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Electric Vehicles as Integrated Energy, Mobility and Digital Systems: A Critical Review of Technologies, Infrastructure and Emerging Trends

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Abstract: Electric vehicles (EVs) are transitioning from stand-alone propulsion products into integrated mobility, energy and digital platforms. This review critically examines the technological foundations and emerging trajectories of battery-electric, hybrid, plug-in hybrid and fuel-cell vehicles, with emphasis on traction batteries, electric machines, power electronics, thermal management, charging infrastructure, grid interaction, connected control, lifecycle sustainability and policy constraints. Global electric-car sales exceeded 17 million in 2024, representing more than one-fifth of new-car sales, but adoption remains geographically uneven and is increasingly limited by charging access, affordability, grid capacity and supply-chain resilience rather than by propulsion feasibility alone. Lithium iron phosphate and nickel-rich layered oxides currently dominate battery-electric vehicles through different cost-energy-safety trade-offs, while sodium-ion and solid-state systems target specific future niches. Fast charging is shifting toward higher-voltage vehicle architectures and higher-power stations, although charging speed remains constrained by lithium plating, heat generation, cell imbalance and local grid demand. Battery-management and thermal-management systems are becoming predictive, cloud-connected and data-driven, but require robust validation, cybersecurity and standardised state-of-health metrics. Smart charging and bidirectional vehicle-to-grid operation can provide grid flexibility, yet battery degradation, interoperability, market rules and user participation remain unresolved. Lifecycle assessment indicates that EV climate benefits depend on electricity mix, vehicle size, battery production and lifetime utilisation; therefore, material efficiency, renewable charging, second-life use and high-yield recycling are essential. The review proposes a co-design framework linking vehicle efficiency, battery durability, charging convenience, grid services and circularity. Future progress will depend on scalable low-cost chemistries, interoperable charging standards, low-carbon manufacturing, safer automation and policy mechanisms that make electrification accessible beyond premium passenger cars.

Keywords: Battery Management, Charging Infrastructure, Electric Vehicle, Lifecycle Assessment, Power Electronics, Smart Charging, Vehicle-To-Grid.

1. Introduction

Road transport electrification is a central element of strategies to reduce petroleum dependence, urban air pollution and greenhouse-gas emissions. Conventional internal-combustion-engine vehicles convert only a minority of fuel energy into useful wheel work and produce local nitrogen oxides, hydrocarbons, carbon monoxide and particulate emissions. Electric drivetrains avoid tailpipe emissions in battery-electric operation and can achieve high tank-to-wheel efficiency through efficient motors, regenerative braking and simplified transmissions [1-4].

The market has moved beyond an early-adopter phase. According to the International Energy Agency, global electric-car sales surpassed 17 million in 2024 and accounted for more than 20% of all new-car sales [5]. The next stage is more demanding: adoption must expand into lower-cost cars, buses, trucks, two- and three-wheelers, high-mileage fleets and regions with weak charging infrastructure. Consequently, EV research is shifting from isolated component improvement toward system optimisation across vehicles, charging networks, electricity grids, manufacturing and material recovery.

An EV is not merely an internal-combustion vehicle with a motor substituted for the engine. Battery voltage, cell chemistry, cooling architecture, inverter switching, motor topology, vehicle mass, aerodynamic drag, software control and charging behaviour interact. A higher-energy battery can increase range but also mass, cost, embodied emissions and thermal-management burden.

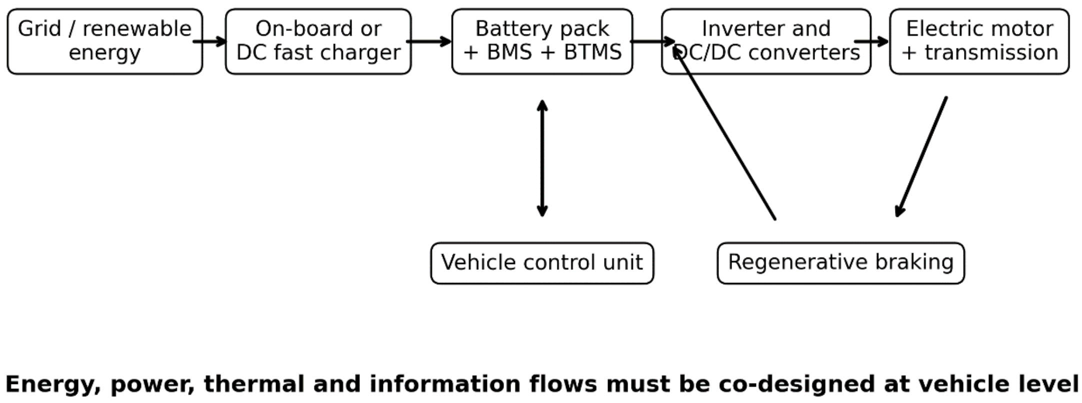

Figure 1. Functional architecture of a modern battery-electric vehicle and its principal energy, power and control interfaces.

Ultra-fast charging improves convenience but can accelerate degradation and impose large grid peaks. Vehicle-to-grid operation can support the power system but introduces cycling, communication and market complexities [6-10].

The source manuscript provided a brief descriptive overview of EV evolution and trends but did not establish a review method, compare competing technologies, quantify trade-offs, or connect vehicle advances with grid and lifecycle constraints. This revised article therefore adopts a critical systems perspective. It addresses vehicle taxonomy and architecture, batteries and management, power electronics and motors, charging, grid integration, thermal and safety engineering, digitalisation, materials, lifecycle sustainability, policy, and research priorities.

2. Review Methodology and Scope

The review synthesised peer-reviewed journal articles, international standards, government and intergovernmental reports, and authoritative technical books. Priority was given to literature published from 2020 onward, while foundational studies were retained for electric-drive theory, vehicle taxonomy and charging concepts. Search themes included electric-vehicle architecture, lithium-ion battery chemistry, battery management, fast charging, battery thermal management, power electronics, traction motors, smart charging, vehicle-to-grid integration, lifecycle assessment, battery recycling and cybersecurity.

The literature was organised into ten domains: market transition; vehicle architecture; energy storage; battery management and thermal control; motors and converters; charging; grid integration; connectivity and automation; lifecycle sustainability; and policy and deployment. Quantitative values were compared only when measurement boundaries were consistent.

For example, cell-level energy density was not treated as equivalent to pack-level energy density, and tailpipe emissions were distinguished from lifecycle emissions.

The review is technology-focused rather than brand-focused. Commercial examples are discussed only where they illustrate an engineering trend such as 800-V architecture, cell-to-pack integration, bidirectional charging or battery swapping. The aim is to identify transferable design principles and unresolved constraints rather than rank current vehicle models.

3. Evolution, Classification and Scope of Electrified Vehicles

3.1 Historical Evolution

Electric propulsion predates the modern gasoline automobile, but early EVs were displaced by the high specific energy, rapid refuelling and mature distribution system of liquid fuels. Renewed interest emerged after oil-price shocks and air-quality regulation, while the commercial turning point came from lithium-ion batteries, high-performance permanent-magnet motors, modern power electronics and digitally controlled battery packs [2, 3].

The present transition differs from previous EV cycles because it is supported simultaneously by climate policy, industrial investment, falling battery cost, consumer experience, renewable electricity and software-defined vehicle platforms. Nonetheless, market growth remains sensitive to incentives, interest rates, model availability and public charging reliability [5].

3.2 Vehicle Classes

Hybrid electric vehicles (HEVs) combine an engine with one or more motors and a small battery that is charged internally. Plug-in hybrid electric vehicles (PHEVs) use a larger externally chargeable battery and can perform a portion of travel electrically. Battery-electric vehicles (BEVs) rely entirely on stored electricity, whereas fuel-cell electric vehicles (FCEVs) convert hydrogen electrochemically and use a smaller battery for transients and regenerative braking [1-4].

Each architecture occupies a different infrastructure and duty-cycle niche. BEVs are highly efficient and increasingly suitable for passenger cars, urban buses and delivery fleets. PHEVs can reduce fuel use when charged frequently but may deliver limited real-world benefit when operated predominantly as combustion vehicles. FCEVs offer rapid refuelling and potentially long range, but hydrogen production, distribution, efficiency and cost remain major barriers.

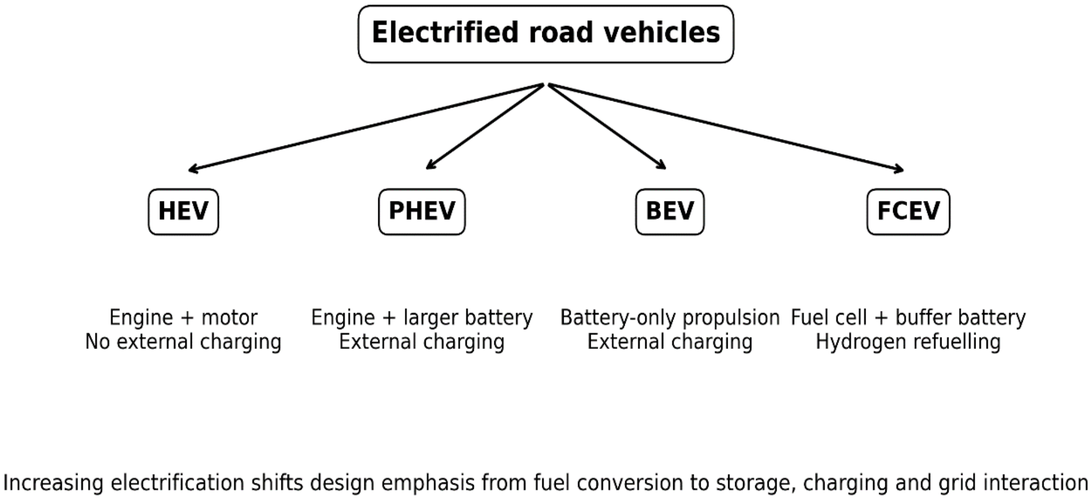

Figure 2. Classification of electrified road-vehicle powertrains and their principal energy pathways.

3.3 Expanding Application Scope

Electrification now extends beyond passenger cars to two-wheelers, three-wheelers, buses, light commercial vehicles, mining trucks, airport equipment, agricultural machinery and off-road vehicles. Urban fleets benefit from predictable routes and depot charging. Heavy long-haul trucks present a more difficult mass-range-charging problem, stimulating research on megawatt charging, battery swapping, dynamic charging and hydrogen fuel cells [5, 11].

In many emerging economies, electric two- and three-wheelers may deliver greater near-term fuel and air-quality benefits than large passenger EVs because of high vehicle utilisation, lower battery capacity and easier charging. Policy and research agendas should therefore avoid equating electrification exclusively with private cars.

Table 1. Comparative scope of major electrified-vehicle architectures

Vehicle type	Primary energy source	Main strengths	Principal limitations	Best-fit use
HEV	Liquid fuel + small battery	No charging dependence; improved urban efficiency	Continued fuel use and tailpipe emissions	Mixed-duty passenger vehicles
PHEV	Grid electricity + liquid fuel	Electric commuting with long-trip flexibility	Complexity; benefit depends on charging behaviour	Users with regular charging and occasional long trips
BEV	Grid-charged battery	Highest drivetrain efficiency; zero tailpipe emissions	Charging time, battery mass and infrastructure	Cars, buses, delivery fleets, two-wheelers
FCEV	Hydrogen + buffer battery	Fast refuelling; potentially long range	Low system efficiency, cost and sparse hydrogen network	Selected heavy-duty or high-utilisation niches
Battery swapping EV	Exchangeable battery	Very short downtime; battery can be centrally managed	Standardisation, ownership and station-capital challenges	Two-wheelers, taxis and fleet operations

4. Vehicle Architecture and Energy Management

4.1 High-Voltage Electrical Architecture

A BEV powertrain contains a traction battery, battery-management system (BMS), contactors and protection, traction inverter, motor, reduction gear, DC/DC converter, on-board charger, low-voltage network and vehicle-control unit. Many high-performance platforms are moving from nominal 400-V systems toward approximately 800 V. For a given power, higher voltage reduces current and resistive loss, enabling smaller conductors and higher charging power, but it increases insulation, switching-device and safety requirements.

Silicon-carbide MOSFETs permit higher switching frequency, lower conduction loss and higher junction temperature than conventional silicon devices. Their cost is partly offset by efficiency, cooling and component-size benefits. Gallium-nitride devices are emerging in lower- and medium-power converters and chargers [12-14].

4.2 Energy-Management Control

Energy-management systems coordinate driver demand, motor efficiency, regenerative braking, battery limits, thermal conditions and auxiliary loads. Rule-based control remains common because it is transparent and certifiable, while model-predictive control can optimise energy over a route horizon. Data-driven and reinforcement-learning approaches may adapt to traffic and driver behaviour, but safety constraints, reproducibility and computational validation remain open issues [15].

For HEVs and PHEVs, energy management also divides power between engine and electric paths. For BEVs, the central problem is not power-source split but minimising energy consumption and degradation while meeting drivability and thermal constraints.

5. Traction Batteries: Chemistry, Pack Design and Emerging Alternatives

5.1 Lithium-Ion Chemistries

Lithium-ion batteries dominate current BEVs because they combine high specific energy, high round-trip efficiency and mature manufacturing. Nickel-manganese-cobalt (NMC) and nickel-cobalt-aluminium (NCA) chemistries offer high energy density but require careful thermal control and use nickel and cobalt. Lithium iron phosphate (LFP) provides strong thermal stability, long cycle life and lower material cost at the expense of lower specific energy and reduced cold-temperature performance [16-18].

The resurgence of LFP demonstrates that cell chemistry selection is application-specific. High-energy nickel-rich cells remain valuable for long-range vehicles where mass and packaging are critical, while LFP is attractive for standard-range cars, buses and stationary-compatible fleets.

Manganese-rich, cobalt-lean and lithium-manganese-iron-phosphate variants seek intermediate performance.

5.2 Cell-To-Pack and Structural Integration

Traditional packs use cells, modules and a pack enclosure. Cell-to-pack architectures reduce inactive module hardware and improve volumetric utilisation. Structural packs integrate the battery enclosure with the vehicle body, potentially reducing mass and increasing torsional stiffness. These designs complicate crash repair, cell replacement, thermal propagation barriers and recycling disassembly. Pack design must balance energy density with crash protection, serviceability and thermal isolation. Maximising volumetric occupancy without propagation-resistant spacing can increase the severity of a single-cell failure.

5.3 Sodium-Ion Batteries

Sodium-ion batteries use abundant sodium and can reduce dependence on lithium, nickel and cobalt. Their lower cell voltage and heavier sodium ion generally limit specific energy relative to leading lithium-ion systems, but they offer attractive low-temperature behaviour, safety and potential cost resilience. Techno-economic assessment indicates that competitiveness depends on achieving manufacturing scale and on future lithium-ion mineral prices [19].

The most plausible near-term applications are short-range vehicles, two-wheelers, low-cost urban cars and stationary storage, where cost and supply-chain diversity can outweigh energy-density penalties.

5.4 Solid-State and Lithium-Metal Batteries

Solid-state batteries replace flammable liquid electrolyte with a solid electrolyte and may enable lithium-metal anodes. Their theoretical advantages include higher energy density and improved abuse tolerance, but interface resistance, dendrite penetration, pressure requirements, manufacturing yield and low-temperature operation remain substantial challenges [20, 21].

Solid-state should not be described as a single mature technology. Sulfide, oxide, polymer and halide electrolytes have distinct conductivity, processability and stability profiles. Early automotive deployment is likely to be limited to premium or low-volume segments before broad cost parity.

5.5 Battery Selection as A Multi-Objective Problem

Battery selection should minimise total vehicle and lifecycle cost rather than maximise a single cell metric. Pack-level energy density, charge acceptance, thermal-management load, warranty life, material availability, recycling value and climate performance must be considered together. An apparently lower-energy chemistry can enable a better vehicle if it supports frequent fast charging, longer life or lower cost.

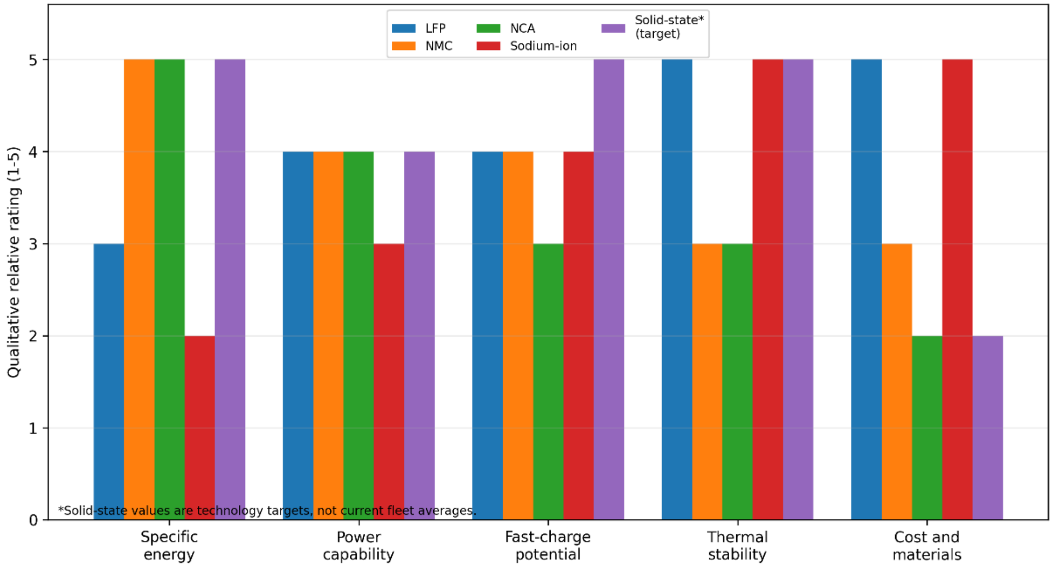

Figure 3. Qualitative battery-chemistry trade-offs for electric-vehicle applications. Ratings are comparative design guidance, not universal measured values.

6. Battery Management, Diagnostics and Thermal Control

6.1 State Estimation

The BMS estimates state of charge (SOC), state of health (SOH), available power and internal temperature from voltage, current and temperature measurements. Coulomb counting is simple but drifts; open-circuit-voltage methods require rest; equivalent-circuit models combined with Kalman filtering provide real-time estimation; electrochemical models offer physical insight but higher computational cost. Machine-learning methods can exploit fleet data but may fail outside their training distribution [22-24].

A major research need is standardised vehicle-level SOH measurement. Capacity, energy, resistance and power can degrade differently, and laboratory capacity tests are not easily applied to vehicles in use. Recent work has proposed onboard charging-based procedures and differential-voltage analysis to improve comparability [25].

6.2 Cell Balancing and Fault Diagnosis

Manufacturing and thermal variation cause cells to diverge over time. Passive balancing dissipates excess energy as heat, while active balancing transfers energy between cells or modules.

Active methods can improve usable capacity but add cost and control complexity. Fault diagnosis must detect sensor errors, internal short circuits, cooling failure, connector resistance and abnormal self-discharge before they escalate [23, 26].

Cloud-connected diagnostics can compare a vehicle against a fleet population and update degradation models. This capability introduces data governance, cybersecurity and over-the-air software assurance requirements.

6.3 Battery Thermal Management

Lithium-ion performance and ageing are strongly temperature dependent. Low temperature reduces power and can promote lithium plating during charging; high temperature accelerates side reactions and can trigger thermal runaway. Air cooling is simple but limited in heat-removal capacity. Liquid cooling offers better uniformity and is common in high-power packs. Phase-change materials, heat pipes, refrigerant direct cooling and hybrid systems are active research areas [27, 28].

Thermal management should be optimised at vehicle level. Aggressive cooling consumes auxiliary energy, whereas insufficient cooling reduces charging speed and life. Preconditioning the battery before fast charging can improve charge acceptance and reduce plating risk.

7. Electric Machines, Transmissions and Power Electronics

7.1 Traction Motors

Permanent-magnet synchronous motors provide high efficiency and power density but depend on rare-earth magnets. Induction motors avoid permanent magnets and offer robust high-speed operation, though rotor losses can reduce efficiency. Wound-field synchronous and externally excited machines reduce rare-earth dependence while retaining controllable flux. Switched-reluctance motors are magnet-free and tolerant of high temperature but face torque ripple, acoustic noise and control challenges [29-31].

No motor is universally superior. Vehicle duty cycle, peak torque, base speed, cooling, cost, noise and material risk determine the optimum. Dual-motor vehicles can operate one motor near its efficient region and disconnect or reduce excitation of the other.

7.2 Inverters and Converters

The traction inverter converts battery DC to controlled AC. Wide-bandgap devices improve efficiency especially at partial load and high switching frequency. Integrated motor-inverter designs reduce cable loss and volume but expose electronics to vibration and heat.

Bidirectional on-board chargers can share power-electronic components with the traction system, lowering component count while increasing functional integration.

Reliability of semiconductor modules, capacitors, busbars and solder or sintered joints is critical because thermal cycling and high current cause fatigue. Condition monitoring and physics-of-failure models are increasingly used for lifetime prediction.

7.3 Transmission and Regenerative Braking

Most BEVs use a single-speed reduction gear because electric motors provide broad torque-speed capability. Multi-speed transmissions can improve high-speed efficiency and gradeability for performance cars and heavy vehicles but add mass and control complexity. Regenerative braking recovers kinetic energy, although recovery is limited by battery charge acceptance, tyre adhesion, motor rating and brake-stability requirements.

Blended braking must provide consistent pedal feel while coordinating regenerative and friction braking. At high SOC, low temperature or low speed, friction brakes supply a larger fraction of deceleration, which can create corrosion and maintenance issues when mechanical brakes are used infrequently.

8. Charging Technologies and Infrastructure

8.1 Conductive Charging Levels

AC charging uses an on-board charger and is suitable for homes, workplaces and long dwell times. DC fast charging bypasses the on-board charger and supplies regulated DC to the pack. Charging power now ranges from a few kilowatts to several hundred kilowatts for passenger vehicles, while heavy-duty megawatt charging is under development [32-34].

Peak charger rating is not equivalent to sustained vehicle charge power. The charging curve is constrained by cell temperature, SOC, voltage limits, charger capability and station sharing. Time from 10% to 80% SOC is usually more meaningful than a maximum-power headline.

8.2 Fast-Charging Limitations

High-rate charging produces ohmic and reaction heat, concentration gradients and risk of lithium plating at the graphite anode. Advanced protocols adjust current in response to temperature, voltage and inferred internal states. High-silicon anodes, improved electrolytes, tabless electrodes and pack preconditioning can increase charge acceptance, but durability must be validated over realistic cycles [35, 36].

From an infrastructure perspective, a cluster of ultra-fast chargers can create a multi-megawatt load with low utilisation and high demand charges. Local battery storage, solar generation, dynamic power allocation and reservation systems can reduce grid reinforcement and improve charger utilisation.

8.3 Wireless and Dynamic Charging

Stationary inductive charging removes the need for manual connectors and is useful for taxis, autonomous vehicles and accessibility. Dynamic wireless charging can reduce onboard battery size on fixed routes, but installation cost, alignment, interoperability and road maintenance remain barriers [37]. Automated conductive charging may compete effectively with wireless systems in depots because it offers high efficiency and lower infrastructure complexity.

8.4 Battery Swapping

Battery swapping separates energy replenishment from charging time and allows centralised charging under controlled temperature and tariff conditions.

Table 2. Charging and energy-replenishment pathways

Charging route	Typical use	Advantages	Technical limitations
Residential AC	Overnight private charging	Low cost; high convenience; grid-friendly when managed	Limited for residents without parking; slow recovery
Workplace/public AC	Long dwell parking	Extends access and supports solar-aligned charging	Requires parking turnover and billing management
DC fast charging	Intercity and rapid top-up	Shorter stops and long-distance usability	High capital cost, grid peaks and battery stress
Megawatt charging	Heavy commercial vehicles	Enables high-energy route operation	Very high site power, thermal and connector demands
Wireless static	Taxis, buses, autonomous fleets	Automated and weather-protected	Lower efficiency, alignment and cost concerns
Battery swapping	Two-wheelers and high-utilisation fleets	Minutes-scale turnaround and central battery control	Standardisation, inventory and ownership complexity

It is particularly attractive for two-wheelers, three-wheelers, taxis and logistics fleets. Widespread passenger-car adoption requires standardised interfaces, battery ownership models, reliable health assessment and high station throughput.

A swap system can improve battery utilisation but may lock operators into proprietary formats. Interoperability and fair valuation of batteries with different SOH are central commercial challenges.

9. Grid Integration, Smart Charging and Vehicle-to-Grid

9.1 Grid Impacts of Unmanaged Charging

EV charging increases electricity demand but the energy requirement is often manageable at system level. Local distribution constraints can be more important than annual generation because vehicles may charge simultaneously after evening arrival. Transformer loading, voltage drop, phase imbalance and feeder congestion depend on spatial clustering and charger power [38, 39].

Time-of-use tariffs and managed charging can shift demand to low-load or high-renewable periods. Grid benefits require communication among vehicle, charger, aggregator and network operator, as well as consumer incentives that preserve mobility needs.

9.2 Bidirectional Services

Vehicle-to-home and vehicle-to-building systems provide backup power and demand management. Vehicle-to-grid (V2G) aggregates many vehicles to deliver frequency regulation, peak reduction or renewable balancing. Because vehicles are parked for much of the day, their connected capacity can be large even when energy availability is constrained [40-42].

The economic value of V2G depends on market access, communication cost, battery degradation, charger efficiency and user participation. Frequent shallow cycling may have modest degradation under controlled temperature, but high SOC residence and aggressive power can accelerate ageing. Warranty and compensation frameworks must reflect the actual incremental wear.

9.3 Interoperability and Cybersecurity

Smart charging relies on standards for connector communication, authentication, metering and grid commands. Interoperability failures can strand users or prevent grid services. Cyberattacks could manipulate charging loads, access personal mobility data or compromise vehicle control; therefore, secure hardware, certificate management, software updates and incident response are integral to charging design [43].

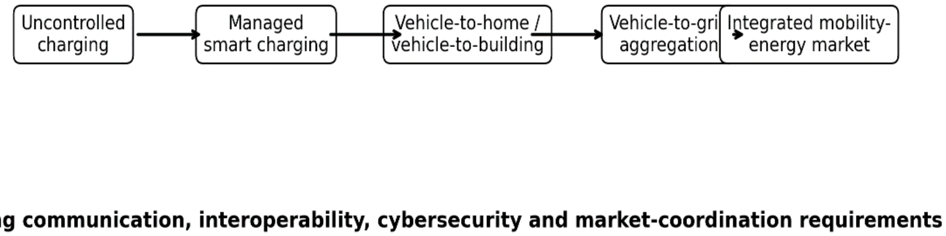

Figure 4. Progression from uncontrolled EV charging to coordinated mobility-energy integration.

10. Connected, Autonomous and Software-Defined EVs

EVs are increasingly software-defined. Centralised computing, zonal electrical architectures, over-the-air updates and cloud diagnostics allow functions to evolve after sale. Battery preconditioning, route-aware energy prediction and charger selection can reduce journey time. Digital twins can support fault diagnosis and remaining-life estimation.

Artificial intelligence is used for perception, energy prediction, thermal control and battery diagnostics. However, opaque models can be difficult to validate under rare conditions. Safety-critical functions require bounded behaviour, redundancy and traceable software processes.

Autonomous driving and electrification are complementary for shared fleets but not automatically energy-saving. Sensors and computers consume power, while cautious or inefficient automated driving can increase travel time. Conversely, smoother velocity planning and coordinated routing can reduce energy demand.

Cybersecurity is a lifecycle obligation. Vehicles may remain in service for 15 years or more, requiring secure updates after communication standards and threats evolve. Battery and charging data also reveal location and behaviour patterns, raising privacy concerns.

11. Lightweight Materials, Aerodynamics and Vehicle Efficiency

Reducing vehicle mass lowers acceleration and climbing energy, although regenerative braking recovers part of kinetic energy. Aluminium, advanced high-strength steel, magnesium and fibre-reinforced polymers can reduce mass, but material production, repairability and joining must be considered. Battery enclosure materials must provide crash resistance, fire containment, corrosion control and electromagnetic compatibility.

Aerodynamic drag dominates energy consumption at highway speed. Low drag coefficient, reduced frontal area, underbody smoothing, active grille control and efficient wheels can extend range without increasing battery size. Low-rolling-resistance tyres reduce energy use but must maintain wet grip, wear and noise performance.

Thermal comfort is another major auxiliary load. Heat pumps, seat heating, infrared panels and zonal climate control can reduce winter energy consumption compared with resistive cabin heating. Integrated thermal systems can transfer heat among battery, motor, electronics and cabin.

12. Safety, Reliability and Standards

12.1 Electrical and Crash Safety

High-voltage isolation, contactor control, insulation monitoring, service disconnects and automatic crash shutdown protect occupants and responders. Battery enclosures must resist intrusion and manage venting. Crashworthiness cannot be inferred from cell safety alone because mechanical deformation can create delayed internal shorts.

Charging connectors require thermal sensing, locking, ground-fault protection and communication. Higher charging current increases sensitivity to contact resistance and cooling failure.

12.2 Thermal Runaway and Propagation

Thermal runaway can be initiated by internal short circuit, overcharge, external heating or mechanical damage. The engineering objective is early detection, suppression of cell-to-cell propagation, controlled venting and sufficient evacuation time. Barriers, spacing, cooling plates, vent channels and gas sensors are used alongside BMS protection [44, 45].

A pack that prevents propagation may accept lower volumetric energy density. This is an example of why maximum energy density is not an adequate design objective.

12.3 Functional Safety and Charging Standards

Functional safety standards govern hazards caused by malfunctioning electrical and electronic systems, while cybersecurity standards address malicious interference. Charging standards define connectors, communication and electrical protection. Global fragmentation remains a barrier to scale, although major regions are converging around fewer fast-charging interfaces.

Standards must evolve with bidirectional charging, automated connection and megawatt systems. Conformance testing and field reliability are as important as nominal interoperability.

13. Lifecycle Sustainability, Critical Materials and Circularity

13.1 Lifecycle Greenhouse-Gas Performance

BEVs have zero tailpipe emissions, but manufacturing and electricity generation create upstream impacts. Battery production increases manufacturing emissions relative to a comparable combustion vehicle, while use-phase emissions depend on grid carbon intensity and efficiency. Most lifecycle studies find lower greenhouse-gas emissions for BEVs over their lifetime in regions with moderately decarbonised electricity, but the magnitude varies with battery size, vehicle lifetime and charging mix [46-48].

Large, heavy EVs consume more materials and energy than smaller EVs. Electrification should therefore be combined with vehicle right-sizing, public transport and efficient mobility rather than used to justify unlimited vehicle growth.

13.2 Mineral Supply and Responsible Sourcing

Lithium, nickel, cobalt, graphite, copper and rare-earth elements face different supply risks. Chemistry diversification, material thrift, alternative motor designs and recycling can reduce vulnerability. LFP lowers nickel and cobalt demand, while sodium-ion may reduce lithium dependence in suitable applications [18, 19].

Responsible sourcing requires traceability, reduced water and land impacts, worker protection and community engagement. Supply-chain resilience should not be assessed only by national availability or price.

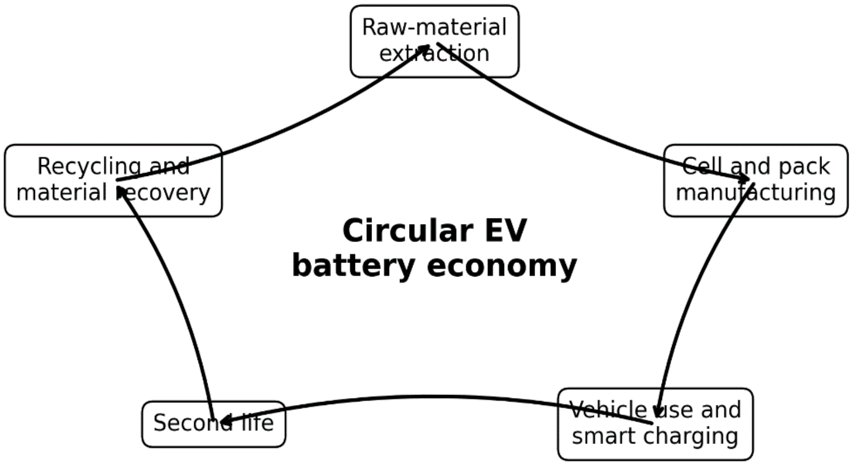

Figure 5. Circular lifecycle framework for electric-vehicle batteries.

13.3 Second Life and Recycling

Retired traction batteries may retain sufficient capacity for stationary storage. Second-life value depends on rapid SOH assessment, pack standardisation, remaining safety and repurposing cost. Direct reuse can defer recycling but should not compromise traceability or fire protection.

Recycling routes include pyrometallurgical, hydrometallurgical and direct-recycling processes. High recovery of lithium, nickel, cobalt, copper and graphite can reduce primary-material demand and manufacturing impacts. Design for disassembly, standardised labelling and digital battery passports can improve economics [49-51].

14. Economics, Policy and Social Deployment

EV purchase price is strongly influenced by battery cost, although total cost of ownership can be favourable because of lower energy and maintenance expenditure. The result depends on annual distance, electricity tariffs, depreciation, insurance and incentives. High-mileage fleets often reach parity earlier than low-use private cars.

Policy instruments include purchase incentives, fuel-economy or zero-emission-vehicle standards, charging investment, tax reform, public procurement and manufacturing support. Stable multi-year policy is more effective than abrupt incentive changes that create market volatility. Policy should also support used EVs, apartment charging and rural infrastructure to prevent electrification from becoming socially exclusive.

Public charging quality must be measured by uptime, accessibility, payment simplicity and actual delivered power, not only charger count. Planning should combine transport demand, land use, distribution-grid capacity and equitable access.

Workforce development is required for high-voltage service, battery repair, charging installation, emergency response and recycling. Independent repair access and affordable diagnostic tools affect lifecycle cost and consumer trust.

15. Key Challenges and Research Priorities

Research should increasingly evaluate complete systems rather than isolated laboratory metrics. A cell with excellent energy density but poor fast-charge life may not reduce vehicle cost. A charger with extreme peak power but low utilisation may be economically and electrically inefficient. A V2G algorithm that ignores driver mobility or battery warranty will not scale.

High-priority technical areas include low-cost cobalt- and nickel-lean chemistries, non-invasive battery diagnostics, extreme-temperature thermal management, resilient charging hardware, wide-bandgap converter reliability, rare-earth-lean motors, bidirectional charging, megawatt-scale fleet charging, and automated battery disassembly.

Equally important are common data definitions, field datasets and reproducible test protocols. Battery degradation and charger-reliability claims should be linked to duty cycle, climate and measurement uncertainty. Open but privacy-preserving fleet data could accelerate model validation.

Table 3. Principal barriers to scalable and sustainable electric mobility.

Challenge	**Current consequence**	**Priority research or policy response**
Battery cost and raw materials	Vehicle affordability and supply concentration	Chemistry diversification, material efficiency and recycling
Fast-charge degradation	Reduced life and uncertain warranty cost	Physics-based charging control and standardised durability testing
Charging access	Adoption barrier for apartment and rural users	Shared residential charging, curbside systems and reliable public networks
Distribution-grid congestion	Transformer and feeder overload	Managed charging, storage, tariffs and grid-aware siting
Thermal runaway	Safety concern and insurance cost	Propagation-resistant packs, early detection and transparent incident data
Software and cybersecurity	Functional and privacy risk	Secure updates, long-term support and interoperable certification
Lifecycle emissions	Benefits vary with grid and vehicle size	Renewable charging, efficient vehicles and low-carbon manufacturing
End-of-life batteries	Waste and lost material value	Battery passports, design for disassembly and high-yield recycling
Heavy-duty electrification	Large energy and charging requirements	Megawatt charging, route planning and technology-neutral duty-cycle analysis
Public trust and equity	Uneven adoption and political resistance	Reliable infrastructure, consumer protection and inclusive incentives

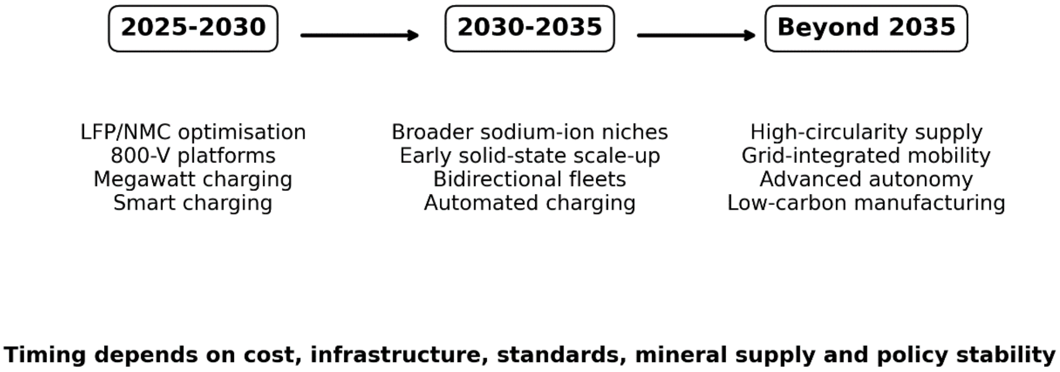

Figure 6. Indicative technology roadmap for electric mobility. Commercial timing is uncertain and region-dependent.

16. Conclusions

Electric vehicles have progressed from alternative powertrains to integrated mobility-energy-digital systems. Their high drivetrain efficiency, regenerative braking and compatibility with low-carbon electricity make them essential to transport decarbonisation. However, the next phase of adoption will be governed less by proof of propulsion and more by affordability, charging access, battery durability, grid integration, software assurance and circular material flows.

Lithium-ion batteries will remain dominant in the near term, with LFP and nickel-rich chemistries serving different market segments. Sodium-ion may expand in cost-sensitive and lower-range applications, while solid-state batteries require resolution of interface, manufacturing and cost challenges before mass deployment. Higher-voltage architectures, silicon-carbide converters and integrated thermal systems will continue to improve efficiency and charging performance.

Smart charging can convert EVs from uncontrolled loads into flexible grid resources. Bidirectional operation has technical potential, but interoperable communication, degradation-aware control, market access and user compensation are prerequisites. Charging-network success should be judged by reliability and accessibility rather than installed connector count.

The environmental advantage of EVs is strongest when vehicles are efficient and appropriately sized, electricity is progressively decarbonised, battery manufacturing is low-carbon, and materials are reused and recycled. Future research and policy must therefore co-optimise vehicle, battery, infrastructure, grid and lifecycle systems. Under this integrated framework, electric mobility can deliver substantial climate, air-quality and energy-security benefits without transferring unacceptable burdens to electricity networks or mineral supply chains.

References

[1] C.C. Chan, The state of the art of electric, hybrid, and fuel cell vehicles. Proceedings of the IEEE, 95(4), (2007) 704–718. https://doi.org/10.1109/JPROC.2007.892489

[2] M. Ehsani, Y. Gao, S. Longo, K. Ebrahimi, Modern Electric, Hybrid Electric, and Fuel Cell Vehicles, 3rd ed. CRC Press, Boca Raton, (2018).

[3] J. Larminie, J. Lowry, Electric Vehicle Technology Explained, 2nd ed. Wiley, Chichester, (2012). https://doi.org/10.1002/9781118361146.ch5

[4] S.F. Tie, C.W. Tan, A review of energy sources and energy management system in electric vehicles. Renewable and Sustainable Energy Reviews, 20, (2013) 82–102. https://doi.org/10.1016/j.rser.2012.11.077

[5] International Energy Agency, Global EV Outlook 2025. IEA, (2025). https://www.iea.org/reports/global-ev-outlook-2025

[6] H.S. Das, M.M. Rahman, S. Li, C.W. Tan, Electric vehicles standards, charging infrastructure, and impact on grid integration: A technological review. Renewable and Sustainable Energy Reviews, 120, (2020) 109618. https://doi.org/10.1016/j.rser.2019.109618

[7] M.A. Hannan, M.M. Hoque, A. Mohamed, A. Ayob, Review of energy storage systems for electric vehicle applications. Renewable and Sustainable Energy Reviews, 69, (2017) 771–789. https://doi.org/10.1016/j.rser.2016.11.171

[8] K.V. Singh, H.O. Bansal, D. Singh, A comprehensive review on hybrid electric vehicles: Architectures and components. Journal of Modern Transportation, 27(2), (2019) 77–107. https://doi.org/10.1007/s40534-019-0184-3

[9] P. Kumar, H.K. Channi, R. Kumar, A. Rajiv, B. Kumari, G. Singh, S. Singh, I.F. Dyab, J. Lozanović, A comprehensive review of vehicle-to-grid integration in electric vehicles: Powering the future. Energy Conversion and Management: X, 25, (2025) 100864. https://doi.org/10.1016/j.ecmx.2024.100864

[10] M.S. Eltohamy, M.H. Tawfiq, M.M.R. Ahmed, Z. Alaas, B. Mohammed, I. Ahmed, H. Youssef, A. Raouf, A comprehensive review of Vehicle-to-Grid (V2G) technology: Technical, economic, regulatory, and social perspectives. Energy Conversion and Management: X, (2025) 101138.

[11] International Energy Agency, (2026).Global EV Outlook 2026. IEA, Paris.

[12] J. Millan, P. Godignon, X. Perpina, A. Perez-Tomas, J. Rebollo, A survey of wide bandgap power semiconductor devices. IEEE Transactions on Power Electronics, 29(5), (2014) 2155–2163. https://doi.org/10.1109/TPEL.2013.2268900

[13] A. Emadi, Advanced Electric Drive Vehicles. CRC Press, Boca Raton, (2014). https://doi.org/10.1201/9781315215570

[14] Stefanskyi, L. Starzak, A. Napieralski, (2015) Silicon carbide power electronics for electric vehicles. In 2015 Tenth International Conference on Ecological Vehicles and Renewable Energies (EVER), IEEE, Monte Carlo, Monaco. https://doi.org/10.1109/EVER.2015.7138047

[15] A.H. Ganesh, B. Xu, A review of reinforcement learning based energy management systems for electrified powertrains: Progress, challenge, and potential solution. Renewable

and Sustainable Energy Reviews, 154, (2022) 111833. https://doi.org/10.1016/j.rser.2021.111833
[16] J.B. Goodenough, K.-S. Park, The Li-Ion rechargeable battery: A perspective. Journal of the American Chemical Society, 135(4), (2013) 1167–1176. https://doi.org/10.1021/ja3091438
[17] A. Manthiram, A reflection on lithium-ion battery cathode chemistry. Nature Communications, 11(1), (2020) 1550. https://doi.org/10.1038/s41467-020-15355-0
[18] International Energy Agency, (2025) Global Critical Minerals Outlook 2025. IEA, Paris.
[19] A. Yao, S.M. Benson, W.C. Chueh, Critically assessing sodium-ion technology roadmaps and scenarios for techno-economic competitiveness against lithium-ion batteries. Nature Energy, 10(3), (2025) 404–416. https://doi.org/10.1038/s41560-024-01701-9
[20] J. Janek, W.A. Zeier, Solid future for battery development. Nature Energy, 1, (2016) 16141. https://doi.org/10.1038/nenergy.2016.141
[21] G. Wang, X. Luo, W. Sun, J. Cai, Assessing the practical feasibility of solid-state lithium–sulfur batteries. Communications Materials, 6(1), (2025) 211. https://doi.org/10.1038/s43246-025-00918-9
[22] R. Xiong, L. Li, J. Tian, Towards a smarter battery management system: A critical review on battery state of health monitoring methods. Journal of Power Sources, 405, (2018) 18–29. https://doi.org/10.1016/j.jpowsour.2018.10.019
[23] R. Suganya, L.L. Joseph, S. Kollem, Understanding lithium-ion battery management systems in electric vehicles: Environmental and health impacts, comparative study, and future trends: A review. Results in Engineering, 24, (2024) 103047. https://doi.org/10.1016/j.rineng.2024.103047
[24] A.O. Ali, O. Abdelrehim, M.M. Saafan, M.R. Elmarghany, A.M. Hamed, Comprehensive review of battery management systems for electric vehicles: Thermal management, charging strategies, and emerging technologies. Journal of Power Sources, 658, (2025) 238269.
[25] P. Bilfinger, M. Schreiber, P. Rosner, K. Abo Gamra, J. Schöberl, C. Grosu, M. Lienkamp, Why we need a standardized state of health measurement procedure for electric vehicle battery packs—a proposal for energy- and capacity-based metrics. npj Clean Energy, 1(1), (2025) 10. https://doi.org/10.1038/s44406-025-00010-8
[26] Y.A. Sultan, A.A. Eladl, M.A. Hassan, S.A. Gamel, Enhancing electric vehicle battery lifespan: Integrating active balancing and machine learning for precise RUL estimation. Scientific Reports, 15(1), (2025) 777. https://doi.org/10.1038/s41598-024-82778-w
[27] F.S. Hwang, T. Confrey, C. Reidy, D. Picovici, D. Callaghan, D. Culliton, C. Nolan, Review of battery thermal management systems in electric vehicles. Renewable and Sustainable Energy Reviews, 192, (2024) 114171. https://doi.org/10.1016/j.rser.2023.114171
[28] F. Akkus, M.Z. Isik, A review of thermal management systems of lithium-ion batteries in electric vehicles. Journal of Traffic and Transportation Engineering (English Edition), 12(6), (2025) 1763–1783. https://doi.org/10.1016/j.jtte.2025.06.002

[29] K.T. Chau, (2015).Electric Vehicle Machines and Drives: Design, Analysis and Application. Wiley-IEEE Press, Singapore.

[30] Z.Q. Zhu, D. Howe, Electrical machines and drives for electric, hybrid, and fuel cell vehicles. Proceedings of the IEEE, 95(4), (2007) 746–765. https://doi.org/10.1109/JPROC.2006.892482

[31] A.M. El-Refaie, Motors/generators for traction/propulsion applications: A review. IEEE Vehicular Technology Magazine, 8(1), (2013) 90–99. https://doi.org/10.1109/MVT.2012.2218438

[32] SAE International, (2017). SAE J1772: Electric Vehicle and Plug-in Hybrid Electric Vehicle Conductive Charge Coupler. https://www.sae.org/standards/j1772-sae-electric-vehicle-plug-hybrid-electric-vehicle-conductive-charge-coupler3

[33] International Electrotechnical Commission, Electric Vehicle Conductive Charging System IEC 61851-1: General Requirements. IEC, (2017).

[34] CharIN, Megawatt Charging System Requirements and Specifications. CharIN, (2024).

[35] A. Tomaszewska, Z. Chu, X. Feng, S. O'Kane, X. Liu, J. Chen, C. Ji, E. Endler, R. Li, L. Liu, Y. Li, Lithium-ion battery fast charging: A review. eTransportation, 1, (2019) 100011. https://doi.org/10.1016/j.etran.2019.100011

[36] H. Liu, C. Li, X. Hu, J. Li, K. Zhang, Y. Xie, R. Wu, Z. Song, Multi-modal framework for battery state of health evaluation using open-source electric vehicle data. Nature Communications, 16(1), (2025) 1137. https://doi.org/10.1038/s41467-025-56485-7

[37] S. Li, C.C. Mi, Wireless power transfer for electric vehicle applications. IEEE Journal of Emerging and Selected Topics in Power Electronics, 3(1), (2014) 4–17. https://doi.org/10.1109/JESTPE.2014.2319453

[38] P. Richardson, D. Flynn, A. Keane, Impact assessment of varying penetrations of electric vehicles on low voltage distribution systems. In IEEE PES General Meeting, IEEE, Minneapolis, MN, USA, (2010). https://doi.org/10.1109/PES.2010.5589940

[39] Jokinen, M. Lehtonen, Flexibility of electric vehicle charging with demand response and dynamic electricity pricing. IEEE Access, 12, (2024) 135076–135091. https://doi.org/10.1109/ACCESS.2024.3459053

[40] W. Kempton, J. Tomic, Vehicle-to-grid power fundamentals: Calculating capacity and net revenue. Journal of Power Sources, 144(1), (2005) 268–279. https://doi.org/10.1016/j.jpowsour.2004.12.025

[41] M. Alghawi, J. Mounsef, Overview of vehicle-to-vehicle energy sharing infrastructure. IEEE Access, 12, (2024) 66108–66129. https://doi.org/10.1109/ACCESS.2024.3388088

[42] S. Meraj, S. Mekhilef, M.B. Mubin, H. Ramiah, M. Seyedmahmoudian, A. Stojcevski, Bidirectional wireless charging system for electric vehicles: A review of power converters and control techniques in V2G application. IEEE Access, 13, (2025) 61012–61042. https://doi.org/10.1109/ACCESS.2025.3561396

[43] International Organization for Standardization, ISO 15118: Road Vehicles – Vehicle to Grid Communication Interface. International Organization for Standardization.

[44] X. Feng, M. Ouyang, X. Liu, L. Lu, Y. Xia, X. He, Thermal runaway mechanism of lithium-ion battery for electric vehicles: A review. Energy Storage Materials, 10, (2018) 246–267. https://doi.org/10.1016/j.ensm.2017.05.013

[45] L. Yao, C. Yu, Y. Xiao, G. Cui, Z. Fei, C. Qu, A comprehensive review of lithium-ion battery safety issues and fault diagnosis strategies throughout the entire lifecycle. Journal of Energy Storage, 136, (2025) 118447. https://doi.org/10.1016/j.est.2025.118447

[46] T.R. Hawkins, B. Singh, G. Majeau-Bettez, A.H. Strømman, Comparative environmental life cycle assessment of conventional and electric vehicles. Journal of Industrial Ecology, 17(1), (2013) 53–64. https://doi.org/10.1111/j.1530-9290.2012.00532.x

[47] G. Bieker, A global comparison of the life-cycle greenhouse gas emissions of combustion engine and electric passenger cars. International Council on Clean Transportation, 49(30), (2021) 847129–102.

[48] International Council on Clean Transportation, (2025).A Global Comparison of the Life-Cycle Greenhouse Gas Emissions of Combustion Engine and Electric Passenger Cars: Updated Assessment. International Council on Clean Transportation.

[49] G. Harper, R. Sommerville, E. Kendrick, L. Driscoll, P. Slater, R. Stolkin, A. Walton, P. Christensen, O. Heidrich, S. Lambert, A. Abbott, Recycling lithium-ion batteries from electric vehicles. Nature, 575(7781), (2019) 75–86.

[50] X. Zeng, J. Li, N. Singh, Recycling of spent lithium-ion battery: A critical review. Critical Reviews in Environmental Science and Technology, 44(10), (2014) 1129–1165. https://doi.org/10.1080/10643389.2013.763578

[51] European Union, Regulation (EU) 2023/1542 concerning batteries and waste batteries. Official Journal of the European Union, (2023). http://data.europa.eu/eli/reg/2023/1542/oj

[52] T.F. Burton, J.L. Gómez Urbano, Y. Zhu, A. Balducci, O. Fontaine, The urgent electrolyte sustainability challenges for electric-vehicle batteries. Nature Communications, 16(1), (2025) 5957. https://doi.org/10.1038/s41467-025-60711-7

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