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Innovative standardised modular management system for replacement and charging of electric vehicle batteries

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Abstract. The article examined the potential for enhancing the production and operational systems of electric vehicles through the implementation of an innovative, standardised modular approach to battery replacement and charging. The study focused on passenger electric cars and electric buses used in urban and intercity transportation, which are equipped with lithium-ion battery systems. Particular attention was given to the systemic limitations of existing electric vehicle infrastructure, including long charging times, the lack of battery and connector standardisation, high production and maintenance costs, and their adverse effects on the widespread adoption of electric mobility solutions. The aim of the study was to develop and substantiate a unified modular model for battery replacement and charging, designed to reduce vehicle downtime and improve operational efficiency. The research methodology incorporated system and comparative analysis, statistical methods, and graphical modelling to investigate modular battery architectures and infrastructure standardisation, alongside an environmental impact assessment comparing electric vehicles with internal combustion vehicles. The study drew on scientific literature, reports from international organisations (International Energy Agency, International Renewable Energy Agency, Organisation for Economic Co-operation and Development, World Health Organization), statistical databases, regulatory documents, and open-access industry sources. The findings confirmed that vehicles with internal combustion engines are significant sources of CO_2, NO_x, and fine particulate matter emissions, contributing to climate change, air pollution, and the deterioration of public health. In contrast, electric vehicles demonstrate a substantially lower environmental impact, higher energy efficiency, and reduced maintenance costs. Based on the analysis, a unified modular battery replacement system was proposed, which facilitates rapid energy replenishment, enhances interoperability, reduces infrastructure costs, and fosters the development of a sustainable electric mobility ecosystem. The study concluded that the lack of sufficient standardisation in battery systems and charging infrastructure hinders large-scale electric vehicle adoption, whereas a modular and unified vehicle architecture substantially reduces downtime and improves manufacturing flexibility and infrastructure scalability

Keywords: environmental concerns; charging infrastructure; economic efficiency; maintenance costs; electric mobility

Introduction

Road transport is a major source of environmental pollution from internal combustion engine emissions, making the adoption of zero-emission electric vehicles a key mitigation measure. One effective approach is the adoption of electric vehicles, which offer both environmental and economic benefits over ICE-powered transportation due to the absence of harmful emissions. However, the complete shift to electric mobility is currently hindered by several financial and logistical challenges. At present, electric vehicles remain expensive, require lengthy battery

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charging times, and suffer from a lack of widespread infrastructure for charging and maintenance. As a result, they are rarely employed in long-distance or international freight and passenger transport (Senn, 2023). As noted by A.R. Mesquita *et al.* (2025), although rapid charging technology is available, it is still cost-prohibitive and more expensive per mile compared to ICE vehicles, prompting commercial transport operators to continue relying on traditional combustion engines. This problem can be solved by applying an innovative method of manufacturing and operating unified batteries for electric vehicles. This will significantly reduce the cost of new electric cars, speed up charging and battery replacement, reduce operating costs, and finally allow the use of electric buses and electric trucks in international and intercity transportation. Z. Liu *et al.* (2023) emphasised that modern rechargeable batteries constitute the core of electric vehicles (EVs), and their continuous improvement is critical for enhancing energy efficiency and minimising environmental impact. This research focused on reducing dependence on scarce and geopolitically sensitive materials, particularly cobalt, whose extraction is associated with significant environmental and ethical concerns. Z. Liu *et al.* demonstrated that partial substitution of cobalt in cathode materials with more abundant transition metals can preserve electrochemical stability and energy density while improving sustainability. F. Chen (2025) underlined that cobalt-free and nickel-free cathode materials, including organic and lithium iron phosphate (LFP) chemistries, can deliver competitive performance with substantially reduced environmental and supply-chain risks. F. Chen confirmed that organic cathode materials are capable of fast charging and stable cycling without relying on critical metals. These findings support a broader transition toward material-efficient battery chemistries. Long-term resource-demand modelling conducted by O.J. Oluwalana & K. Grzesik (2025) further underscored the urgency of such transitions, as quantitative assessments of global battery material flows projected substantial increases in demand for lithium, nickel, cobalt, and graphite, thereby highlighting the critical importance of supply chain diversification and recycling-based mitigation strategies. Advances in solid-state battery technology are also considered central to the future development of EVs. Solid-state batteries offer the potential for higher energy density, improved safety, and shorter charging times; however, they remain constrained by challenges related to interfacial stability and scalable electrolyte materials. A comprehensive scientific review synthesising experimental and modelling results identifies these barriers as the primary obstacles to commercial deployment, as observed by A. Joshi *et al.* (2025). According to J. Husmann *et al.* (2024), despite progress in battery chemistry, EV manufacturing remains energy-intensive and contributes to life-cycle carbon emissions. Life-cycle assessment studies indicate that integrating renewable energy sources into battery and vehicle production, combined with increased use of recycled materials, can significantly reduce greenhouse-gas emissions relative to conventional automotive manufacturing. Another major barrier to widespread EV adoption is the limited availability of fast-charging infrastructure. High-power fast-charging stations can substantially reduce charging times while improving accessibility, provided that grid integration and load management are adequately addressed (ChargerIGS, 2025). Y.A. Alhazmi (2025) argued the role of modular charging architectures and battery-swapping systems in alleviating grid stress and enhancing operational flexibility, particularly for public and commercial vehicle fleets. According to estimates K.L. Pedersen *et al.* (2025) integrating EVs into smart-grid systems further enhances energy efficiency by enabling bidirectional power flows and vehicle-to-grid services, allowing EVs to function as distributed energy-storage units that support renewable-energy balancing and grid stability. Collectively, advances in battery chemistry, manufacturing practices, charging infrastructure, and recycling technologies contribute to the formation of a more resilient and environmentally efficient electric mobility system, which is essential for reducing the ecological footprint of the transportation sector. The purpose of this research was to formulate and validate a modular approach to battery replacement and charging in order to decrease vehicle downtime and increase operational effectiveness.

Materials and Methods

The object of the research was the electric transport development system, encompassing EVs and electric buses, examined in the context of the implementation of advanced battery technologies and charging infrastructure. The subject of the research comprised the technological, economic, and organisational aspects of battery use, including standardisation, modular charging solutions, and battery swapping systems, as well as their impact on the efficiency and sustainable development of the transport sector. The methodological framework of the research was based on systemic and structural-functional approaches, which made it possible to conceptualise electric transport as a complex socio-technical system characterised by multilevel interactions among technologies, infrastructure, and market conditions. The assessment of the advantages and potential risks associated with the implementation of electric transport was grounded in a comprehensive analysis of scientific publications, peer-reviewed journal articles, monographs, and analytical reviews, including the works of R. Jiang *et al.* (2025), A. Mdallal *et al.* (2025), and A. Temporelli *et al.* (2020). The source base also included reports of international organisations, regulatory documents, academic studies, and statistical data related to environmental standards, the impact of electric transport on public health, and the economic benefits of EVs, notably materials published by the International Energy Agency (IEA, 2025a; 2025b) and International Renewable Energy Agency (IRENA, 2024). Data from the World Health Organisation (WHO, 2024) were used to assess the effects of ambient air quality on human health. The study further applied a comparative analysis of Ukrainian and international experiences in the implementation of electric transport solutions, with particular attention to the practices of the European Union, Japan, South Korea and others. This approach enabled the identification of common patterns and key differences in the development of charging infrastructure and the deployment of battery technologies. To assess future development prospects, prognostic analysis was employed, based on the synthesis of data from international organisations and recent scientific studies, which facilitated the identification of potential development scenarios for electric mobility. Given that the article contains a substantial amount of graphical material, the data visualisation method was applied to present trends in electric transport development, battery technology structures, and comparative performance indicators.

Results and Discussion

EVs play a pivotal role in mitigating environmental impacts by substantially reducing greenhouse gas emissions and facilitating the global transition towards sustainable development. Continuous advancements in battery technologies are critical for enhancing energy efficiency, reducing production costs, and extending battery service life. Moreover, the development of the EV ecosystem contributes to economic growth by creating new employment opportunities, stimulating technological innovation, and accelerating the expansion of charging infrastructure. Collectively, these factors improve the accessibility and affordability of EVs, reduce dependence on fossil fuels, and support the formation of a resilient and sustainable energy system. In light of the rapid growth in EV adoption and the persistent challenges associated with large-scale deployment, this field remains highly relevant for both academic research and practical implementation. However, air pollution (particularly urban smog) continues to pose significant environmental and public health challenges in large metropolitan areas. Emissions from internal combustion engines release considerable amounts of nitrogen oxides, carbon monoxide, and fine particulate matter, which are key constituents of urban smog (IEA, 2025a). Under unfavourable meteorological conditions, these pollutants accumulate, thereby intensifying smog formation. Elevated concentrations of particulate matter ($PM_{2.5}$), nitrogen oxides, and ground-level ozone are associated with increased incidence of respiratory and cardiovascular diseases (Fig. 1). Figure 1 indicated that the highest levels of carbon dioxide emissions are attributable to major emitting countries, notably China, the United States, and India. The findings underscored the urgent need for effective measures aimed at reducing harmful emissions into the environment. Among the viable strategies for addressing this challenge, the electrification of various modes of transport is widely recognised as a key pathway towards emission reduction. Meanwhile, air pollution resulting from ICE use continues to be a major environmental issue in metropolitan and industrial zones. The environmental hazards linked to ICE vehicles stem from the release of several toxic substances during the combustion of fossil fuels. Although industrial activity is a leading source of pollution, wealthier nations often shift manufacturing facilities away from populated areas or even beyond national borders. However, one pollution source that cannot be relocated is road transport. In fact, the more affluent and densely populated a country is, the greater the concentration of transport-related emissions.

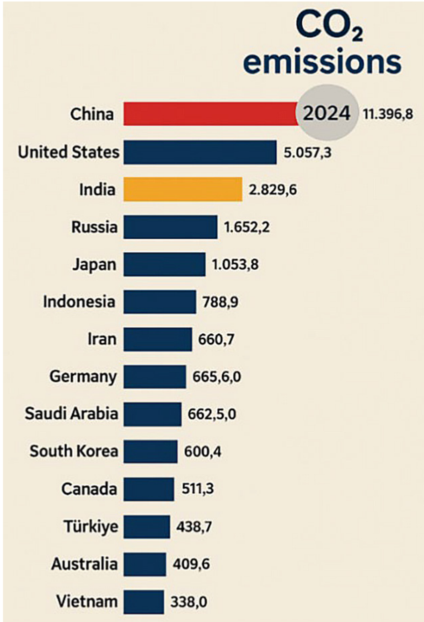

Figure 1. The countries with the most CO_2 emissions in the world
Source: Annual CO_2 emissions (2025), IEA (2025a)

The key environmental concerns associated with ICE vehicle use include:

1. CO_2 emissions and climate change. The burning of gasoline, diesel, and natural gas releases substantial amounts of carbon dioxide – a leading greenhouse gas. ICE vehicles are among the primary contributors to transportation-related CO_2 emissions. The increasing atmospheric concentration of CO_2 intensifies the greenhouse effect, accelerates climate change, and negatively impacts ecosystems, public health, and can even trigger extreme weather events.

2. NO_x emissions. Nitrogen oxides, formed during the combustion process, are highly harmful air pollutants. These gases irritate the respiratory system and may lead to asthma and other pulmonary conditions. NO_x also contributes to ground-level ozone formation, which harms both human health and plant life.

3. CO pollution. Carbon monoxide is a toxic gas resulting from incomplete fuel combustion. It disrupts oxygen delivery in the bloodstream by binding to hemoglobin, posing serious health risks, particularly in congested urban areas where CO levels often exceed safe limits.

4. Particulate matter and soot. Internal combustion engines – particularly diesel-powered ones – generate particulate matter (PM_{10} and $PM_{2.5}$) capable of penetrating deep into the lungs and even entering the bloodstream.

Long-term exposure to these microscopic particles is linked to an increased risk of respiratory and cardiovascular diseases, as well as certain types of cancer. Furthermore, fine soot particles settle on urban infrastructure, vegetation, and water bodies, causing widespread environmental degradation.

5. Moving beyond ICEs: alternatives and the future of sustainable transport. In light of tighter environmental regulations, many nations and automotive companies are turning to alternative propulsion technologies, such as electric and hydrogen-powered vehicles. Innovations in fuel-efficient vehicle design and the expansion of charging infrastructure reflect the global effort to combat air pollution and support the shift toward cleaner mobility solutions.

Adopting alternative energy sources in the transportation sector not only reduces emissions but also contributes positively to public health and improves the environmental quality of urban areas. The growing appeal of EVs stems from their ecological advantages, lower operating costs, and ongoing technological advancements. EVs offer a variety of features that enhance comfort, safety, and user experience (Fig. 2). EVs are highly eco-friendly, as they do not emit tailpipe gases such as CO_2, nitrogen oxides, or particulate matter, making them considerably more environmentally friendly than conventional vehicles. They also offer lower maintenance costs. With fewer moving parts, EVs require servicing far less frequently. Instead of regular oil changes or filter replacements, maintenance typically involves basic inspections, saving both time and money for owners. Another advantage is improved energy efficiency. EVs consume energy far more efficiently than internal combustion engine vehicles, partly thanks to regenerative braking systems that convert kinetic energy into electricity to recharge the battery. In addition, EVs provide rapid acceleration and quiet operation. Electric motors deliver torque instantly, enabling swift acceleration, while their minimal noise levels make the ride more peaceful and enjoyable for both drivers and passengers.

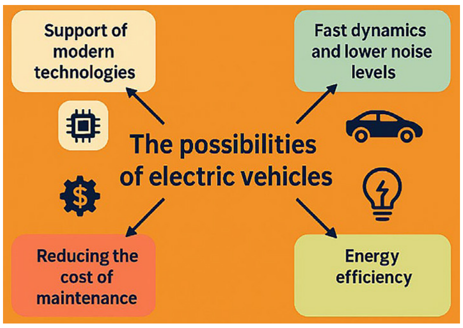

Figure 2. Features and benefits of EVs
Source: developed by the author

Figure 2 presents an infographic outlining the main capabilities and benefits of EVs. It emphasises several key aspects. Firstly, EVs offer fast dynamics and reduced noise levels. Their electric motors deliver high torque from the outset, ensuring smooth and quiet operation. Secondly, they promote environmental purity. The absence of exhaust emissions helps to decrease air pollution and improve environmental conditions, particularly in urban areas. Thirdly, EVs demonstrate superior energy efficiency. Their motors operate with significantly higher efficiency than internal combustion engines, losing less energy during use. Fourthly, maintenance costs are lower. With fewer moving parts, EVs require servicing less frequently, which reduces both time and financial expenditure. Finally, EVs support modern technologies. They incorporate advanced digital, automated, and connected systems, enhancing overall comfort and functionality for drivers and passengers. Overall, the infographic in Figure 2 concisely demonstrates the main technological, environmental, and economic advantages of EVs, highlighting their potential as a promising direction for the future of transportation. Many contemporary EVs incorporate a wide range of advanced digital features that enhance safety, functionality, and user convenience. For example, Tesla vehicles support extensive over-the-air (OTA) software update systems, allowing new functions and performance improvements to be installed remotely via the vehicle interface or mobile application (Rawal, 2025). Audi similarly offers its "Functions on Demand" platform, enabling the activation of additional software-based capabilities without requiring hardware modifications (The future of automotive technology..., 2023). Another example is the Xiaomi SU7 (2024), which integrates the Xiaomi Pilot/Hyper Automated Driving (HAD) autonomous system. This system relies on continuous OTA updates to refine automated navigation, improve sensor performance, and extend AI-driven driving functionalities. Together, these examples illustrate the increasing reliance of modern EVs on cloud connectivity, remote diagnostics, and continuously evolving software ecosystems. EVs have emerged as a vital tool in the global effort to combat smog and reduce greenhouse gas emissions. Various types of EVs are available, each offering distinct features, benefits, and potential limitations (Fig. 3).

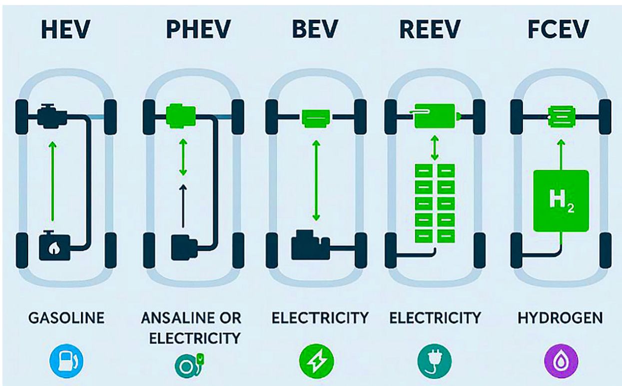

Figure 3. Types of EVs
Note: HEV – Hybrid Electric Vehicle; PHEV – Plug-in Hybrid Electric Vehicle; BEV – Battery Electric Vehicle; REEV – Range-Extended Electric Vehicle; FCEV – Fuel Cell Electric Vehicle
Source: developed by the author based on A complete guide to the types... (2024)

Figure 3 provided a comparative schematic representation of the main types of EVs, illustrating differences in their power sources, energy storage systems, and propulsion architectures. The HEV (Hybrid Electric Vehicle) combines an internal combustion engine with an electric motor, allowing limited electric assistance without external charging. The PHEV (Plug-in Hybrid Electric Vehicle) operates similarly but includes a larger battery that can be charged from the electrical grid, enabling extended electric-only driving. The BEV (Battery Electric Vehicle) relies exclusively on battery-stored electricity and includes no combustion engine, representing the fully electric drivetrain. The REEV (Range-Extended Electric Vehicle) primarily uses an electric motor for propulsion but incorporates a small combustion engine functioning solely as a generator to recharge the battery and extend driving range. Finally, the FCEV (Fuel Cell Electric Vehicle) uses hydrogen stored onboard to generate electricity through a fuel-cell system, supplying continuous power to the electric motor.

Overall, the Figure 3 visually demonstrates the technological diversity of electric mobility solutions, highlighting their varying degrees of electrification, reliance on external charging, and use of alternative energy sources. EVs play a vital role in reducing environmental pollution and promoting sustainable development by significantly cutting greenhouse gas emissions. Battery improvement is a key factor in increasing energy efficiency, lowering production costs, and extending lifespan. EV development also stimulates economic growth by creating jobs, advancing technologies, and expanding charging infrastructure, thereby improving accessibility and reducing dependence on fossil fuels. These dynamics make EVs a crucial subject for ongoing research and implementation. Internal combustion engine (ICE) vehicles remain a primary source of air pollution in urban and industrial areas, emitting substances like CO_2, NO_x, and particulate matter that contribute to smog, respiratory issues, and climate change.

Internal combustion engines create several environmental and health challenges. They emit large quantities of CO_2, which significantly contributes to global warming. Emissions of NO_x negatively affect respiratory health and facilitate the formation of ground-level ozone. CO poses risks to human health by disrupting the body's ability to transport oxygen. Additionally, particulate matter and soot increase the likelihood of cardiovascular diseases and accumulate on urban surfaces and infrastructure. These environmental burdens have accelerated the global movement toward green transport solutions, strengthened by increasingly strict emission standards and the rapid development of electric and hydrogen-powered vehicles. EVs offer several key advantages compared to conventional ICE-powered cars. They produce zero tailpipe emissions, eliminating harmful pollutants during operation. EVs also require lower maintenance, as they contain fewer mechanical components susceptible to wear. Their high energy efficiency, supported by regenerative braking, allows more effective use of stored electrical energy. The electric motor lifespan tends to be longer due to reduced mechanical friction and fewer moving parts. EVs operate quietly, thus helping decrease noise pollution in urban environments. The instantaneous availability of torque enables rapid acceleration and improved driving dynamics. Modern EVs also incorporate advanced technological features, including autopilot systems, remote vehicle access, and comprehensive mobile app integration.

EVs can be classified into several technological categories. BEVs operate exclusively on electrical energy stored in batteries; examples include the Tesla Model S and the Nissan Leaf. HEVs combine a traditional internal combustion engine with an electric motor, as seen in the Toyota Prius. PHEVs use both electric and combustion propulsion and can be externally charged from the electric grid; a prominent example is the Mitsubishi Outlander PHEV. FCEVs generate electricity using hydrogen as a fuel source; the Toyota Mirai is a widely known representative of this category. Hydrogen-powered vehicles present a mix of advantages and disadvantages. On the positive side, they produce zero harmful emissions, releasing only water vapour as a byproduct, which makes them highly environmentally friendly. They also allow for rapid refuelling, typically taking only three to five minutes, and offer a substantial driving range of around 500-800 km. Additionally, hydrogen systems do not depend on scarce metals and perform better than conventional engines in cold climates. However, their widespread adoption faces several challenges. The refuelling infrastructure is still limited in most parts of the world. Producing hydrogen is expensive and often energy-intensive. Fuel cells require costly materials, and safety concerns remain due to the high flammability of hydrogen, which complicates storage and handling. Battery Technologies play a pivotal role in determining the performance, safety, and environmental impact of EVs. Lithium-ion batteries dominate the EV market due to their high energy density, fast-charging capability, and relatively long service life. These qualities allow EVs to travel longer distances and recharge more quickly, making them highly practical for everyday use. Nevertheless, lithium-ion batteries remain expensive, pose thermal safety risks, and raise environmental concerns, particularly in relation to the mining of raw materials and the challenges of recycling at the end of their lifespan. Solid-state batteries are emerging as a promising alternative, offering even higher energy density, improved operational safety, and a longer lifespan. Despite their potential, widespread adoption is hindered by high manufacturing costs and significant technological challenges associated with mass production. Other battery technologies are also gaining attention. Sodium-ion batteries offer a more affordable and environmentally friendly option, though their energy density is lower than that of lithium-based batteries. LFP batteries are recognised for their stability and safety, making them a reliable choice, but they typically provide a slightly shorter driving range compared to high-nickel lithium chemistries. Together, these developments illustrate the ongoing evolution of battery technology and the trade-offs between cost, performance, safety, and environmental impact.

Future developments in electric mobility were expected to prioritise increases in battery energy density, reductions in production and lifecycle costs, and the diversification of complementary low-carbon energy technologies, including hydrogen-based systems. Emerging innovations, such as rechargeable liquid electrolyte batteries and next-generation solid-state energy storage technologies, were anticipated to enhance the operational performance, energy efficiency, and user convenience of EVs. Collectively, these technological advances were projected to strengthen the competitiveness of EVs relative to conventional internal combustion engine vehicles, thereby accelerating their integration into the global transport system (Fig. 4).

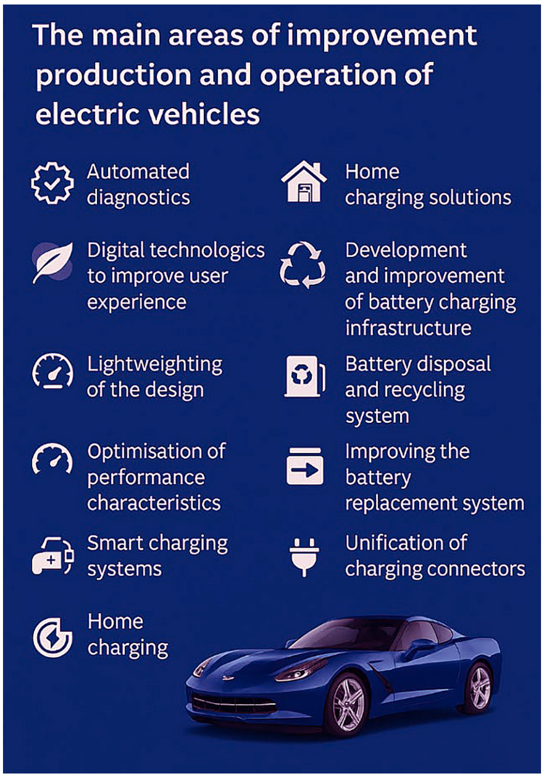

Figure 4. Main areas of improvement in the production and operation of EVs
Source: developed by the author

Figure 4 demonstrated a structured overview of the main directions for improving the engineering solutions and operational characteristics of modern EVs is presented. All development vectors are grouped into two technical categories: on-board technological systems and infrastructure- and lifecycle-related improvements. The left column illustrates areas directly related to the vehicle's internal systems, including automated diagnostics, digital user-interface technologies, lightweight structural design, optimisation of performance parameters, and the implementation of smart charging algorithms. The right column highlights external and system-level enhancements, such as home charging solutions, the expansion of charging infrastructure, battery recycling and disposal processes, advanced battery replacement mechanisms, modular vehicle architectures, and the standardisation of charging connectors. The implementation of a unified modular system for the factory production, operation, and replacement of EV battery packs constituted a complex, multifaceted undertaking that required the systematic resolution of organisational, technical, technological, and economic challenges. A central prerequisite for such a system was the harmonisation of components and technical standards across manufacturers and platforms. Battery unification, in particular, involved the standardisation of battery dimensions, interfaces, and connection protocols, which enabled joint manufacturing, economies of scale, and simplified maintenance and replacement procedures. For instance, the development of standardised battery modules applicable across multiple vehicle models increased production flexibility, reduced unit costs, and facilitated more efficient lifecycle management of battery systems (Fig. 5).

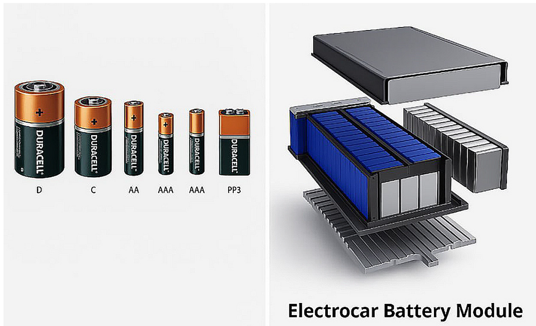

Figure 5. Using the modular principle of sectional production, operation and replacement of consumer batteries and EV batteries
Source: developed by the author

Figure 5 illustrated a comparative representation of battery technologies, combining two visual components. The left section shows a standardised line-up of conventional cylindrical consumer batteries (D, C, AA, AAA, and 9V), serving as a reference model for size unification. The right section presents an EV battery pack shown in cross-section, highlighting its modular architecture. Individual modules, internal cell arrays, structural housing, and cooling elements are visible, demonstrating the layered and serviceable design of a modern EV battery system. This configuration emphasises the principles of modularity, maintainability, and scalability in contemporary EV battery engineering. The unification of charging connectors through the adoption of a single, interoperable charging port standard for EVs (such as CCS or CHAdeMO) was expected to improve access to charging infrastructure and enhance user convenience. Standardisation in this area also contributed to reducing the capital and operational costs of charging stations by eliminating the need to support multiple incompatible connector types, thereby improving the economic efficiency and scalability of charging infrastructure deployment (Fig. 6).

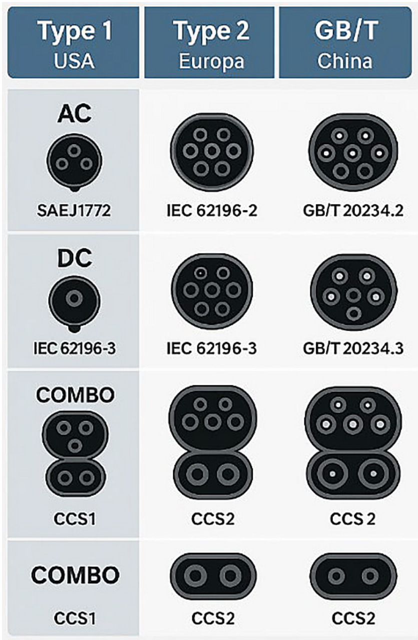

Figure 6. Types of EV charging connectors
Source: developed by the author based on P. Zhang (2025)

Figure 6 illustrated the three major EV charging connector standards used worldwide: Type 1 (United States of America (USA)), Type 2 (Europe), and GB/T (China). Each standard includes configurations for alternating current (AC) charging, direct current (DC) fast charging, and combined systems (COMBO/CCS) designed to support high-power charging. Type 1 (SAE J1772, United States) was predominantly used in North America and supported AC charging, as well as integration with the Combined Charging System (CCS1) for DC charging. Type 2 (IEC 62196-2, Europe) functioned as the universal European solution for AC charging (Type 2) and formed the basis for DC fast charging through the CCS2 configuration, enabling a high degree of interoperability within the European market. GB/T (China) employed separate connectors for AC and DC charging and did not provide compatibility with CCS-based systems, thereby limiting cross-regional interoperability. The coexistence of multiple charging standards generated a number of systemic challenges, including technical incompatibility of EVs across regional markets, increased reliance on adapters and specialised charging infrastructure, higher capital and operational costs for infrastructure development, and additional complexity in global EV manufacturing, distribution, and market integration. CCS1/CCS2 is increasingly promoted as the international standard for fast charging across the EU, USA, South Korea, and parts of Asia. CHAdeMO, although still used (notably in Japan), is progressively being displaced by CCS. China's GB/T is evolving toward the new ChaoJi standard, which aims to unify GB/T and CHAdeMO under a single high-power charging interface.

Based on Figure 6 and prevailing industry trends, several key conclusions can be drawn. First, the combination of Type 2 and CCS2 exhibited the strongest potential to emerge as a de facto global standard for EV charging, owing to its broad adoption within major markets and its technical adaptability. Second, the unification of charging connectors could reduce the manufacturing costs of charging infrastructure by an estimated 30-40 per cent, thereby enhancing economic efficiency and lowering barriers to infrastructure expansion. Third, the adoption of a single, harmonised connector interface would simplify the operation of EVs and eliminate cross-market incompatibility barriers, facilitating greater user mobility across regions. Fourth, standardisation was projected to accelerate the deployment of charging infrastructure, particularly in developing markets where cost constraints and technical fragmentation currently impede rapid uptake. Furthermore, the implementation of standardised modular components that are suitable for a range of vehicle models and classes was expected to reduce production costs, lower the purchase price of EVs, and simplify repair and maintenance processes (Fig. 7).

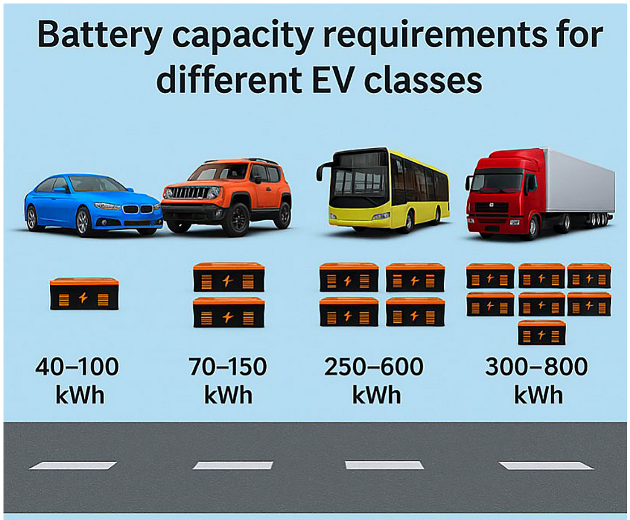

Figure 7. Number of lithium-ion modular sectional batteries required for different types of vehicles
Source: developed by the author

Figure 7 presents the concept of a unified modular battery architecture that can be scaled according to the energy demand of different classes of EVs – from passenger cars to heavy-duty EV platforms. It illustrates four categories of vehicles, each associated with an approximate total battery capacity (40-800 kWh), achieved through the combination of standardised battery modules of a uniform form factor. This approach demonstrates the possibility of using a single type of modular EV battery that can be assembled in various quantities to meet specific energy requirements. Such a configuration simplifies manufacturing, facilitates maintenance, ensures component interchangeability, and increases the scalability of battery systems for future EV platforms. Deploying high-speed battery swap stations instead of traditional charging points can significantly reduce downtime, particularly on long-distance trips. This method has already proven successful in China with companies like NIO. Additionally, offering battery leasing options helps lower the upfront cost of EVs, making it easier for users to replace old batteries without large, one-time expenses. This approach can make EVs more accessible while ensuring drivers benefit from the latest battery technology. Investing in battery recycling infrastructure and integrating recycled materials into production can lower manufacturing costs, improve sustainability, and address the issue of battery disposal. Expanding fast-charging networks enables EVs to reach up to 80% charge in just 20-30 minutes, enhancing convenience and promoting wider EV adoption. The provision of government incentives and manufacturer-supported home charging solutions, including subsidies for the installation of residential charging infrastructure, was expected to reduce upfront costs and significantly enhance the practicality and economic attractiveness of EV ownership for consumers. The integration of EV charging into smart grid systems enabled the optimisation of electricity distribution by shifting charging demand to off-peak periods, when electricity prices were lower and grid capacity was less constrained, thereby reducing pressure on energy infrastructure and improving overall system efficiency. At the same time, advances in battery technologies, particularly the development of solid-state batteries, were expected to deliver higher energy density, extended driving range, and shorter charging times, while improvements in regenerative braking systems enhanced the recovery of kinetic energy and increased the effective utilisation of stored electricity. In addition, the incorporation of lightweight materials, such as aluminium alloys and advanced composite materials, into EV design, including battery systems, reduced overall vehicle mass, which in turn improved energy efficiency and contributed to better driving performance and extended range. The integration of EVs with mobile applications enhanced user interaction by enabling drivers to monitor battery status, locate nearby charging stations, receive system alerts, and plan routes that incorporated optimal charging points. In parallel, the implementation of over-the-air software update mechanisms allowed manufacturers to continuously improve battery management systems, enhance safety features, and introduce new functionalities without requiring physical visits to service centres, thereby reducing maintenance costs and increasing operational efficiency. The deployment of built-in self-diagnostic systems further contributed to the early detection of technical faults, improving overall vehicle reliability and minimising downtime and lifecycle maintenance expenditures. At the industry level, sustainable progress in the EV sector required a comprehensive and integrated development strategy that combined component standardisation, the expansion of battery swapping networks, the large-scale deployment of charging infrastructure, and the adoption of advanced lightweight materials. Collectively, these measures reduced production and ownership costs, enhanced vehicle performance, and increased the accessibility of EVs to a broader range of consumers.

With regard to Ukraine and global experience in EV development, Ukraine, similarly to many other countries, has been actively engaged in the expansion of electric mobility, drawing upon international best practices while adapting them to domestic economic, regulatory, and infrastructural conditions. Ukrainian cities now host over 11,000 charging stations, although major highways still lack sufficient coverage (There are 20,000 more electric…, 2023). Private companies like TOKA and AutoEnterprise have significantly contributed to the expansion of fast-charging stations, especially in urban areas and along key transit routes. Government support, such as exemptions from VAT (Value-Added Tax) and excise duties, makes EVs more affordable and motivates consumers to switch to electric mobility. As a result, the number of EVs in Ukraine has grown steadily (UkraineInvest, 2024). Used electric cars, particularly models like the Nissan Leaf, remain a popular option due to the lower cost compared to new vehicles. Imports from the U.S. and Europe make EV ownership more attainable for many Ukrainians. The two main factors influencing EV growth in Ukraine are the purchasing power of the population and the availability of charging infrastructure. Although city coverage is improving, highway infrastructure still lags behind. Electric buses and other forms of electric public transport are being introduced in cities like Kyiv, helping reduce urban air pollution. EV-sharing services are also gaining traction, offering flexible mobility without the need for car ownership. Ukraine's National transport strategy through 2030 outlines further support for EVs, including expanding the national charging network and increasing incentives for clean vehicles (Ministry for Communities and Territories Development of Ukraine, 2022). Global approaches to EV development vary across regions, reflecting differences in government policy, market structure, and technological focus. In Europe, countries provide strong government incentives, including subsidies and tax breaks. Norway leads the continent with the highest EV adoption rate, supported by VAT exemptions and access to bus lanes, while Germany and France also invest heavily in both EV infrastructure and purchase incentives (Williment, 2025). China, as the largest EV market globally, leads in production and infrastructure, with companies such as Contemporary Amperex Technology Co. Limited (CATL) and Build Your Dreams (BYD) dominating battery manufacturing and battery swapping widely implemented by firms like NextEV Inc. (NIO) (Jiang *et al.*, 2025). In the United States, private companies, most notably Tesla, have built extensive fast-charging networks, while the government supports EV adoption through tax credits and funding for research and development in new battery technologies. In Japan, the focus has been on hydrogen-powered vehicles, supported by dedicated infrastructure developed for events such as the Olympics, with companies like Toyota and Honda innovating in hydrogen and solid-state battery technologies. South Korea, home to major battery producers including LG Chem and Samsung SDI, invests in battery technology and infrastructure while offering subsidies and funding advanced research. International experience shows that the global success of EVs depends on a combination of infrastructure development, government support, and technological advancement. Measures such as increasing access to chargers, providing financial incentives, and standardising batteries are essential to promote EV adoption. Examples of innovative battery use highlight these possibilities: in Japan, old EV batteries are repurposed to power streetlights; in Paris, they operate elevators; and in Amsterdam, they supply energy to an entire stadium. These cases demonstrate how technology, infrastructure, and policy together can drive the sustainable development of electric mobility, offering lessons that could inform Ukraine's EV strategy.

European countries demonstrate a systematic approach to promoting electric mobility by providing substantial governmental incentives, including tax reductions, purchase subsidies, and non-monetary benefits. For instance, in Norway, owners of zero-emission vehicles benefit from a 25% VAT exemption, access to bus lanes, and reduced toll and ferry charges. These policies have enabled Norway to achieve the highest EV market share in the world (Alternative Fuels Observatory, 2025; Norway the world leader…, 2025). China, the world's largest electric-vehicle market, combines large-scale battery production (CATL, BYD) with innovative infrastructure solutions, particularly battery-swapping networks. CATL has announced plans to deploy more than 2,500 battery-swap stations in over 120 cities by the end of 2026, while NIO and CATL are collaborating to harmonise industry standards and expand global swapping capabilities (Zhang, 2025; Chen, 2025). In the United States, private companies, most prominently Tesla, play a leading role in deploying nationwide fast-charging networks. Concurrently, the federal government supports EV adoption through tax credits and investment in advanced battery research and development (Canis *et al.*, 2019). Japan has prioritised hydrogen-fuel technologies and the development of solid-state batteries, with leading companies such as Toyota and Honda driving innovation in these areas. A notable example of Japanese ingenuity is the reuse of retired EV batteries to power street lighting in towns near Fukushima, demonstrating the potential of second-life battery applications (Schmidt, 2019). Similarly, South Korea, home to major battery manufacturers including LG Chem and Samsung SDI, has continued to invest in advanced battery research and development as well as the expansion of charging infrastructure, supported by national subsidy programmes (Bharadwaj, 2023). International experience demonstrated that the effective development of the EV sector depends on the coordinated implementation of three key elements: the systematic expansion of charging infrastructure, consistent governmental support through subsidies, tax incentives, and regulatory measures, and robust technological innovation, including the standardisation of battery modules and charging connectors. Countries that successfully integrate these components tend to achieve the most rapid growth in EV adoption. Illustrative examples of innovative second-life battery applications, such as powering LED (Light Emitting Diode) streetlights in Fukushima, operating elevators in Paris, and supplying energy to stadiums in Amsterdam, further highlight the potential for repurposing used EV batteries within urban energy infrastructures, thereby contributing to both sustainability and the efficient utilisation of resources.

In the course of this study, relevant scientific literature was reviewed and the findings of other authors were compared with the results obtained in the present research. V. Porfirenko (2025) analysed the standardisation of battery production for electric buses and assessed the feasibility of modular battery replacement in international transport operations. The study demonstrated that the implementation of unified battery modules with fast replacement capabilities can reduce vehicle downtime to 10-15 minutes and decrease the total cost of ownership in comparison with diesel buses. The results of the present research confirm the advantages of a unified modular battery system and extend this concept beyond public transport to passenger EVs, commercial fleets, and city-level battery swapping infrastructure. A. Mdallal *et al.* (2025) examined the evolution of EV charging standards and emphasised that interoperable solutions, particularly the CCS, are critical for sustainable infrastructure development and for mitigating range anxiety. These conclusions are complemented by the present study, which demonstrates that charging connector unification is significantly more effective when combined with modular battery standardisation, enabling the integrated use of fast charging and battery swapping within a unified technological ecosystem. Y.A. Alhazmi (2025) provided a systematic review of battery swapping stations, analysing their technical, economic, legal, and social dimensions. The author highlighted that the effectiveness of battery swapping systems depends heavily on deep battery standardisation and on business models compatible with conventional charging solutions. The results obtained in this study were consistent with this assessment and additionally suggested that a unified modular battery architecture constituted a prerequisite for the large-scale deployment of battery swapping stations in both urban and long-distance transport systems. A. Temporelli *et al.* (2020) conducted a life-cycle assessment of EV batteries and concluded that battery production constitutes the largest share of the environmental footprint of EVs, while recycling processes and second-life applications significantly influence overall carbon impacts. Within the present research, these findings provide a strong rationale for unified modular battery designs, which facilitate disassembly, sorting, recycling, and second-life utilisation in stationary energy storage systems. Similarly, a review of second-life battery applications by J. Schmidt (2019) demonstrated that EV batteries with a reduced state of health (SOH $\approx$ 70-80%) can still be effectively used in grid-connected and microgrid energy storage, offering substantial economic and environmental benefits. The results of the present study align with these conclusions and further underscore the importance of embedding design-for-second-life principles at the earliest stages of modular battery development. Overall, the analysis of the reviewed scientific works confirms that modularity, standardisation, and second-life integration are widely recognised as key directions in global EV research. The results obtained in this study are consistent with current scientific trends while providing a broader systems-level perspective on the integration of these approaches.

Conclusions

In the course of this research, a comprehensive analysis was conducted on the technological, infrastructural, and organisational foundations required for the effective development of EV systems. The study examined current global trends in EV manufacturing, the evolution of charging infrastructures, and the growing importance of unified standards across both vehicle components and energy systems. It was determined that one of the most significant barriers to large-scale EV deployment remains the lack of harmonisation in battery design, charging connectors, and replacement procedures. This fragmentation increases production costs, complicates maintenance, and slows down the expansion of EV fleets. The conducted analysis highlighted that a modular and unified approach to EV production offers substantial advantages. Standardised battery modules and structural components enable flexible manufacturing, reduce production complexity, and allow multiple vehicle classes to share common technological platforms. It was demonstrated that modular battery systems, in particular, address a critical challenge – long charging times – by enabling battery swapping, thereby drastically reducing vehicle downtime. This approach supports the formation of new urban charging ecosystems based on rapid infrastructure turnover, high user throughput, and integration into smart-energy networks. Furthermore, the findings substantiate that unified charging connectors, cross-compatible components, and interoperable digital systems enhance the scalability of EV infrastructures. Such standardisation also accelerates international cooperation, investment attractiveness, and the long-term sustainability of the EV sector. The research substantiates the conclusion that transitioning toward standardised, innovative, and eco-friendly EV architectures is a strategic step toward achieving cleaner urban mobility, increased energy efficiency, and broader public accessibility. Future research should focus on developing lifecycle models for unified battery modules, assessing economic efficiency of battery-swap networks, and exploring advanced materials that can further extend battery performance within unified system architectures. Additional studies on second-life battery applications will also play a critical role in reinforcing circular-economy principles within the EV industry.

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Conflict of Interest

None.

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Інноваційна стандартизована модульна система управління для заміни та заряджання акумуляторних батарей електричних транспортних засобів

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Анотація. У статті було досліджено потенціал підвищення ефективності виробничих та експлуатаційних систем електромобілів через впровадження інноваційного, стандартизованого модульного підходу до заміни батарей та заряджання. Дослідження було зосереджене на пасажирських електромобілях та електробусах, що використовуються в міських та міжміських перевезеннях і оснащені літій-іонними батарейними системами. Особлива увага приділялася системним обмеженням існуючої інфраструктури електротранспорту, зокрема тривалому часу заряджання, відсутності стандартизації батарей та роз'ємів, високим витратам на виробництво та обслуговування, а також їхньому негативному впливу на широке впровадження рішень у сфері електромобільності. Метою дослідження було розроблення та обґрунтування уніфікованої модульної моделі заміни батарей та заряджання, призначеної для зменшення часу простою транспортних засобів та підвищення експлуатаційної ефективності. Методологія дослідження включала системний та порівняльний аналіз, статистичні методи та графічне моделювання для вивчення модульних архітектур батарей та стандартизації інфраструктури, а також оцінку впливу на довкілля з порівнянням електромобілів та автомобілів із двигунами внутрішнього згоряння. Дослідження спиралося на наукову літературу, звіти міжнародних організацій (Міжнародного енергетичного агентства, Міжнародного агентства з відновлюваної енергії, Організації економічного співробітництва та розвитку, Всесвітньої організації охорони здоров'я), статистичні бази даних, нормативні документи та відкриті галузеві джерела. Результати підтвердили, що транспортні засоби з двигунами внутрішнього згоряння є значними джерелами викидів CO_2, NO_x та дрібнодисперсних частинок, що сприяє зміні клімату, забрудненню повітря та погіршенню стану громадського здоров'я. Натомість електромобілі демонструють суттєво нижчий вплив на довкілля, вищу енергоефективність та зменшені витрати на обслуговування. На основі проведеного аналізу було запропоновано уніфіковану модульну систему заміни батарей, яка забезпечує швидке поповнення енергії, підвищує сумісність, знижує витрати на інфраструктуру та сприяє розвитку сталого екосистемного середовища електромобільності. Дослідження дійшло висновку, що відсутність достатньої стандартизації батарейних систем та інфраструктури заряджання гальмує масштабне впровадження електромобілів, тоді як модульна та уніфікована архітектура транспортних засобів значно зменшує час простою та підвищує гнучкість виробництва й масштабованість інфраструктури

Ключові слова: екологічні проблеми; зарядна інфраструктура; економічна ефективність; витрати на технічне обслуговування; електрична мобільність