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ARTICLE

Standardization of Electric Vehicle Battery Production in International Electric Bus Transportation Based on the Innovative Modular Principle

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ABSTRACT

This study provides a comprehensive analysis of the development, industrial production, and operational deployment of electric buses in international transportation, with particular attention to the standardization of electric vehicle (EV) battery technologies through a modular rapid-replacement principle. The ongoing transition from internal combustion engine vehicles to electrified transport systems reflects both the global decarbonization agenda and the demand for sustainable long-distance passenger mobility. Electric buses demonstrate clear advantages, including substantial reductions in greenhouse gas emissions, mitigation of urban noise pollution, and higher energy efficiency, thus contributing to the achievement of international climate goals and the modernization of cross-border transport networks. Nevertheless, several technological and infrastructural barriers continue to constrain large-scale adoption. High manufacturing costs of traction batteries, limitations in vehicle driving range, and insufficient charging infrastructure significantly affect operational reliability in long-distance and cross-border contexts. Within this framework, the study evaluates the innovative concept of modular battery replacement, which is designed to standardize battery dimensions and interfaces across manufacturers and enable rapid exchange of depleted modules. Empirical assessments demonstrate that such a system can reduce downtime to 10–15 minutes, enhance operational efficiency, and lower the total cost of ownership relative to conventional diesel bus fleets. The findings confirm that modular battery replacement and standardization constitute a viable technological pathway toward accelerating the adoption of electric buses in international transportation. By ensuring interoperability, minimizing infrastructure dependence, and improving cost-effectiveness, modular systems can play a pivotal role in shaping the future of sustainable, environmentally responsible, and economically efficient passenger mobility.

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1. Introduction

A wide range of ecological challenges, including global warming and severe air pollution from the exhaust gases of internal combustion engines (ICEs), which operate on fossil fuels, have created a strong impetus for the search for and development of environmentally friendly vehicles [1], he global market for electric vehicles (EVs) has been expanding rapidly, and Ukraine is no exception. However, the large-scale adoption of EVs is still hindered by several technical and economic barriers, including high battery costs, limited driving range before battery depletion, and long recharging times [1]. In Ukraine, one important stimulus for EV adoption has been the introduction of a zero import duty for vehicles equipped with electric motors, which has positively influenced the growth of both commercial and private EV markets [2]. Nevertheless, a major operational drawback remains: the long duration of relatively inexpensive slow battery charging, and the high cost associated with accelerated fast charging. This currently makes it difficult to use commercial electric buses and trucks in international and intercity transportation; moreover, fast charging on route can be more expensive than refueling comparable diesel vehicles [3]. This article proposes an innovative solution to this problem through the creation of a unified modular system for the standardized production and operation of EV batteries. Such an approach could significantly reduce charging downtime, improve operational efficiency, and make electric buses more competitive in long-distance passenger and cargo transportation. The market for energy-saving technologies worldwide has been developing rapidly in recent years, with increasing volumes of alternative energy sources—such as solar and wind power plants, as well as household energy independence systems—already operating effectively and contributing to sustainable development goals [1]. In most cases, the economic effect of alternative energy adoption is based on the partial or complete abandonment of fossil fuel–based sources, thereby saving financial resources that can be redirected toward more strategic uses. In the field of EVs, however, there are still unresolved economic and policy-related issues. Owners of electric vehicles, similarly to owners of cars with traditional fuel engines, contribute to the physical deterioration of road infrastructure (as do owners of cars with a classic fuel-powered engine), without reimbursing the expenditures to the extent that owners of cars with a classic power plant do [4]. They do not pay excise taxes on fuel (gasoline, gas or diesel) when refueling the battery, which gose to the state budget and forms, in particular, the financial basis for the development and restoration of road infrastructure. Although this creates a budgetary gap, it is expected that the combined environmental and economic benefits of EV adoption will outweigh these losses in the long term. Structurally, EVs are similar to conventional vehicles, as their design is largely based on that of classic cars. They share components such as wheels, suspension, steering mechanisms, and pedals. The main difference is that instead of an internal combustion engine (ICE), an electric motor is installed in an electric car, and the source of its power is a battery.

Advantages of electric vehicles:

- Efficiency. The expenditure of annual recharging of an electric car is almost 63% lower than the annual refueling of a comparable fuel-powered car [1,5].
- Environmental friendliness. EVs produce no exhaust emissions during operation, significantly reducing air pollution, and have lower engine and transmission maintenance costs compared to gasoline-powered vehicles [5,6].
- Low noise level. This advantage is especially relevant in megacities with high traffic density [7] .
- Better dynamics. Maximum torque is achieved from the first revolution of the motor [8].
- Safety. The center of gravity of the car is shifted downward due to battery placement, reducing the risk of rollovers and improving stability during sharp manoeuvres [9].

But, like all cars, electric cars have their drawbacks, namely:

- Limited range. Typically, EVs can travel 150 to 350 km on a single charge (depending on the model). Premium models such as Tesla and Jaguar can exceed this range[1,10–16].

- High price. The cost of EVs is approximately 1.5 to 2 times higher than that of most conventional middle-class cars[1,17].
- Sensitivity to air temperature. Battery capacity decreases during cold weather – by about 20 % at +5 °C and up to 50% at −12 °C [5,18].
- Cabin climate control impact. The air conditioning system is battery-powered, which can reduce driving range by about 20%. An independent heater can be installed, but it adds extra cost[5,18].
- Weak recharging infrastructure. In small towns, charging stations are rare or absent, forcing EV owners to charge their vehicles at home or at work[2,19].
- Unprofitable commercial use of electric vehicles and electric buses in international transport. Fast charging along a route is currently more expensive than refueling comparable diesel buses or trucks, while slow charging is too time-consuming and disrupts cargo or passenger schedules[3,20].

2. Literature Review

One of the first Ukrainian companies to receive a certificate of conformity for production was Skywell. This is a 12-meter NJL 6129 BEV bus designed to carry 81 passengers, including 32 seats. The maximum speed is 70 km/h and the range is 300 km. It takes 40–80 minutes to charge the electric batteries. The electric bus is equipped with LED lighting, illuminated steps, a low floor, an electrically heated driver's seat, and a video monitoring system for parking and doors during stops[21].

The classification of electric vehicles as fully environmentally friendly transport is still a matter of debate. Greenhouse gas emissions during the production, refueling, operation, and disposal of such cars are not zero. However, throughout their entire life cycle – largely due to the higher efficiency of the electric motor – electric vehicles produce at least 22% less CO_2 emissions, and in countries with decarbonized energy, this figure can reach 70–80%[1,5]. In Ukraine, 53% of electricity is generated by nuclear power plants, but the greater the share of renewable (solar, wind) energy, the more environmentally friendly EVs will become[1].

The rate of electric car purchases is growing in Ukraine. While in 2012–2013 EVs were just beginning to appear, by the end of 2020 more than 20,000 EVs were registered. At the same time, in January-September 2020, 5,384 EVs and 297,046 passenger cars with internal combustion engines were registered in Ukraine, meaning that the ratio of EVs to conventional and hybrid cars is approximately 2 to 98[2]. The peculiarity of the Ukrainian electric car market is that the vast majority of it is made up of used foreign cars from the United States and some European countries[2].

Until the end of 2022, the Tax Code of Ukraine provided for a preferential regime for the import of electric vehicles. EVs were exempt from value added tax (VAT), and there was also a special excise tax, the amount of which depended on the battery capacity. Since 2020, service centers of the Ministry of Internal Affairs have issued green license plates for electric vehicles and electric buses. Owners of green license plates are entitled to park in specially designated places (including guaranteed access to recharging stations) and to take advantage of the road signs "For electric vehicles", "Except for electric vehicles", and "Electric vehicle charging station"[2].

Another important aspect of stimulating demand for electric vehicles is the development of a convenient infrastructure that allows the owner to charge the car without difficulty. According to the IRS Group marketing agency, as of September 2020, there were 8,529 charging stations in Ukraine, representing an increase of more than 50 % in one year[2].

A large share of the Ukrainian charging station market is held by Kharkiv-based Autoenterprise, which manufactures charging stations, manages its own charging network, and imports electric vehicles. The company's directornotes that engineering developments are the main focus of the company. Autoenterprise produces commercial charging stations (including high-speed ones) as well as complexes that can charge up to 5–6 cars at a time. About one-third of its chargers are sold domestically, while the rest are exported. The company operates under the "white label" concept, meaning that the chargers it produces are used by companies around the world under their own brands.

Autoenterprise also participates in the sharing economy through initiatives such as the Charge Sharing program, which allows businesses to develop their own charging networks and provide charging services at self-determined rates, and the AE Car Sharing project, a per-minute electric vehicle rental service. In addition, the company develops electric vehicles such as trolleybuses, tractors, and ATVs [2].

Theoretical and practical aspects of the production, technical operation, and environmental friendliness of EVs and electric buses have been addressed in numerous studies. The issues of technical and linear operation, optimization of urban electric transport, and the modular principle of using urban electric buses are discussed in works by Porfirenko et al [4,17,22–26].

In practical terms, it is impossible not to recognize the leading role of China and its automakers in standardizing and unifying the production and operation of electric vehicle batteries. China has become a global leader in the implementation of modular battery swapping technology for electric vehicles [1,27]. Companies such as Nio, Changan, Geely, and CATL are actively developing this infrastructure that enables battery swaps in minutes. For example, the Nio Power Swap system uses a fully automated station to replace a discharged battery in about 3–5 minutes [1,27].

These solutions have been successfully scaled up in urban public transport, especially in electric buses, where downtime should be minimized. Other countries, such as Japan (ENEOS + Honda), Israel (Better Place, now closed), and Germany, have not yet reached a comparable level of implementation. Internationally, there is still no unified standard for replaceable batteries in passenger or commercial electric vehicles. China's development of proprietary technical specifications may result in a "de facto" standard through market dominance, potentially causing technological lock-in in other regions [1,27].

From a global perspective, China is promoting initiatives at the ISO/IEC and ITU-T levels to standardize EV battery production and replacement.

The proliferation of battery-compatible models – such as Changan Oshan 520 and Geely Maple Youxing 6 – strengthens the influence of CATL and Nio as technological "standard setters" in the field of modular battery swapping systems, including the physical dimensions of battery packs, high-voltage connectors, communication protocols between vehicle and battery, and automated swapping station interfaces [1,27].

Other countries may face the choice of developing alternative protocols or adapting to Chinese standards. With strong government support, corporate leadership from Nio, CATL, Geely, and Changan, and rapid infrastructure development, China is building an ecosystem that could become the global benchmark for modular battery production and operation [1,27].

Another operational challenge associated with electric vehicles, and one that remains underexplored in the scientific literature, concerns fire safety. Current firefighting practices and equipment, designed primarily for vehicles with internal combustion engines, are often inadequate for high-voltage battery systems. Thermal runaway in lithium-ion batteries can result in rapid temperature escalation, release of toxic gases, and difficulty in fully extinguishing fires, even after visible flames are suppressed [25]. Reports from fire safety agencies indicate that EV battery fires may reignite hours or even days after the initial incident, requiring prolonged cooling and monitoring [18,20]. At present, there are no widely adopted standardized methods or dedicated firefighting agents specifically designed for EVs, which represents an additional operational risk for both private and commercial use [9,18,20].

3. Research Methodology

To achieve the research goal and solve the outlined problems, the study employed the following general scientific methods: statistical analysis, comparative analysis, and the expert survey method. The expert survey method in this research refers to a structured questionnaire distributed to specialists in electric vehicle manufacturing, infrastructure development, and transport policy, aimed at collecting qualitative assessments on the feasibility, operational challenges, and prospects of modular battery swapping systems. The survey included both closed-ended and open-ended questions, enabling a combination of quantitative rating and qualitative opinion analysis [2,4,22].

This study adopts a mixed-method approach, combining:

1. Statistical analysis of operational and technical indicators of electric bus deployment, based on quantitative datasets;
2. Case study analysis, comparing the adoption of modu-

lar battery technology in China and Ukraine;

3. Expert surveys to capture professional insights into challenges of battery replacement systems and international standardization processes.

The mixed-method approach in this context integrates quantitative data (statistical indicators, performance metrics) with qualitative case evidence (institutional context, regulatory environment, and operational practices). Comparative analysis, structured in the form of a SWOT framework, is applied to identify strengths, weaknesses, opportunities, and threats in different models of modular battery integration, highlighting the technological and regulatory environments in which these systems are developed [1,17,23].

Data

The study draws on multiple sources of primary (empirical) and secondary data.

- Primary data include the results of the expert survey conducted in 2024 among 25 industry specialists from Ukraine and China.
- Secondary data consist of statistical reports, industry databases, and peer-reviewed publications. Quantitative indicators include:
  - energy consumption rates of diesel and electric buses,
  - battery capacities and lifespans,
  - infrastructure capital and operational expenditures,
  - emission metrics for diesel vs. electric fleets.

For China, data were collected from the China Association of Automobile Manufacturers (CAAM), Bloomberg NEF, industry white papers, and case descriptions of BYD's modular battery swapping operations [1,3,27].

For Ukraine, sources included official statistics from the State Statistics Service of Ukraine, the Ministry of Infrastructure, Autoenterprise market reports, and independent analytical publications [2,4,21,23].

The Chinese case study examines BYD's fully operational modular replacement system in public bus networks, assessing infrastructure integration, standardization measures, and operational efficiency. The Ukrainian case study focuses on Autoenterprise's domestic modular battery initiatives, technical and regulatory challenges, and the barriers to scaling within the current infrastructure and investment environment [1–4,21,27].

4. Results

At present, the situation with battery recharging of electric vehicles (EVs), especially with fast-express recharging, does not allow electric buses and electric trucks to be widely used in international and intercity (long-distance) traffic. Slow, inexpensive recharging is unacceptable here due to its long duration, while fast recharging often exceeds the expenditure of gasoline/diesel refueling of comparable internal combustion engine vehicles (ICEVs). According to Bloomberg NEF data [3], the expenditure on fast recharging of EVs can be up to 1.7 times higher than gasoline refueling in certain European markets such as the UK.

If an EV user charges their vehicle using private charging infrastructure during off-peak electricity tariff periods (e.g., at night), the total annual recharging expenditure can be significantly lower than fuel costs — potentially saving up to €1,000 per year, whereas reliance on fast public charging could lead to an extra €1,200 annual expenditure. These figures are influenced by national electricity tariff policies, government incentives, and the density of high-speed charging infrastructure [1,3,13].

The SWOT analysis conducted in this study indicates that, despite clear environmental benefits, the weaknesses (limited range, high upfront costs, insufficient international infrastructure) and threats (technological lock-in, lack of harmonized standards) currently outweigh the opportunities for rapid deployment of electric buses in long-haul international transportation.

Steps for transition to international electric road transportation:

The following steps are structured based on a synthesis of literature sources [1,2,4,22] and expert survey results:

1. Assessment of demand and route:

1.1. Identification of key markets and high-demand international routes.

1.2. Competitor analysis, including service types and fleet composition.

2. Licensing and regulation:

2.1. Obtaining international passenger transport licenses in accordance with multilateral treaties (e.g., Interbus Agreement), bilateral agreements, and national regulations.

2.2. Familiarization with the rules and technical standards. Of each country along the route, ensuring compliance before deployment.

3. Infrastructure and logistics:

3.1. Ensuring availability of vehicles capable of completing planned route segments within battery capacity limits.

3.2. Identification of charging and service points along the route, considering compatibility with modular battery swapping where available.

4. Insurance and security:

4.1. Arranging international insurance coverage for vehicles, cargo and passengers.

4.2. Establishing continuous monitoring systems for safety and fleet management.

5. Human resources:

5.1. Employing drivers with proven international transportation experience.

5.2. Providing staff training on international driving norms, EV-specific maintenance, and emergency protocols.

Key barriers identified

Based on comparative and case study analyses [1,2,4,21], the main reasons for the limited deployment of electric buses in international routes include:

1. Limited range:

1.1. Most modern electric buses have a range of 150–350 km per charge, making them unsuitable for many long-haul operations without frequent stops.

2. Insufficient charging/swapping infrastructure:

2.1. Lack of developed infrastructure on international routes.

2.2. Absence of standardized charging or battery-swapping interfaces across borders.

3. High capital costs:

3.1. Electric buses are 1.5–2 times more expensive than their diesel counterparts

3.2. High investment required for compatible infrastructure.

4. Technological limitations:

4.1. Battery energy density remains insufficient for long-distance routes without operational compromise.

4.2. Long charging times disrupt schedules.

5. Economic feasibility:

5.1. Diesel buses remain more cost-effective for operators due to their reliability and longer range.

5.2. The benefits of using electric buses may be less obvious in the short term.

6. Environmental and policy framework gaps:

6.1. Lack of harmonized cross-border environmental policies that would mandate zero-emission fleets.

Although electric buses have great potential, there are a number of reasons why they have not yet become the mainstream choice for international transportation. Improvements in battery technology, the development of recharging infrastructure, and the introduction of stricter environmental standards could accelerate the transition to electric buses in the future.

Case example: Kyiv–Cologne route

The Kyiv–Cologne corridor (approximately 1,800 –1,900 km) is among the busiest international bus routes linking Ukraine's capital with Germany's major economic center. It is operated by established carriers such as FlixBus, Ecolines, and EuroClub, whose primary objective is to provide safe and comfortable long-haul passenger services.

The route typically includes intermediate stops in Lviv (Ukraine), Przemy śl, Krak ów, Wroc ław (Poland), as well as Berlin, and Dortmund (Germany). These stops serve for passenger rest, driver changeovers, technical inspections, and refueling at purpose-built bus service stations.

The operational cost structure of the diesel bus service is dominated by fuel expenditures. With an average diesel consumption of 30 L/100 km, a one-way trip requires ~540 L of diesel. At an average European diesel price of €1.50–€1.80/L [22], this equals €810‒€972 in fuel costs. Additional expenditures include driver wages (factoring in mandatory rest periods under EU Regulation (EC) No 561/2006), vehicle maintenance, motorway tolls (e.g., in Poland and Germany), insurance, and administrative overhead.

These bring the total operational cost per one-way trip to approximately €1,000‒€1,500, depending on route specifics, seasonal fuel price fluctuations, and toll tariffs.

From an environmental perspective, long-haul diesel buses contribute significantly to greenhouse gas emissions. With an average emission factor of 2.68 kg CO_2 per liter of diesel [23], a one-way trip emits approximately 1,447 kg CO_2, alongside nitrogen oxides (NOx) and particulate matter. In contrast, electric buses eliminate tailpipe emissions during operation, which can reduce total CO_2 emissions by up to 70–80% when powered from decarbonized grids [8]. However, for long routes such as Kyiv–Cologne, deployment is constrained by range limitations, insufficient high-power charging stations along the corridor, and the absence of cross-border standardization in battery-swapping infrastructure. The internal structure of an electric bus differs from a conventional diesel bus mainly due to the presence of an electric motor and high-capacity traction batteries. **Figure 1** illustrates the typical technical layout of the main components of a modern electric bus, intended primarily for urban and suburban passenger services (operational radius up to 50 km). While such vehicles are not configured for long-haul routes like Kyiv–Cologne—mainly due to their seating arrangement and interior design—the illustration is provided here to demonstrate the general placement and integration of key systems in contemporary electric buses (**Figure 1**):

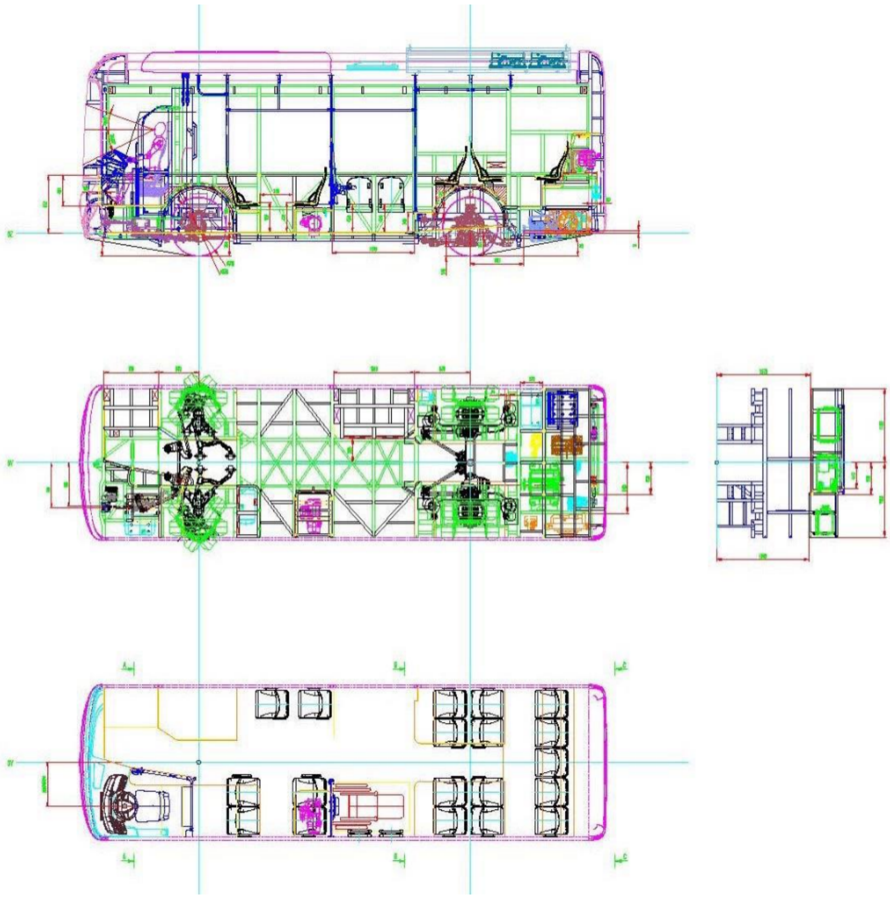

Figure 1. Modern technical structure of an electric bus.

Main components of an electric bus (as illustrated in **Figure 1**):

- Batteries (highlighted in *blue* in **Figure 1**) — store the electrical energy required for propulsion. Depending on the model, they may be located on the roof, under the floor, or at the rear. Capacity ranges from several tens to several hundred kilowatt-hours, enabling anything from short urban trips to limited intercity operations [8,9,18].
- Electric motor (*red*) — converts electrical energy from the batteries into mechanical energy to drive the vehicle. Compared with internal combustion engines, electric motors are quieter, more efficient, and produce zero emissions at the point of use.
- Energy management system (EMS) (*orange*) — controls battery charge and discharge cycles, optimizes power delivery to the motor, and integrates regenerative braking systems to recover energy during deceleration.
- Passenger compartment (*light grey*) — similar in layout to that of a diesel bus but quieter, improving comfort. Includes seating, standing areas, accessible spaces, and climate control systems.
- Information systems (*green*) — onboard displays and audio announcements provide passengers with stop and route information.

– Charging port (*yellow*) — interface for connecting the bus to depot chargers or high-power public charging stations. Depending on the battery capacity and charger rating, full charging can take from under an hour (DC fast charging) to several hours (AC charging).

The main challenge in using electric buses for long-distance routes is their limited range. Modern electric buses typically operate between 200 and 400 km on a single charge, which is far below the 1,800 km required for the Kyiv–Cologne route. As a result, multiple recharging stops would be needed during the journey.

Charging time ranges from 1 to 4 hours depending on charger power and battery capacity. Ensuring the availability of a sufficient number of high-power charging stations along the route is essential for reliable operation. A lack of such infrastructure, or insufficient coverage, would cause significant delays in the timetable — unacceptable for commercial passenger transport. Extended charging times can also affect passenger comfort by increasing total travel duration.

Although the Kyiv–Cologne route presents clear environmental benefits if operated by electric buses, its practical implementation would require significant investment in charging infrastructure and careful route planning that accounts for charging time. At the current stage of technology development, electric buses cannot yet replace diesel buses for long distances without affecting the schedule reliability and passenger comfort.

One promising solution is the adoption of a modular battery replacement system. This technology allows you to quickly replace discharged batteries with fully charged ones, reducing downtime to 10–15 minutes — comparable to diesel refueling without queuing.

The modular principle involves the use of standard replaceable batteries that can be easily removed and inserted into dedicated compartments in the electric bus. At specially equipped stations, charged batteries are stored and ready for installation. Upon arrival, the discharged battery is quickly removed and replaced with a charged one, eliminating long charging times and significantly increasing operational efficiency over long distances.

The main advantage of modular battery replacement is the ability to ensure the continuous operation of electric buses without significant delays in the schedule. This helps to maintain passenger comfort and the competitiveness of electric vehicles compared to diesel buses. However, to implement this system, it is necessary to create a developed infrastructure of specialized stations for replacing batteries along the route. This requires significant investment and coordination between transport operators, bus manufacturers, and energy providers. The modular principle of replacing electric batteries can be an effective solution for the introduction of electric buses both on the Kyiv-Cologne route and for the entire system of electric intercity and international road transportation. This technology reduces the downtime of electric buses to a minimum and ensures uninterrupted long-distance transportation. Despite the significant initial investment in infrastructure, the long-term benefits, including reduced greenhouse gas emissions and improved environmental performance, can make this approach profitable and promising.

A related innovation is the modular-sectional design of battery packs for electric vehicles of all types — passenger cars, buses, and trucks. In this system, batteries are produced as standard modules of approximately 50–60 kWh each, which can be combined into blocks of one, two, three, or more modules depending on the vehicle's energy needs. Each module has a standard size and connection interface, enabling quick and easy replacement during operation. Passenger cars may use a single module (or even a 30 kWh "half" module for small city cars), while buses and trucks may require two or more modules. This flexibility allows operators to configure vehicles according to specific operational requirements. The principle is analogous to the standardized AA, AAA, C, or D batteries used in consumer electronics such as remote controls, tuners, or air conditioners (**Figure 2**). While these batteries may vary by brand, capacity, or chemistry, their size and connection remain the same. This allows any device designed for a given battery size to use products from different manufacturers without modification. Applying the same approach to electric vehicle batteries would eliminate reliance on vehicle-specific charging solutions, reduce the need for high-cost fast charging, and shorten "refueling" time to the few minutes needed for a battery swap.

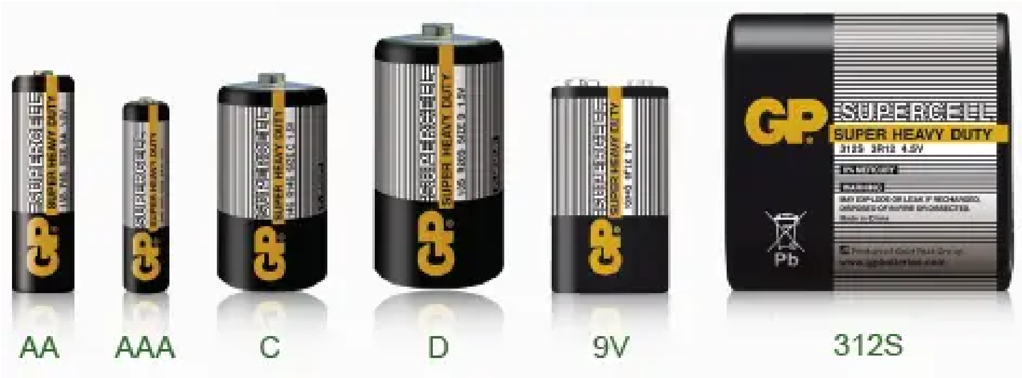

Figure 2. Utilizing a similar module-sectional principle for consumer and electric vehicle battery production, operation and replacement.

The standardized module size (approximately 50–60 kWh per section) would be determined at the design and manufacturing stage for all electric vehicles without exception. Smaller variants (e.g., 30 kWh "half" modules) could serve microcars or vehicles with low daily mileage, while larger vehicles could combine multiple modules:

- Passenger cars – 1 module (60 kWh) for typical range needs.
- All-wheel-drive cars and SUVs (Sport Utility Vehicles) – 2 modules (120 kWh).
- Electric buses – 3–4 modules (180–240 kWh).
- Trucks – 5–7 modules (300–420 kWh).

An objective diagnostic system at each station would assess the health and remaining capacity of modules being replaced. If a damaged module is exchanged for a fully functional one, the cost difference would be based on restoration rather than full replacement.

Stations could also incorporate battery refurbishment capabilities: replacing defective cells, rebalancing packs, and restoring capacity. Charging at such stations would occur mainly during off-peak hours, using slower and cheaper methods, thereby lowering operating costs. This would be particularly effective for long-haul and international routes, where consistent service reliability is crucial.

The process of replacing standardized battery modules, as illustrated in **Figure 2**, can be organized quickly and efficiently. At specialized stations, discharged modules are removed and replaced with fully charged ones in just 10–15 minutes—comparable to refueling a diesel bus without queuing. This rapid exchange minimizes downtime and ensures uninterrupted operation of electric vehicles in international, intercity, urban, and rural services.

To ensure transparency and efficiency, each station should be equipped with an instant diagnostic system capable of determining the residual capacity of every module at full charge. Payment for battery use could then be based on the remaining capacity, ensuring fair cost allocation between operators.

Modern EV battery design (**Figure 3**) allows replacement not only at the module level but also of individual components, thereby reducing repair costs and restoring the battery's rated capacity. In addition to replacing modules, specialized facilities could carry out maintenance and refurbishment, including defect diagnostics, cell replacement, module repackaging, and capacity restoration. Such a system would benefit not only electric buses but also electric cars, SUVs, and trucks, extending service life and improving cost efficiency.

To substantiate the choice of 60 kWh as the nominal capacity for a single modular battery section applicable to a wide range of electric vehicles—including international long-haul buses—we first analyze battery capacities of current mass-produced passenger EVs. This benchmark helps determine a realistic average capacity, considering technological competition, operational degradation, and seasonal (low-temperature) performance losses. According to open sources[10–16], battery capacities for popular electric vehicle models are as follows:

- Tesla Model 3: 50–82 kWh[10]
- Nissan Leaf: 40–62 kWh[11]
- Chevrolet Bolt EV: 66 kWh[12]
- Hyundai Kona Electric: 64 kWh[13]
- BMW i3: 42.2 kWh[14]
- Audi e-tron: 71–95 kWh[15]

– Volkswagen ID.3: 45–77 kWh[16]

To determine the average capacity, we take the average of the capacities for each model and then find the overall average capacity:

– Tesla Model 3: (50 + 82) / 2 = 66 kWh
– Nissan Leaf: (40 + 62) / 2 = 51 kWh
– Chevrolet Bolt EV: 66 kWh
– Hyundai Kona Electric: 64 kWh
– BMW i3: 42.2 kWh
– Audi e-tron: (71 + 95) / 2 = 83 kWh
– Volkswagen ID.3: (45 + 77) / 2 = 61 kWh

Total average capacity:

$$\text{Averagecapacity} = \frac{66+51+66+64+42{,}2+83+61}{7} \approx 61{,}6\text{kWh}$$

Given the competitive environment, manufacturers are striving to increase battery capacity to increase the range on a single charge. However, over time, battery capacity decreases due to ageing, charging and discharging cycles, and exposure to low temperatures in winter.

Figure 3. Modular lithium-ion battery architecture applicable to international electric buses.

Typically, capacity loss can be up to 20–40% over 5–8 years of operation. With this in mind, 60 kWh for a single modular section is a reasonable value that takes into account the decline in performance over time.

One 60 kWh modular battery pack is versatile and can be used in different types of vehicles:

✓ **Passenger cars:** one module (60 kWh) will provide an acceptable range for most small city models.
✓ **All-wheel drive passenger cars, Jeep, SUVs**: two modules (120 kWh).
✓ **Electric buses:** three to four modules (180–240 kWh) to ensure efficient operation on urban routes.

✓ **Trucks:** five to seven modules (120–180 kWh) to ensure sufficient range and load capacity.

The number of lithium-ion batteries required for vehicles such as passenger cars, SUVs, electric buses and trucks depends on the specific requirements for battery capacity, voltage, and battery pack design. This is usually measured not by the number of individual batteries, but by the total capacity of the battery pack. This is how it works (**Figure 4**):

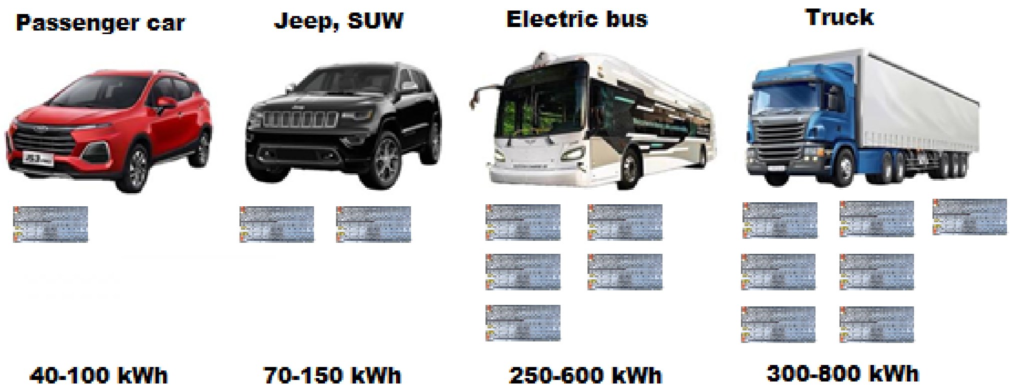

Figure 4. Approximate number of lithium-ion modular sectional batteries required for different types of electric vehicles.

Data are compiled from manufacturer specifications and technical reviews[8–16,18–20].

1. **Passenger car** (e.g., Tesla Model S[10], Nissan Leaf[11]):
   - ✓ Battery capacity: 40 to 100 kWh.
   - ✓ Number of battery cells: Passenger electric vehicles typically have 4,000 to 7,000 18650 lithium-ion cells (as in the Tesla Model S). These are individual small batteries assembled in modules.
   - ✓ Battery pack: Contains several modules, each consisting of hundreds of battery cells.
2. **Jeep and SUV** (e.g., Audi e-tron[15], Hyundai Kona Electric[13]):
   - ✓ Battery capacity: From 70 to 150 kWh (depending on the model).
   - ✓ Number of battery cells: Jeeps and SUVs need more battery capacity than passenger cars, so they can contain from 5,000 to 8,000 cells, or even more.
   - ✓ Battery pack: Consists of more modules to increase capacity and power.
3. **Electric bus** (e.g., BYD K9[8,20]):
   - ✓ Battery capacity: From 250 to 600 kWh.
   - ✓ Number of battery cells: Electric buses can have more than 20,000–30,000 cells, depending on the required capacity and battery pack design.
   - ✓ Battery pack: A large unit that can take up a significant amount of space in the floor or roof of the bus.
4. **Truck** (e.g., Tesla Semi[10], other heavy-duty EVs[19]):
   - ✓ Battery capacity: From 300 to 800 kWh (depending on size and purpose).
   - ✓ Number of battery cells: Trucks like the Tesla Semi can have 30,000 to 40,000 cells or even more.
   - ✓ Battery pack: A highly integrated unit that includes several large modules that provide significant range and power for heavy-duty vehicles.

The battery shown in **Figure 4** serves as a demonstration model and may differ from the actual configurations used in mass production. Both paired and stacked battery arrangements are possible, provided that dimensional parameters are strictly standardized. The number of lithium-ion cells in each vehicle category is measured in thousands, assembled into modules and blocks. Passenger cars and SUVs typically have smaller battery packs, whereas electric buses and trucks require significantly larger packs to meet higher power demands. The selection of the number of battery cells depends on the required energy capacity, vehicle weight, and operational purpose[10–16]. The optimal capacity of a single modular battery section — 60 kWh — is determined from the average capacity of modern EV batteries, considering market competition and real-world factors such as capacity degradation over time and performance loss in winter conditions[10–16,18]. This modular system allows easy adjustment of the number of sections to match the needs of different vehicle types, ensuring both flexibility and operational efficiency. The modular principle of battery production and operation offers significant advantages for EV development. It combines flexibility, fast servicing, and cost-effectiveness, reducing downtime and improving environmental performance. Investment in infrastructure for rapid battery replacement, diagnostics, and refurbishment can substantially increase the attractiveness of EVs for both commercial operators and private users[1,19,20,27].

Transitioning to modular battery pack production represents a strategic task for manufacturers. Standardization of battery modules enables broad cross-compatibility and supports adoption across various vehicle classes — from passenger cars to heavy trucks and electric buses.

1. **Universality and Standardization:**
   - The use of standardized module section sizes simplifies battery production and maintenance.
   - The same design allows integration into various vehicles: cars (one module), trucks (two or three), electric buses (three or four).
2. **Convenience and Speed of Replacement:**
   - Modular construction allows discharged batteries to be replaced with charged ones in just 10–15 minutes, minimizing downtime.
   - Replacements are carried out at specialized stations along operational routes.
3. **Cost-effectiveness and Flexibility:**
   - Standardized mass-produced modules reduce production and servicing costs. Fleet operators can adjust the number of modules according to route needs, optimizing resource use and lowering expenses.

Challenges for implementation:

1. **Development of Standards**:
   - Joint industry efforts are required to define common dimensions, connectors, and interfaces to ensure cross-brand compatibility.
2. **Infrastructure Deployment:**
   - Specialized replacement stations must be strategically located along main corridors to ensure operational reliability.
   - Stations should be strategically located along major routes to ensure user convenience and minimize downtime.
3. **Diagnostics and Refurbishment Systems:**
   Real-time battery health assessment will facilitate transparent billing and long-term sustainability through repair and recovery rather than full replacement[1,19,20,27]. The transition to standardized modular battery sections will enhance the flexibility and efficiency of electric transport, improve service speed, and reduce overall life-cycle costs.

To estimate the cost-effectiveness of implementing such a modular system on the Kyiv–Cologne international route, the following input parameters were considered based on information sources[1,10,13,15,19] and the author's calculations):

1. Route distance: approximately 1700 km.
2. Average electricity consumption for an electric bus: 1.2 kWh per km.
3. Electricity price: €0.15 per kWh.
4. Capacity of one battery section: 60 kWh.
5. Number of battery sections per bus: 4 sections (total capacity = 240 kWh).
6. Average range per full charge: 240 km.
7. Replacement time per set: 15 minutes.
8. Required replacements per trip: 7 replacements.
9. Average diesel price: €1.50/L.
10. Average diesel consumption: 30 L/100 km.

Calculation of operating costs for an electric bus.

The electricity cost of completing the entire Kyiv–Cologne route is calculated as follows:

$$Total\ electricity\ consumption\ = 1700\ km * 1,2\text{кВт} \cdot \frac{h}{km} = 2040\text{к}\ kWh$$

$$Electricity\ cost = \frac{2040kWh}{h} * \frac{\frac{€0,15}{W}}{h} = \text{€}306$$

The cost of replacing battery sections:

It is assumed that the replacement cost is €10 per swap, which includes maintenance and operational expenses of the replacement stations.

Section replacement cost = 7*€10 = €70

Total cost of the electric bus:

Total cost = €306 + €70 = €376

Cost of diesel fuel for the entire route:

$$Total\ diesel\ consumption = \frac{1700km}{100} * \frac{30l}{100km} = 510l$$

$$Cost\ of\ diesel\ fuel = 510l * \frac{€1,5}{l} = €765$$

Cost comparison and potential savings for an electric bus:

$$\text{Savings} = €765–€376 = €389$$

Additional factors:

1. **Reduced CO_2 Emissions:** Replacing diesel buses with electric buses can substantially lower greenhouse gas emissions. Given that the combustion of one litre of diesel fuel produces approximately 2.68 kg of CO_2 [6], the total CO_2 savings for the Kyiv–Cologne route can be calculated as follows:

$$510l * 2,68kg\frac{CO_2}{l} = 1366,8\ kg\ CO_2$$

2. **Cost of Maintenance:** Electric buses generally have lower maintenance costs than diesel buses due to fewer moving parts, the absence of oil changes, and reduced brake wear from regenerative braking systems [20]. For example, according to the International Transport Forum, maintenance expenditures for electric buses can be 20–30% lower compared to equivalent diesel models.
3. **Infrastructure Costs**: Implementation of stations for rapid replacement of modular sections requires significant initial investment. However, in the long term, these expenditures can be offset by reduced operating costs, particularly due to lower energy prices, reduced maintenance needs, and higher operational efficiency.

For this calculation, we intentionally omit the purchase cost difference between a diesel international bus and an electric bus, assuming that in the near future, the cost of electric buses will converge with that of internal combustion engine (ICE) buses. The global trend of decreasing EV prices supports this assumption [1]. Historically, mass production and economies of scale in the EV industry have led to progressive cost reductions [20]. We also do not account for the cost of consumables (e.g., lubricants, antifreeze, brake and transmission fluids), as these are clearly higher for ICE vehicles. Likewise, maintenance costs are generally lower for EVs due to fewer moving parts and reduced mechanical wear [20]. Finally, the monetary value of the primary advantage of electric buses—the environmental benefit—is not fully factored into the calculation. Unlike ICE buses, electric buses produce no tailpipe emissions, thus eliminating direct emissions of CO_2, NO_x, and particulate matter during operation [6].

5. Conclusions

The automotive industry and vehicle markets are undergoing rapid transformation. Among the new propulsion principles, electric drivetrains for buses, cars, and trucks stand out as the most environmentally friendly and promising solutions. Many automotive manufacturers worldwide already produce electric vehicles, including electric buses. China is currently leading in this field, actively applying the modular principle of producing and operating standardized batteries, which enables rapid battery replacement for electric buses and other EVs. Thanks to large-scale implementation and control over the supply chain, China is effectively setting "de facto" standards that other markets may eventually be compelled to adopt if they fail to develop their own alternatives.

The analysis in this study demonstrates that applying the modular unified battery replacement system in international passenger transport is both technically and economically feasible. For the Kyiv–Cologne route, the total operating cost of an electric bus (€376) is significantly lower than that of a diesel bus (€765), resulting in savings of €389 per trip. Additionally, each trip by an electric bus reduces CO_2 emissions by approximately 1,366.8 kg, contributing directly to improved air quality and environmental sustainability.

The modular sectional battery system offers universality, flexibility, and operational efficiency. Standardized module sections allow for battery replacement in 10–15 minutes—comparable to diesel refueling—thus minimizing downtime and maintaining service schedules. Such a system is applicable across all types of electric vehicles, from passenger cars to heavy-duty trucks, and can be supported by a network of strategically located replacement stations along major international routes. Implementing this approach requires initial investment in infrastructure and the establishment of instant diagnostic and repair systems to ensure battery reliability and long service life. However, the long-term benefits—including lower operating costs, reduced dependence on fossil fuels, higher vehicle efficiency, and a smaller carbon footprint—outweigh the initial expenses. As battery technology advances, capacities will increase, charging costs will decline, and the range per charge will extend, further enhancing the competitiveness of electric buses.

In summary, the transition to electric buses with modular sectional battery systems for international routes such as Kyiv–Cologne is a promising direction for the transport sector. It offers clear economic and environmental advantages, supports sustainable development, and has the potential to make electric buses a primary mode of long-distance passenger transport in the near future, providing both efficiency and comfort for passengers.

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