment (₴40,000 vs. ₴115,000 for batteries), their significantly higher operational costs (₴60,668/year vs. ₴33,227/year) result in a less favorable total cost of ownership. Additionally, diesel generators produce substantial CO_2 emissions (500 g/kWh), whereas batteries operate with zero direct emissions, making them a more environmentally sustainable alternative. Despite the higher upfront cost, the longer lifespan of lithium-ion batteries (10 years vs. 5 years for generators) and their lower cost per kWh of electricity (₴6.7/kWh vs. ₴22.1/kWh) further reinforce their long-term economic advantages. These findings underscore the potential of battery storage systems to serve as a viable, cost-effective, and sustainable backup power solution, particularly in applications where minimizing emissions and reducing dependency on fuel supply chains are critical factors.

2.3. Second-Life Batteries as a Promising Backup Power Solution

SLBs, repurposed from EV, represent an innovative and cost-effective solution for reliable backup power. Although no longer suitable for automotive use, these batteries retain significant energy storage capacity, making them ideal for stationary applications. Their integration into power systems offers a unique combination of technical reliability, economic feasibility, and ecological benefits. By extending their lifecycle, SLBs align with circular economy principles, reduce environmental waste, and support a transition to sustainable energy infrastructure.

Unlike traditional diesel generators, SLBs activate in under a second, ensuring uninterrupted operation for critical systems such as HVsubstations. Their cost-effectiveness is particularly notable, with acquisition costs significantly lower than those of new battery systems, and operational expenses minimized due to their maintenance-free nature and lack of fuel dependency. Furthermore, SLBs operate without emissions, presenting a zero-carbon alternative to diesel generators.

The integration of second-life EV batteries into the power system requires a holistic approach, encompassing battery management, system coupling, and grid-level deployment to ensure technical reliability, economic feasibility, and environmental sustainability, as illustrated in Fig. 3. It provides a deep comparison of the total costs associated with various backup power solutions over a seven-year operational period, offering valuable insights into the economic implications of each technology. This visual representation emphasizes the stark differences in cost trajectories between traditional diesel generators, new lithium-ion batteries, and second-life batteries, both standalone and integrated with solar panels. The financial analysis highlights the increasing operational expenses of diesel generators due to fuel dependency and maintenance costs, which significantly outpace the more stable and predictable costs of battery-based solutions.

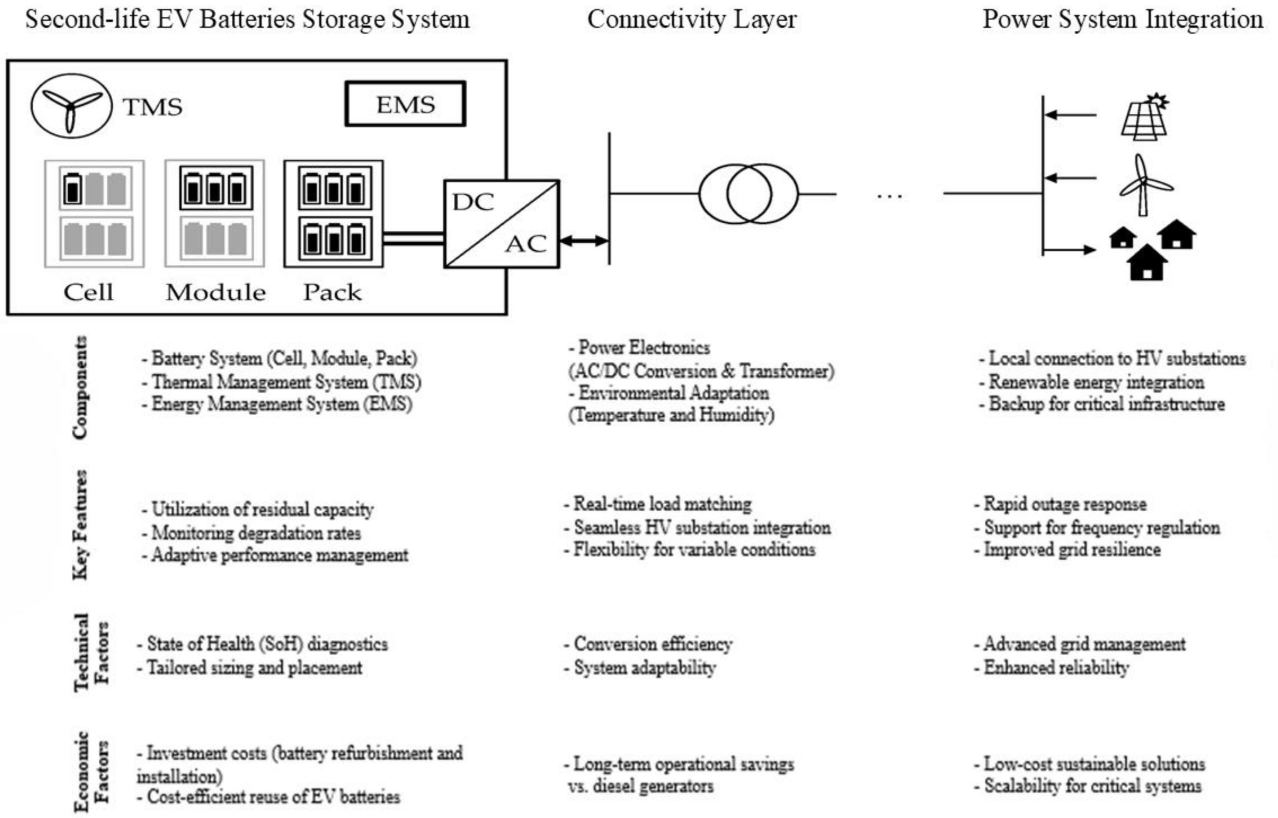

Figure 3. Framework for Integrating Second-Life EV Batteries into the Power System

Of particular interest is the cost-efficiency demonstrated by second-life batteries, especially when paired with renewable energy sources like solar panels. This hybrid approach leverages the lower initial investment of repurposed batteries while achieving further savings through reduced reliance on grid electricity and fossil fuels. Such systems align with modern energy strategies aimed at reducing greenhouse gas emissions and promoting sustainable energy practices. The results also underline the adaptability of second-life batteries for critical applications like HV substations, where economic and environmental performance must balance technical reliability.

This comparison reinforces the argument for transitioning to sustainable backup power solutions, demonstrating that second-life batteries not only provide a cost-effective alternative but also support broader energy resilience and decarbonization objectives. Tab. 3 provides a comparative analysis of diesel generators, new lithium-ion batteries (LIBs), and second-life batteries, including configurations integrated with solar panels. It must be specified separately that installation of a battery park requires the allocation of sufficient space within the substation's territory to accommodate the necessary infrastructure. When combined with photovoltaic panels, the space requirements increase significantly, as additional areas are needed for the solar arrays and their associated equipment. Proper planning and site assessment are crucial to ensure the efficient utilization of available land while maintaining operational flexibility and safety standards.

The table highlights key technical, economic, and environmental metrics, offering a comprehensive perspective on the benefits and limitations of each solution. The data presented in Tab.2 highlights the unique advantages of SLBs as a sustainable and economically viable option for backup power systems. These batteries exhibit significant cost savings, both in initial investment and ongoing operational expenses, compared to new batteries and diesel generators. Furthermore, their zero-emission operation aligns with global efforts to mitigate climate change, positioning them as a critical component in sustainable power systems.

Table 2. Estimation of Cost, Energy and Environmental Benefits of Backup Power Solutions

Parameter	Diesel Generators	New LIBs	Second-Life Batteries	New LIBs + Solar Panels	SLBs + Solar Panels
Capacity/Power (kWh/kW)	-	100	80	120	90
Efficiency (%)	30	90	85	90	85
Backup Duration (hours)	10	8	6	8+ solar	6+ solar
Response Time (seconds)	10	<1	<1	<1	<1
Cycle Durability (cycles)	-	>1000	500-1000	>1000	500-1000
Equipment Cost (₴/unit)	40000	115000	80000	265000	200000
Operational Costs (₴/year)	60668	33227	25000	5227	4000
CO_2 Emissions (g/kWh)	480-500	0	0	0	0
Lifespan (years)	5	10	5	10	5
Electricity Cost (₴/kWh)	22.1	6.7	5.5	2.5	2.0

The analysis of various backup power solutions requires a detailed comparison of their cost dynamics over time. Fig. 4 illustrates the results of an analysis of total expenses incurred over seven years for five different backup power options: diesel generators, new lithium-ion batteries (LIBs), SLBs, new LIBs integrated with solar panels, and SLBs combined with solar panels. These options are evaluated based on initial investment, operational costs, and maintenance requirements, providing a clear perspective on the long-term economic viability of each solution. This comparison highlights the advantages of integrating RES and SLBs for achieving cost efficiency and sustainability in backup power systems.

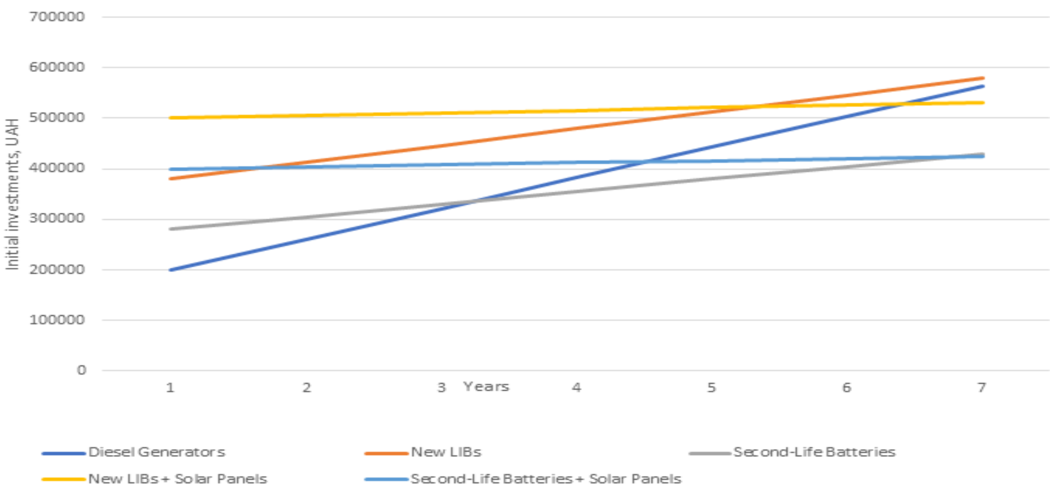

Figure 4. Total Cost Dynamics for Different Backup Power Solutions

When combined with solar panels, SLBs further enhance the resilience and sustainability of power systems. This hybrid approach not only extends backup durations but also reduces reliance on grid power and fossil fuels. By integrating SLBs into power systems, particularly for critical applications like HVsubstations, it is possible to achieve a balance between economic efficiency, environmental benefits, and technical reliability. This comparison underscores the potential of SLBs to transform backup power strategies, paving the way for a cleaner and more resilient energy future.

Implementing second-life EV batteries in power grid applications presents multiple challenges, ranging from technical degradation to regulatory and financial barriers. While SLBs offer a promising solution for backup power at substations, their performance, cost-effectiveness, and long-term sustainability depend on addressing key risks associated with deployment. Tab. 3 outlines the main risk categories, describing their potential impact and proposing mitigation strategies to enhance the feasibility and reliability of SLBs in the energy system.

Table 3. Risk Assessment and Mitigation Strategies for SLB Deployment

Risk Category	Description	Potential Mitigation Strategies
Technical Risks	SLB degradation over time, reduced cycle life, and declining efficiency in high-demand applications.	Implement predictive battery health models, integrate real-time monitoring systems, and apply advanced battery management systems (BMS)
Economic Risks	High initial investment costs and uncertain return on investment due to fluctuating electricity prices.	Optimize financial models, implement government incentives, and leverage energy arbitrage for cost recovery.
Regulatory Risks	Lack of standardized policies for second-life battery integration in grid infrastructure.	Develop national SLB standards, work on certification frameworks, and establish grid compliance guidelines.
Operational Risks	Challenges in integrating SLBs into existing grid infrastructure, potential compatibility issues with different substations.	Enhance smart grid capabilities, implement modular SLB architectures, and ensure compatibility testing with substations.
Safety and Environmental Risks	Potential risks of thermal runaway, fire hazards, and improper recycling of SLBs after secondary use.	Enforce strict safety protocols, develop fire prevention systems, and establish SLB recycling and disposal regulations.

A comprehensive risk assessment is essential for ensuring the long-term success of SLB deployment in energy infrastructure. By addressing technical, economic, regulatory, operational, and environmental challenges, stakeholders can maximize the efficiency and reliability of SLBs. Proactive measures such as real-time monitoring, policy adaptation, financial incentives, and integration with smart grid technologies will play a crucial role in overcoming these risks and accelerating SLB adoption in Ukraine's energy sector.

2.4. Backup Power for HVSubstations: Challenges and Opportunities

HV Substations play a pivotal role in ensuring the stability and reliability of power systems. They serve as critical nodes for electricity transmission and distribution, connecting generation facilities to consumers. However, the growing complexity of power systems, combined with external challenges such as grid overloads and infrastructure attacks, has highlighted the need for robust and efficient backup power solutions. This section explores the significance of HVsubstations, the potential of SLBs as a solution, and the importance of clustering substations to optimize battery deployment.

Ukraine possesses an extensive energy infrastructure that includes numerous high-voltage substations, playing a pivotal role in ensuring the stability of electricity supply. High-voltage substations are essential for the transformation, distribution, and transmission of electricity within the country's power system. With the growing demand for modernization of energy networks, particularly in wartime conditions, substations serve as critical nodes for integrating innovative technologies, including backup power solutions.

Ukrainian substations adhere to strict standards for electrical safety, reliability, and energy efficiency, as outlined in national regulations and guidelines. Of particular importance are the issues of redundancy and stable power supply, which become critical during emergency or post-emergency situations. According to the Rules for the Arrangement of Electrical Installations (PUE), substations must be equipped with backup power systems, such as battery storage or specialized uninterruptible power supplies, to prevent disruptions in the operation of key consumers.

Traditional approaches to substation backup power rely heavily on diesel generators. While these systems provide reliable power during outages, they are expensive to operate and maintain. Additionally, their reliance on fossil fuels contributes to greenhouse gas emissions, making them less aligned with global sustainability goals. These limitations have driven the search for more sustainable and cost-effective alternatives, such as second-life batteries. In the context of the increased vulnerability of Ukraine's energy infrastructure, implementing innovative approaches to backup power is an urgent task. Specifically, the deployment of second-life electric vehicle batteries at substations enables the combination of technical efficiency with ecological and economic viability. Such solutions enhance the resilience of the power system, reduce CO_2 emissions, and ensure a stable electricity supply even under extraordinary conditions.

The growing threat of infrastructure attacks and grid instability further underscores the importance of robust backup systems. HVsubstations, often targeted during conflicts, require fast and reliable power sources to maintain critical functions such as relay protection and system automation. This necessity has spurred interest in exploring SLBs as a viable solution for substation backup power. HV Substations are pivotal for ensuring the reliable operation and resilience of Ukraine's power system. Based on several years statistics, the country's substations are categorized by their voltage levels, capacity, and distribution [57–59, 60–62]. Tab. 4 represents the Distribution of HV substations in Ukraine as for 2020 [62]. HV substations play an essential role in stabilizing Ukraine's national power grid and facilitating interregional energy transmission. Among these, 330 kV substations are particularly significant due to their widespread presence and substantial cumulative capacity, making them a primary target for infrastructure improvements and enhancements.

On the other hand, distribution substations operating at 110 kV and below serve as crucial connectors between HVtransmission systems and end-users in urban and rural areas. The large number of 6–10 kV substations highlights the extensive reach of the power system to individual consumers. However, their impact on overall system reliability is limited due to their localized scope and smaller scale.

Table 4. Distribution of HV Substations in Ukraine (2020) [62]

Category	Voltage Level	Number of Substations	Total Capacity (MVA)	Comments
Transmission	**750 kV**	9	19 735	Critical for long-distance energy transmission and connecting major power plants.
	400–500 kV	2	1699	Used for interregional energy transmission; limited number reflects their specialized applications.
	330 kV	78	42326,9	Most common high-capacity substations, crucial for integrating renewable energy and regional supply.
	220 kV	14	4236,8	Regional distribution substations supporting medium-sized loads.
	110 kV	4	170	Rarely used in transmission networks but essential for specific applications.
Distribution	**110 (150) kV**	1495	-	Main distribution substations for urban and rural areas.
	35 kV	6633	-	Widely used for rural energy distribution and medium-sized industrial facilities.
	6–10 kV (TP/RP)	204860	-	Predominantly serve end-users like residential, commercial, and small industrial consumers.

For backup power integration, HV Substations operating at 330 kV and above present the most strategic opportunities for deploying secondary batteries. Their critical load profiles and central role in maintaining grid stability underscore their importance. Substations operating at 220 kV and 110 kV, while less critical, also offer potential for targeted backup power solutions, particularly in regions experiencing frequent outages. This prioritization ensures a more effective and resource-efficient enhancement of the power system's resilience.

The analysis underscores the strategic importance of integrating SLBs into backup systems for HVsubstations, particularly at 330 kV and above. These substations, given their central role in energy transmission and stability, offer the highest impact potential for resilience improvements. By leveraging these insights, Ukraine’s energy infrastructure can enhance its robustness against outages and external disruptions, aligning with broader goals of energy resilience and sustainability.

SLBs offer a range of advantages for backup power at HVsubstations. Their ability to deliver instantaneous power makes them an ideal choice for critical applications where even brief delays can lead to significant operational disruptions. These batteries can effectively support relay protection systems, ensuring the rapid detection and isolation of faults to protect the grid. The modularity of SLBs allows for scalable deployment, catering to the specific needs of each substation. This flexibility is particularly valuable in scenarios where power demand and backup requirements vary widely. Moreover, the integration of batteries into energy management systems enables advanced functionalities such as peak shaving, load balancing, and demand response, enhancing overall grid resilience.

3. Results and Discussions

3.1. Clustering Substations for Optimized Second life EV Battery Utilization

Substations in an energy system typically have similar characteristics in terms of technical capabilities and nominal power ratings. However, these substations are located in different nodes of the power grid, which can vary in terms of energy balance. Some substations are situated in energy-deficient areas, where the demand for power often exceeds local generation capacity, while others are located in self-sufficient regions with abundant energy resources. This geographic variation leads to significant differences in energy needs, even among stations with the same nominal power capacity.

As a result, the need for batteries in substations with the same power ratings may differ considerably based on the specific conditions of each node. Substations in energy-deficient areas may require larger energy reserves to ensure stable operation during power outages or peak demand periods, while those in self-sufficient areas may have lower battery requirements. This discrepancy in energy needs necessitates the application of clustering techniques to optimize battery distribution and ensure that each substation is equipped with the appropriate level of backup energy storage, considering the local energy balance and demand.Clustering substations based on their energy requirements, load profiles, and operational conditions allows for a more efficient allocation of second-life batteries, ensuring that each substation receives the optimal amount of backup power. This approach helps in minimizing costs, improving system reliability, and supporting the integration of sustainable energy solutions across the grid.

The clustering method is a technique used to group data points into subsets or clusters based on their similarities, where each cluster shares common characteristics. The goal of clustering is to organize data into meaningful structures, making it easier to analyze patterns and relationships. In the context of energy systems, clustering is typically applied to group substations, energy storage units, or other components based on factors such as load demands, energy consumption, geographic location, and operational conditions.

The key benefit of the clustering method is its ability to simplify complex systems by categorizing entities with similar attributes. This approach allows for more efficient resource allocation, as similar clusters can be treated with the same optimization strategies or operational guidelines. For example, by clustering substations with similar energy demands, one can optimize battery usage and distribution, ensuring that each group receives the most suitable solution based on its specific needs. Additionally, clustering can enhance decision-making processes, improve performance, and support scalability within large systems, as it enables targeted solutions for different subgroups rather than a generic, one-size-fits-all approach.

Clustering substations is a critical step in optimizing the deployment of second-life EV batteries (SLBs), ensuring that resources are allocated efficiently based on the specific operational needs and characteristics of each substation. The proposed clustering methodology categorizes substations into four distinct groups, each defined by load levels, outage frequencies, required reserve capacity, and the criticality of their functions within the power grid. This approach allows for tailored battery solutions, enhancing both the reliability and sustainability of backup power systems.

Rationale for Clustering Approach

Traditional reliability categories for energy consumers are primarily based on the criticality of facilities and general requirements for ensuring uninterrupted power supply. However, these approaches often overlook key operational parameters that influence the feasibility and efficiency of secondary battery deployment.

In contrast, our cluster-based approach introduces three core innovations:

1. Customization of Solutions – Adapting SLB deployment based on operational characteristics rather than a one-size-fits-all model.
2. Resource Optimization – Preventing the over-dimensioning or under-utilization of energy storage systems by aligning reserve capacity with real demand.
3. Integration of Battery-Specific Technical Constraints – Considering degradation patterns, efficiency losses, and cycle life when designing backup solutions.

By adopting this clustering methodology, backup power deployment becomes not just an organizational tool, but a strategic framework that aligns with technical, economic, and environmental priorities.

Key Objectives of Clustering

The implementation of clustering in SLB deployment serves multiple objectives:

Resilience Enhancement: Ensuring that backup power solutions align with outage patterns and operational demands, minimizing downtime and supporting critical infrastructure.

Economic Optimization: Avoiding unnecessary capital expenditure by tailoring storage system capacity to actual energy demand, maximizing cost-effectiveness.

Environmental Sustainability: Facilitating the integration of renewable energy sources (e.g., PV systems) into backup power configurations, reducing dependency on fossil fuels.

Scalability and Adaptability: Allowing for dynamic adjustments in battery deployment as energy infrastructure evolves over time.

Mathematical Framework for Clustering

To ensure a data-driven and replicable clustering method, a multi-criteria decision-making approach is adopted. Let $C = \{C_1, C_2, C_3, C_4, ...\}$ represent the set of clusters, where each cluster C_i is defined by parameters, represented in Tab. 5.

Table 5. Key Operational Parameters for SLB Feasibility Assessment

Parameter	Notation	Description
Load Level	$P_{load,i}$	Average power demand of the substation (kW)
Outage Duration	$T_{outage,i}$	Average duration of power outages (hours)
Frequency of Outages	$F_{outage,i}$	Number of outages per year
Required Reserve Power	$P_{reserve,i}$	Minimum backup power needed to sustain operations (kW)
Required Reserve Energy	$E_{reserve,i}$	Minimum stored energy required for uninterrupted operation (kWh)
Available Battery Installation Area	$A_{battery,i}$	Space available for SLB system deployment (m²)
Available Solar Panel Area	$A_{PV,i}$	Space available for PV system integration (m²)
Load Coefficient	$\eta_{load,i}$	Ratio of actual load to nominal capacity of the substation
Idle Power	$P_{idle,i}$	Power consumption in idle (standby) mode

Parameter	Notation	Description
Short-Circuit Power	$P_{SC,i}$	Short-term power during fault conditions, useful for estimating peak current levels
Energy Balance of the Node	$B_{node,i}$	Difference between generation and consumption in the node
Sensitivity to Voltage Fluctuations	$V_{sens,i}$	The degree to which a substation is affected by voltage regulation precision

Using these parameters, the fo rmal equation for cluster classification can be defined as follows:

$$C_i = \left\{ P_{load,i} T_{outage,i}, F_{outage,i}, P_{reserve,i}, E_{reserve,i}, ..., X_i \right\} \tag{1}$$

Multi-Criteria Decision Model for SLB Feasibility

While clustering substations establishes a structured foundation for backup power planning, selecting the most appropriate energy storage solution for each cluster requires a systematic decision-making framework. The Multi-Criteria Decision-Making (MCDM) approach is used to evaluate the feasibility of SLBs by considering multiple operational parameters, ensuring that technical, economic, and spatial factors are incorporated into the final selection process.

To quantify SLB feasibility, a weighted scoring model is introduced. Each parameter influences the selection process differently, and their importance is reflected through weighting coefficients (WWW), which help rank substations based on their suitability for SLB deployment.

The SLB Suitability Score ($S_{SLB,i}$) is calculated using the following equation:

$$S_{SLB,i} = \omega_1 P_{load,i} + \omega_2 T_{outage,i} + \omega_3 F_{outage,i} + \omega_4 P_{reserve,i} + \omega_5 E_{reserve,i} + ... + \omega_n X_i\,, \tag{2}$$

where ω_1, ω_2, ω_3,…, ω_n - weight coefficients reflecting the impact of each parameter.

The SLB Suitability Score $S_{SLB,i}$ determines *the most appropriate backup power strategy:*

- If $S_{SLB,i} \le S_{\min}$ → SLBs alone are insufficient; hybrid solutions (SLB + Diesel) are required.
- If $S_{\min} \le S_{SLB,i} \le S_{mid}$ → SLBs can be partially deployed, with solar PV integration optimizing performance.
- If $S_{SLB,i} \ge S_{\max}$ → SLBs are fully viable as a standalone backup power solution.

To ensure efficient deployment of second-life batteries, substations are categorized into clusters based on key operational parameters: load level, frequency of outages, required reserve capacity, and duration of outages. Each cluster represents a unique set of conditions, formalized mathematically as a subset of operational parameters. Tab. 6 outlines these clusters, specifying the required number of batteries and space for deployment.

Table 6. Proposed Clustering of Substations for Secondary Battery Deployment

Cluster	Load Level	Frequency of Outages	Voltage Level (kV)	Reserve Power (kW)	Outage Duration (hrs)	Required Energy (kWh)	Number of Batteries	Required Area (m²)
C1	High	Stochastic	330–750	150	1–2	150–300	5–8	20–30
C2	Medium	Occasional	110–220	100	2–3	200–300	6–10	25–35
C3	Low	Moderate	35–110	50	3–4	150–200	4–6	15–25
C4	Minimal	Frequent	6–35	30	4–6	120–180	3–4	10–15

The determination of reserve power capacity for each cluster is based on the load level and criticality of consumers, which depend on the substation category. High-load substations (C1) serve strategic facilities and large industrial consumers, necessitating a significant reserve capacity to ensure uninterrupted operation.

Medium-load (C2) and low-load (C3) substations cater to less critical facilities, resulting in lower reserve energy requirements. Minimal-load clusters (C4) include facilities where short-term power interruptions are not critical, leading to the lowest reserve energy needs.

The outage duration was determined based on historical outage data and the response time for power restoration across different substation categories. High-voltage substations (C1, C2) typically have more advanced redundancy schemes, reducing downtime. In contrast, smaller substations (C3, C4), which supply local networks, may experience longer outages due to limited access to alternative power sources and the need for mobile backup solutions. The number of required batteries was calculated considering the average load level of each substation and the available usable capacity of second-life batteries. The calculation assumes a nominal battery capacity of 40 kWh, with 80 % of its energy being effectively usable (32 kWh). This approach ensures realistic estimates of the number of batteries required for each cluster, providing sufficient energy reserves to maintain the substation's essential functions throughout the projected outage duration. By associating each cluster with specific operational parameters, it becomes feasible to optimize both the number of batteries and the area required for installation. This approach enhances resource efficiency and ensures scalability, aligning with the diverse demands of Ukraine's power system.

Tailored strategies for each cluster involve modeling degradation rates, assessing economic and environmental impacts, and determining optimal battery capacities. This clustering framework supports a holistic approach to integrating SLBsinto Ukraine's power system, ensuring resilience, sustainability, and cost-effectiveness across all operational scenarios. HV Substations are indispensable for grid stability, and their backup systems must evolve to address modern challenges. SLBs emerge as a compelling alternative to diesel generators, offering faster response times, lower costs, and environmental benefits. By clustering substations based on operational characteristics, it is possible to maximize the effectiveness of battery systems while minimizing costs.

3.2. Economic and Operational Analysis of Second-Life Battery Deployment

The current approaches to backup power systems rely predominantly on traditional solutions such as diesel generators and new battery technologies. While these systems have been effective historically, they face mounting limitations in today's context of economic constraints, environmental demands, and evolving grid requirements. Diesel generators contribute significantly to greenhouse gas emissions and incur high operational costs, whereas new battery systems often require substantial upfront investments. Despite these challenges, the potential of SLBs as a cost-effective, sustainable, and technically viable alternative remains largely untapped due to the lack of a comprehensive methodological framework.

The absence of a unified methodology for SLBs limits their integration into power systems, leaving many opportunities unexplored. Existing studies often focus on individual aspects, such as battery aging or economic feasibility, without considering the broader implications of lifecycle optimization, operational diversity, and sustainability. Developing a robust methodology is essential to address the technical complexities of SLB deployment, including their varying degradation patterns, compatibility with existing systems, and ability to enhance grid reliability. Such a framework would ensure that SLBs are not only economically viable but also operationally efficient and environmentally beneficial.

To effectively evaluate the feasibility of deploying SLBs for substation backup power, it is critical to establish well-defined scenario parameters. These parameters provide the foundational data required to model battery performance, cost implications, and operational dynamics across different clusters of substations. Key metrics such as load demand, outage frequency, required backup duration, and energy storage capacity are essential to tailoring solutions that meet the unique needs of each cluster. By addressing these parameters, the analysis ensures that battery deployment strategies align with the operational realities of Ukraine's power grid.

The methodology for deploying SLBs across different substation clusters is grounded in a systematic approach that evaluates technical, economic, and operational parameters. Central to this approach is the calculation of the required reserve capacity for each cluster, based on outage durations and energy demands.

The reserve capacity $Q_{reserve,i}$ is determined as follows:

$$Q_{reserve,i} = P_{load} T_{outage}, \tag{3}$$

where P_{load} represents the load demand and T_{outage} is the expected outage duration in hrs. This ensures that the battery systems are appropriately sized to meet the backup requirements of each cluster.

Once the reserve capacity is established, the number of SLB units required N_{SLB} is calculated by dividing the reserve capacity by the capacity of a single SLB unit:

$$N_{SLB} = \frac{Q_{reserve}}{Q_{SLB-unit}}. \tag{4}$$

This calculation ensures efficient utilization of available battery units while meeting the operational demands of each cluster. The cost implications, including equipment, installation, and maintenance, are subsequently derived based on the number of SLB units.

Economic assessment incorporates both initial and operational costs. The total equipment cost $C_{equipment}$ is determined as follows:

$$C_{equipment} = N_{SLB} C_{SLB-unit}. \tag{5}$$

Tab. 7 presents the calculated parameters for deploying SLBs across four distinct substation clusters. These parameters include outage durations, required reserve capacities, the number of SLB units, and associated costs. By addressing the unique operational characteristics of each cluster, the table provides a detailed roadmap for cost-effective and reliable SLB deployment. The values highlight the tailored strategies necessary to optimize backup power solutions, demonstrating the economic and environmental advantages of SLB integration.

Table 7. Cluster-Specific Battery Requirements and Costs

Parameter	Cluster 1	Cluster 2	Cluster 3	Cluster 4
Reserve Power (kW)	150	100	50	30
Outage Duration (hrs)	1–2	2–3	3–4	4–6
Required Energy (kWh)	150–300	200–300	150–200	120–180
SLB Unit Capacity (kWh, effective 80%)	32	32	32	32
Number of SLB Units Required	5–10	7–10	5–7	4–6
Cost per SLB Unit (₴)	79,385	79,385	79,385	79,385
Total Equipment Cost (₴)	396,925–793,850	555,695–793,850	396,925–555,695	317,540–476,310
Installation Cost per Unit (₴)	2,340	2,340	2,340	2,340
Total Installation Cost (₴)	11,700–23,400	16,380–23,400	11,700–16,380	9,360–14,040
Maintenance Cost per Unit (₴/year)	970	970	970	970
Total Maintenance Cost (₴/year)	4,850–9,700	6,790–9,700	4,850–6,790	3,880–5,820
Estimated Battery Degradation per Year (%)	5–6	4–5	3–4	3–4
Expected Battery Lifespan (years)	5–7	6–8	7–9	8–10

The parameters outlined in Table 6 underscore the diversity of requirements across substation clusters. From high-demand, high-frequency outages in urban areas to the lower demand yet critical reliability needs in rural substations, these distinctions highlight the necessity of customized battery solutions. Accurate modeling of these parameters ensures that deployment strategies are both technically feasible and economically viable.

Building upon the initial scenario parameters, Table 6 synthesizes the economic and operational implications for each substation cluster. This table captures the projected capital expenditures, annual operational costs, and energy output efficiency for deploying second-life batteries.

Battery degradation is a critical factor influencing the performance and longevity of energy storage systems, including second-life EV batteries. Degradation occurs due to a combination of cyclic and calendar aging, with the rate and extent of degradation varying significantly across different applications and operational conditions. For instance, stationary energy storage systems often experience slower degradation compared to mobile applications, owing to less dynamic operating conditions and optimized usage patterns [63–65]. To address these complexities, an integral degradation index has been developed [66], which incorporates both cyclic and calendar aging factors. This index provides a comprehensive assessment of the remaining capacity and operational lifespan of second-life batteries. It is particularly valuable in planning and optimizing battery usage for backup power systems, ensuring both reliability and economic efficiency in deployment. The inclusion of this index in the analysis enhances the ability to predict performance and schedule maintenance effectively, thereby maximizing the utility of second-life batteries in energy storage applications [66].

Additionally, metrics such as break-even time and emissions reductions highlight the broader economic and environmental impacts of these solutions.By correlating these metrics with the specific requirements of each cluster, this analysis provides actionable insights into how SLBs can be optimally utilized to enhance the resilience and sustainability of Ukraine's power system.

The integration of SLBs into HV Substations not only enhances reliability but also supports broader goals of sustainability and resilience. Future efforts should focus on detailed data collection, modeling, and pilot projects to refine this approach and unlock its full potential.

3.3. Cluster-Based Planning for Second-Life Battery Integration

Clustering HV Substations based on operational characteristics is essential for optimizing the deployment of SLBs. Tab.8 provides tailored recommendations for each cluster, focusing on the specific requirements of substations and the optimal configurations for SLBs to meet these needs.

Table 8. Cluster-Specific SLB Feasibility and Deployment Framework

Cluster	SLB Feasibility	Primary Requirements	Recommendations	Expected Impact
C1 (High Load, Rare Outages, Critical Infrastructure)	🔷 Possible with Hybrid Backup (SLB + Diesel Genset)	High power output, rapid response, robust cycle performance.	Deploy SLBs with high discharge rates and cycle life. Integrate with smart monitoring systems to manage frequent cycles. Hybrid backup with diesel gensets is recommended.	✓ Enhanced reliability during outages, ✓ reduced reliance on diesel generators, ✓ lower operational costs.
C2 (Medium Load, Occasional Outages, Key Substations)	✅ Suitable (SLB or SLB + PV for Optimization)	Sustained energy capacity for prolonged outages.	Use modular SLB systems with high energy density. Consider hybrid systems integrating SLBs and renewable sources like solar.	✓ Continuous service to critical facilities, ✓ optimized cost and resource efficiency, ✓ reduced emissions.
C3 (Low Load, Moderate Outages, Regional Nodes)	✅ ✅ Fully Suitable for Standalone SLB Solutions	Minimal active cycles, longevity during standby periods.	Select SLBs with low self-discharge rates and long calendar life. Ensure minimal maintenance requirements.	✓ Long-term viability, ✓ cost-effective solutions for remote areas, ✓ reduced need for frequent battery replacements.
C4 (Minimal Load, Frequent Outages, Rural Areas)	✅✅✅ Ideal for SLB Deployment	Scalable capacity, fast integration, high reliability.	Implement scalable SLB systems to adapt to changing load profiles. Use advanced energy management systems for peak shaving and load balancing.	✓ Increased grid resilience, ✓ optimized urban energy ✓ infrastructure, improved sustainability.

The successful adoption of SLBs as a solution for backup power in Ukraine's power system requires not only technological advancements and operational strategies but also a robust legislative framework. Addressing gaps in regulation and policy will ensure a streamlined deployment process, economic feasibility, and alignment with national and international sustainability goals. To facilitate the effective deployment and integration of SLBs in Ukraine's power system, targeted legislative and regulatory European and Ukrainian frameworks are essential [67–72].

To ensure that Ukraine's efforts to integrate SLBs into its energy infrastructure align with best practices and facilitate international collaboration, it is essential to harmonize national legislation with established European and global standards.European Union (EU) directives, such as the Battery Regulation [67], emphasize the importance of sustainability, lifecycle management, and recycling of batteries. By adopting these guidelines, Ukraine can foster compatibility with EU market requirements and create opportunities for cross-border trade and technology transfer. Furthermore, aligning with standards set by the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) will enhance safety, performance, and environmental compliance.

Adopting European and international standards positions Ukraine to integrate SLBs effectively while fostering collaboration and trade with global partners. These measures will also enhance the safety, performance, and sustainability of battery systems, creating a foundation for long-term energy resilience. Legislative alignment is not merely a compliance activity but a strategic move to modernize Ukraine's energy sector and align it with global sustainability goals. Tab. 9 below outlines key legislative actions, categorized into policy areas, specific measures, and their expected impact on facilitating the integration of SLBs into critical energy infrastructure.

Table 9. Legislative Recommendations for Supporting SLBs in Backup Power Systems

Area of Focus	Recommendation	Justification
Safety and Performance Standards	Develop and implement national standards for SLB safety and performance.	Ensures SLBs meet safety and operational benchmarks, fostering trust among stakeholders.
Incentives for Adoption	Introduce tax breaks, grants, or subsidies for SLB deployment.	Offsets high initial costs, encouraging adoption in critical sectors.
Circular Economy Policies	Mandate recycling and repurposing of EV batteries for second-life applications.	Promotes sustainable resource use and reduces environmental impacts.
Energy Market Integration	Recognize and incentivize SLBs in energy markets for ancillary services.	Makes SLB deployment economically viable and supports grid stability.
Pilot Projects	Support public-private pilot projects to demonstrate SLB deployment.	Validates technical and economic feasibility, creating a basis for large-scale adoption.
Data Sharing Requirements	Mandate data collection and sharing on SLB performance.	Improves models for degradation, capacity estimation, and operational efficiency.
European Standards Alignment	Align national legislation with European standards for SLBs.	Facilitates cross-border collaboration, trade, and access to advanced technologies.

Implementing the legislative actions outlined in Table 8 can significantly accelerate the adoption of SLBs in Ukraine's energy infrastructure. By creating clear regulatory pathways, offering financial incentives, and ensuring alignment with sustainability goals, these measures address key barriers to deployment. Furthermore, the integration of SLBs will enhance the resilience of Ukraine's power grid, reducing dependency on fossil fuels and supporting the transition to a low-carbon economy. Such initiatives not only bolster energy security but also position Ukraine as a leader in sustainable energy innovation in the region. Legislative action in these areas will create a supportive ecosystem for second-life batteries, ensuring their effective integration into Ukraine's energy infrastructure and contributing to a sustainable and resilient energy future.

4. Conclusions

This study presents a comprehensive framework for deploying second-life EV batteries as reliable and sustainable backup power solutions in Ukraine's energy system. The research highlights the critical role of HV substations in maintaining grid stability and emphasizes the vulnerabilities of traditional backup solutions, such as diesel generators and new lithium-ion batteries, especially regarding their cost, environmental impact, and operational performance. The comparison between diesel generators and LIBs demonstrates distinct trade-offs, where despite the higher initial cost of batteries, they offer significant long-term cost savings and environmental benefits.

The proposed cluster-based approach allows for a more nuanced and effective distribution of second-life batteries across substations with different energy requirements. While substations generally have similar technical capabilities and nominal power ratings, their energy needs vary greatly depending on their location in the grid. Some substations are in energy-deficient areas where demand often exceeds local generation, requiring larger reserves, while others are in self-sufficient regions with abundant energy resources and may need less backup power. This variability in energy demands and conditions across different substations makes a one-size-fits-all solution inefficient.

Therefore, the use of a clustering methodology enables precise resource allocation by grouping substations into categories based on their load profiles, energy balance, and operational conditions. This tailored approach ensures that each substation is equipped with an optimal level of backup power, reducing unnecessary costs while improving system reliability and supporting the integration of sustainable energy solutions. The clustering method takes into account the unique conditions of each substation, including the availability of space for batteries, the criticality of infrastructure, and the frequency and duration of outages. This more granular approach provides an effective solution to optimize battery deployment across the grid, ensuring that each region receives the appropriate backup support, enhancing both economic and environmental efficiency.

This study demonstrates that second-life batteries, when strategically deployed based on these clusters, can reduce costs, improve system resilience, and support a more sustainable energy infrastructure. By integrating these solutions with renewable energy sources such as solar panels, SLBs can further enhance the sustainability and operational efficiency of the power grid. Furthermore, the findings highlight the importance of legislative and financial support to facilitate the widespread adoption of SLBs, creating an environment conducive to the long-term success of these technologies.

References

1. On approval of the Energy Strategy of Ukraine for the period until 2050: Resolution of the Cabinet of Ministers of Ukraine dated April 21, 2023 No. 373-r. Retrieved December 10, 2024, from https://zakon.rada.gov.ua/laws/show/373-2023-%D1%80#Textoku](https://zakon.rada.gov.ua/laws/show/373-2023-%D1%80#Textoku [in Ukrainian].
2. Ministry of Energy of Ukraine. (2023, May 1). *Ukraine – The Energy Hub of Europe. The Government Approved the Energy Strategy Until 2050*. Retrieved December 15, 2024, from https://www.mev.gov.ua/novyna/ukrayina-enerhetychnyy-khab-yevropy-uryad-skhvalyv-enerhetychnu-stratehiyu-do-2050-roku [in Ukrainian].
3. European Commission, Directorate-General for Energy. *EU strategy on power system integration*. Document 52020DC0299. COM(2020) 299 final. Retrieved December 12, 2024, from https://energy.ec.europa.eu/topics/energy-systems-integration/eu-strategy-energy-system-integration_en
4. Cilliers, J. (2023, April 15). *Uncovering the reality of Ukraine's decimated energy infrastructure*. Retrieved June 22, 2023, from https://www.undp.org/ukraine/blog/uncovering-reality-ukraines-decimated-energy-infrastructure
5. UNDP Resilience Building and Recovery Programme. (2023). Retrieved December 19, 2024, from https://www.undp.org/ukraine/undp-resilience-building-and-recovery-programme
6. Pavlenko, O., Antonenko, A., Nitsovych, R., Yevtushok, S., & Sukhodolia, O. (2022). *Otsinka stiikosti enerhetychnoi infrastruktury Ukrainy*. Dixi Hrup. Retrieved December 25, 2024, from https://dixigroup.org/wp-content/uploads/2022/05/dixi-energy-resilience-str.pdf [in Ukrainian].
7. Babak, V., & Kulyk, M. (2023). Development of the New Electro-thermal Power system Structure for Providing of Ukraine's Energy Market Profitability. In A. Zaporozhets (Ed.), *Systems, Decision and Control in Energy V. Studies in Systems, Decision and Control*, 481 (pp. 3–21). Springer, Cham. https://doi.org/10.1007/978-3-031-5088-7_1
8. 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

9. Nikitin, Ye., Yevtukhova, T., Novoseltsev, O., & Komkov, I. (2024). Regional energy efficiency programs. Current status and development prospects. *Energy Technologies & Resource Saving*, *78*(1), 34–47 [in Ukrainian]. https://doi.org/10.33070/etars.1.2024.03
10. Zaporozhets, A., Babak, V., Sverdlova, A., Shcherbak, L., & Kuts, Y. (2022). Review of the state of air pollution by energy objects in ukraine. *System Research in Energy*, *2*(71), 42–52. https://doi.org/10.15407/srenergy2022.02.042
11. On energy efficiency: Law of Ukraine. Retrieved December 11, 2024, from https://zakon.rada.gov.ua/laws/show/1818-20#Text](https://zakon.rada.gov.ua/laws/show/1818-20#Text [in Ukrainian].
12. Kostyshyn, V.S., Fedoriv, M.Y., & Batsala, Y.V. (2017). *Electrical Part of Stations and Substations*. IFNTUOG, Ivano-Frankivsk (243 p.).
13. McDonald, J. D. (2016). *Electric power substations engineering*. CRC press. https://doi.org/10.1201/9781420007312
14. 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, Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/87175
15. Second Life Battery Capacity – Globally 2030. (2019). [WWW Document]. *Statista*. Retrieved January 4, 2025, from https://www.statista.com/statistics/876624/global-second-life-battery-capacity/
16. 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
17. 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
18. 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
19. 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. Series: Earth and Environmental Science*, 1254, 012030. https://doi.org/10.1088/1755-1315/1254/1/012030
20. Zaporozhets, A., Kostenko, G., & Zgurovets, O. (2023). Preconditions and Main Features of Electric Vehicles Application for Frequency Regulation in the Power System. *3rd International Workshop on Information Technologies: Theoretical and Applied Problems (ITTAP 2023)*. CEUR Workshop Proceedings, 3628, 43–54. Retrieved December 18, 2024, from https://ceur-ws.org/Vol-3628/paper4.pdf; Available at SSRN: URL: https://ssrn.com/abstract=4709501
21. Wang, C., Ju, P., Wu, F., Pan, X., & Wang, Z. (2022). A systematic review on power system resilience from the perspective of generation, network, and load. *Renewable and Sustainable Energy Reviews*, 167, 112567, https://doi.org/10.1016/j.rser.2022.112567
22. Rzheutska, L. (2023, March 16). Shcho dopomohlo ukrainskii enerhetytsi perezhyty vazhku zymu. *Deutsche Welle*. Retrieved December 22, 2024, from https://www.dw.com/uk/so-dopomoglo-ukrainskij-energetici-pereziti-vazku-zimu-raketnih-udariv-rf/a-64995509 [in Ukrainian].
23. Lin, Y., Bie, Z., & Qiu, A. (2018). A review of key strategies in realizing power system resilience. *Global Energy Interconnection*, *1*(1), 70–78. https://doi.org/10.14171/j.2096-5117.gei.2018.01.009
24. Cabinet Office. (2011). Keeping the Country Running: Natural Hazards and Infrastructure (A Guide to improving the resilience of critical infrastructure and essential services). Retrieved January 2, 2025, from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/61342/natural-hazards-infrastructure.pdf
25. Yao, Y., Liu, W., & Jain, R. (2022, April 24–28). Power System Resilience Evaluation Framework and Metric Review: Preprint. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5D00-80817. Retrieved December 25, 2024, from https://www.nrel.gov/docs/fy22osti/80817.pdf
26. Zaporozhets, A., Babak, V., Kostenko, G., Zgurovets, O., Denisov, V., & Nechaieva, T. (2024). Power System Resilience: An Overview of Current Metrics and Assessment Criteria. *Systems, Decision and Control in Energy VI. Studies in Systems, Decision and Control*, 561 (pp. 35–38). Springer, Cham. https://doi.org/10.1007/978-3-031-68372-5_2
27. 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
28. Gouveia, C., Moreira, J., Moreira, C. L., & Pecas Lopes, J. A. (2013). Coordinating storage and demand response for microgrid emergency operation. *IEEE Transactions on Smart Grid*, *4*(4), 1898–1908. https://doi.org/10.1109/TSG.2013.2257895
29. Scala, A., Mureddu, M., Chessa, A., Caldarelli, G., & Damiano, A. (2013). Distributed Generation and Resilience in Power Grids. *Critical Information Infrastructures Security, Lecture Notes in Computer Science*, 7722 (pp. 71–79). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-41485-5_7

30. Engel, H., Hertzke, P., & Siccardo, G. (2019). Second-Life EV Batteries: The Newest Value Pool in Energy Storage. McKinsey & Company, Chicago, IL, USA. Retrieved December 15, 2024, from https://www.mckinsey.com/~/media/McKinsey/Industries/Automotive%20and%20Assembly/Our%20Insights/Second%20life%20EV%20batteries%20The%20newest%20value%20pool%20in%20energy%20storage/Second-life-EV-batteries-The-newest-value-pool-in-energy-storage.ashx
31. Falk, J., Nedjalkov, A., Angelmahr, M., & Schade, W. (2020). Applying Lithium-Ion Second Life Batteries for Off-Grid Solar Powered System—A Socio-Economic Case Study for Rural Development. *Zeitschrift für Energiewirtschaft*, 44, 47–60. Retrieved December 11, 2024, from https://link.springer.com/article/10.1007/s12398-020-00273-x
32. Zhu, J., Mathews, I., Ren, D., Li, W., Cogswell, D., Xing, B., Sedlatschek, T., Kantareddy, S. N. R., Yi, M., Gao, T., Xia, Y., Zhou, Q., Wierzbicki1, T., & Bazant, M. Z. (2021). End-of-life or second-life options for retired electric vehicle batteries. *Cell Reports Physical Science*, *2*(8), 100537. https://doi.org/10.1016/j.xcrp.2021.100537
33. 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
34. Cusenza, M. A., Guarino, F., Longo, S., Mistretta, M., & Cellura, M. (2019). Reuse of electric vehicle batteries in buildings: An integrated load match analysis and life cycle assessment approach. *Energy and Buildings*, 186, 339–354. https://doi.org/10.1016/j.enbuild.2019.01.032
35. 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
36. EEA, European Environment Agency. (2023). *Trends and projections in Europe 2023*. (83 p.). https://doi.org/10.2800/595102
37. Lytvyn, V. (2023). *Ensuring Backup Power Supply Considering Wartime and Peacetime in Ukraine*. Friedrich Ebert Foundation (40 p.).
38. Ministry of Energy and Coal Industry of Ukraine. (2017). *Rules for Electric Installation*. Kyiv (617 p.). Retrieved December 11, 2024, from https://zakon.isu.net.ua/sites/default/files/normdocs/pue.pdf [in Ukrainian].
39. Denysov, V., Babak, V., Zaporozhets, A., Nechaieva, T., Kostenko, G. (2024). Quasi-dynamic Energy Complexes Optimal Use on the Forecasting Horizon. In V. Babak, A. Zaporozhets (Eds.), *Systems, Decision and Control in Energy VI. Studies in Systems, Decision and C*ontrol, 561 (pp. 81–107). Springer, Cham. https://doi.org/10.1007/978-3-031-68372-5_4
40. Denysov, V. Babak, V., Zaporozhets, A., Nechaieva, T., & Kostenko, G. (2024). Power system Optimization Potential with Consideration of Technological Limitations. *Nexus of Sustainability. Studies in Systems, Decision and Control*, 559 (pp. 113–126). Springer, Cham. https://doi.org/10.1007/978-3-031-66764-0_5
41. 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
42. Bielokha, H., Chupryna, L., Denisyuk, S., Eutukhova, T., & Novoseltsev, O. (2023). Hybrid Power systems and the Logic of Their Service-Dominant Implementation: Screening the Pathway to Improve Results. *Energy Engineering*, *120*(6), 1307–1323. https://doi.org/10.32604/ee.2023.025863
43. About the electricity market: Law of Ukraine. Retrieved December 11, 2024, from https://zakon.rada.gov.ua/laws/show/2019-19#Text [in Ukrainian].
44. Pro zatverdzhennia Poriadku vzhyttia tymchasovykh nadzvychainykh zakhodiv z podolannia naslidkiv tryvaloho porushennia normalnoi roboty rynku elektrychnoi enerhii: Postanova Kabinetu Ministriv Ukrainy vid 13.08.2014 r. № 372. Retrieved December 30, 2024, from http://zakon5.rada.gov.ua/laws/show/372-2014-%D0%BF [in Ukrainian].
45. Zgurovets, O., & Kulyk, M. (2022). Possibilities to form a modern reserve of supporting of a frequency 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 [in Ukrainian]. https://doi.org/10.15407/pge2022.01-02.020
46. Denysov, V., Kostenko, G., Babak, V., Shulzhenko, S., & Zaporozhets, A. (2023). Accounting the Forecasting Stochasticity at the Power System Modes Optimization. In A. Zaporozhets (Ed.), *Systems, Decision and Control in Energy V. Studies in Systems, Decision and Control*, 481 (pp. 43–55). Springer, Cham. https://doi.org/10.1007/978-3-031-35088-7_3
47. Buratynskyi, I., Nechaieva, T., & Leshchenko, I. (2024). Assessment of the Economic Efficiency of Battery Energy Storage Systems in the Electricity Market Segments. In V. Babak, A. Zaporozhets (Eds.) *Systems, Decision and Control in Energy VI. Studies in Systems, Decision and Control*, 552 (pp. 37–50). Springer, Cham. https://doi.org/10.1007/978-3-031-67091-6_2
48. Denysov, V., & Eutukhova, T. (2024). Dynamic Models for Developing Reference Scenarios of Power system in the Low-Carbon Transition. *System Research in Energy*, *1*(76), 17–26. https://doi.org/10.15407/srenergy2024.01.017
49. Derii, V. (2023). Electric Energy Storages. *System Research in Energy*, *1*(72), 12–24 [in Ukrainian]. https://doi.org/10.15407/srenergy2023.01.012

50. 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 O. Kyrylenko, S. Denysiuk, R. Strzelecki, I. Blinov, I. Zaitsev, & A. Zaporozhets (Eds.), *Power Systems Research and Operation. Studies in Systems, Decision and Control*, 512 (pp. 69–87). Springer, Cham. https://doi.org/10.1007/978-3-031-44772-3_4
51. Zamulko, A., Chernetska, Y., & Prasol, A. (2024). Determination of the Limit Values of Electric Energy Consumption Using Optimization Modeling. *System Research in Energy*, *1*(76), 27–34 [in Ukrainian]. https://doi.org/10.15407/srenergy2024.01.027
52. 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
53. Maliarenko, O., & Ivanenko, N. (2024). Taking Into Account Limitations on Greenhouse Gas Emissions in the Fuel Consumption Forecasting Model at the National Level. *System Research in Energy*, *1*(76), 73–84 [in Ukrainian]. https://doi.org/10.15407/srenergy2024.01.073
54. 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
55. Hubashov, D. (2022, December 4). How Electricity Consumption Changed After the Attack on the Power Grid. Retrieved December 12, 2024, from https://texty.org.ua/articles/108160/naskilky-my-menshe-spozhyvayemo-elektroenerhiyi/ [in Ukrainian].
56. Key Characteristics of Diesel Generators. Retrieved January 10, 2025, from https://chatgpt.com/c/67580d94-79bc-8008-ad62-cff9aa5cbdd9
57. Zhurakhivskyi, A.V., Kinash, B.M., & Pastukh, O.R. (2012). *Reliability of Electrical Systems and Networks*. Lviv Polytechnic Publishing House, Lviv (280 p.). ISBN 978-617-607-293-5
58. Moteff, J. D. (2012). *Critical infrastructure resilience: the evolution of policy and programs and issues for congress*. Congressional Research Service, R42683. Retrieved June 22, 2023, from https://sgp.fas.org/crs/homesec/R42683.pdf
59. Argyrou, M. C., Christodoulides, P., & Kalogirou, S. A. (2018). Energy storage for electricity generation and related processes: Technologies appraisal and grid scale applications. *Renewable and Sustainable Energy Reviews*, 94, 804–821. https://doi.org/10.1016/j.rser.2018.06.044
60. Report on the Results of Activities of the National Energy and Utilities Regulatory Commission in 2017. (2018). NEURC, Kyiv.
61. Report on the Results of Activities of the National Energy and Utilities Regulatory Commission in 2019. (2020). NEURC, Kyiv.
62. Report on the Results of Activities of the National Energy and Utilities Regulatory Commission in 2020. (2021). NEURC, Kyiv.
63. Pagliaro, M., & Meneguzzo, F. (2019). Lithium Battery Reusing and Recycling: A Circular Economy Insight. *Heliyon*, 5(6), e01866. https://doi.org/10.1016/j.heliyon.2019.e01866
64. Park, S., Ahn, J., Kang, T., Park, S., Kim, Y., Cho, I., & Kim, J. (2020). Review of state-of-the-art battery state estimation technologies for battery management systems of stationary energy storage systems. *Journal of Power Electronics*, 20, 1526–1540. https://doi.org/10.1007/s43236-020-00122-7
65. Casals, L. C., García, B. A., & 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
66. 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
67. Regulation (EU) 2023/1542 of the European Parliament and of the Council of 12 July 2023 concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC. (2023). *Official Journal of the European Union*, L 191/1. Retrieved December 20, 2024, from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023R1542 (Last accessed: 20.12.2024).
68. European Commission. (2019, December 11). The European Green Deal [Communication from the European Commission]. Brussels. COM (2019) 640 final. Retrieved December 10, 2024, from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX- :52019DC0640
69. A new Circular Economy Action Plan For a cleaner and more competitive Europe COM/2020/98 final (Online). Retrieved December 10, 2024, from https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN
70. Strategic Action Plan on Batteries: Building a Strategic Battery Value Chain in Europe COM/2019/176 final. Retrieved December 10, 2024, from https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A52019DC0176
71. European Parliament. (2021). Legislative Train Schedule States Navigation Menu Fit for 55 Package under the European Green Deal [EB/OL]. Retrieved December 10, 2024, from https://www.europarl.europa. eu/Legislative-train/theme-a-european- green-deal/package-fit-for-55

72. Battery Passport Content Guidance. Executive Summary. Retrieved December 10, 2024, from https://thebatterypass.eu/assets/images/content-guidance/pdf/2023_Battery_Passport_Content_Guidance_Executive_Summary.pdf

КЛАСТЕРНИЙ ПІДХІД ДО ВИКОРИСТАННЯ ВТОРИННИХ БАТАРЕЙ ЕЛЕКТРОТРАНСПОРТУ ДЛЯ НАДІЙНОГО ТА СТАЛОГО РЕЗЕРВНОГО ЖИВЛЕННЯ В ЕНЕРГОСИСТЕМАХ

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Анотація. *У надзвичайних ситуаціях забезпечення енергосистеми надійним резервним живленням критично важливе для стабільності та безперебійної роботи інфраструктури. Виклики воєнного часу та зростаюча вразливість енергетичної інфраструктури, зокрема високовольтних підстанцій, потребують інноваційних підходів, які поєднують економічну ефективність, технічну надійність та сталий розвиток. Метою даного дослідження є розробка комплексних рішень для забезпечення резервного живлення високовольтних підстанцій України, що відповідають сучасним викликам енергетичної безпеки та екологічної сталості. У статті розглядається потенціал вторинних батарей електромобілів як перспективної альтернативи традиційним рішенням, зокрема дизельним генераторам. Використання вторинних батарей пропонує новий підхід до забезпечення енергетичної ефективності та сталого розвитку. Кластерний підхід, застосований у дослідженні, дозволяє оптимізувати розподіл ресурсів між підстанціями, враховуючи рівень навантаження, частоту відключень та необхідну резервну потужність. Це забезпечує адаптацію рішень до специфічних потреб кожного кластера, підвищуючи ефективність використання ресурсів. У ході дослідження виконано детальну оцінку економічних, технічних і екологічних характеристик різних рішень, включаючи дизельні генератори, нові батареї та вторинні батареї, у тому числі в комбінації з відновлюваними джерелами енергії, такими як фотоелектричні модулі. Результати дослідження показують, що вторинні батареї, особливо в комбінації з ВДЕ, забезпечують переваги, такі як зниження витрат, скорочення викидів* CO_2 *та підвищення енергетичної стійкості. Запропоновані рекомендації для впровадження вторинних батарей охоплюють законодавчі, технічні та економічні аспекти, з акцентом на створенні сприятливих умов для їх інтеграції. Це дослідження пропонує дорожню карту для інтеграції вторинних батарей електромобілів як стійкого і масштабованого рішення для підтримки енергетичної безпеки, переходу до низьковуглецевої економіки та підвищення стійкості енергосистеми України.*

Ключові слова: інтеграція вторинних батарей, резервне живлення, енергетична стійкість, високовольтні підстанції, кластерний підхід, сталий розвиток, циркулярна економіка.

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