

Review

Life-Cycle Carbon Emissions of Electric Vehicles in China: A Review

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Highlights

What are the main findings?

- The life-cycle carbon footprint of electric vehicles in China is systematically reviewed, identifying that manufacturing-phase embodied carbon accounts for 30–70% of total emissions, while the use phase holds over 80% decarbonization potential.
- Vehicle-to-Grid (V2G) presents dual environmental effects: it may increase emissions in coal-dominated grid transition stages, but it delivers substantial carbon reduction under high renewable energy penetration, with nonlinear sensitivity to carbon pricing and peak–valley electricity price gaps.

What are the implications of the main findings?

- This review examines the life-cycle carbon footprint of electric vehicles in China and shows that the relative contribution of each life-cycle stage varies with battery production practices, the electricity mix, and vehicle lifetime.
- Targeted decarbonization pathways from both micro supply chain upgrading and macro policy governance are proposed, providing scientific support for the full life-cycle carbon neutrality of China's EV industry.

Abstract

Accelerating the low-carbon transition of transport is essential to addressing global climate change. Although the rapid growth of the electric vehicle (EV) fleet highlights the environmental benefits of electrified mobility, carbon-intensive upstream electricity generation and energy-intensive battery production continue to constrain the life-cycle emissions reduction potential of EVs. Focusing on China, this structured narrative review examines 121 core references from 2004 to 2026 to synthesize carbon-accounting methods and emissions across the manufacturing, use, and end-of-life stages. A supplementary keyword co-occurrence analysis of 1180 Web of Science records provides an overview of the research field. The reviewed evidence indicates that embodied emissions from manufacturing account for more than 30% of total life-cycle emissions, making this stage important to life-cycle decarbonization. The use stage offers the greatest emissions reduction potential and is closely linked to regional grid carbon intensity and vehicle-to-grid (V2G) scheduling. At the end of life, second-life battery use and closed-loop recycling can reduce the burden associated with initial production and support material circularity. Drawing on these findings and the development of China's EV industry, this review proposes decarbonization pathways for



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enterprises and policymakers to support the coordinated development of the transport and energy sectors.

Keywords: electric vehicles; carbon footprint; vehicle-to-grid; life cycle assessment

1. Introduction

Amidst the dual challenges of global economic stagnation and escalating environmental crises, sustainable development has emerged as a ubiquitous strategic consensus to reconcile climate stability with economic prosperity. According to the International Energy Agency (IEA), the transportation sector accounts for approximately one-quarter of global carbon emissions. Within this sector, road transport represents a dominant emission source, with passenger vehicles alone responsible for roughly 45% of the sector's total footprint [1]. Consequently, the deep decarbonization of mobility is indispensable for achieving global climate targets. Driven by this imperative, electric vehicles (EVs) have experienced exponential growth and are universally acknowledged as the pivotal technological pathway for decarbonizing transportation. In 2025, global EV sales surged past 20 million units, maintaining a robust 25% year-on-year growth trajectory; notably, the Chinese market spearheaded this momentum, with domestic new energy vehicle sales reaching 16.49 million units [1]. At the strategic level, electrified transport technologies—including electric vehicles and tramways integrated with renewable energy and hybrid energy-storage systems—are also regarded as important drivers of emerging high-tech industries and green economic recovery [2]. This paradigm shift is being rapidly accelerated by assertive institutional frameworks worldwide. For instance, the European Union's "Fit for 55" package mandates zero tailpipe emissions for all new passenger cars by 2035, while China's "New Energy Vehicle Industry Development Plan (2021–2035)" unequivocally cements the mainstream status of EVs in its future automotive ecosystem.

However, when focusing on China's unique energy and industrial structures, whether the large-scale deployment of EVs can achieve deep decarbonization across their full life-cycle remains widely questioned. This skepticism primarily stems from two dimensions: First, the current baseline load of China's power grid remains heavily dependent on coal-fired power generation. If EVs are charged within a grid dominated by coal-fired power generation, they may merely shift carbon emissions from the tailpipe to the power plant [3–5]. Second, the manufacturing phase of EVs is highly energy-intensive. The production process of power batteries entails substantial energy and resource consumption, which burdens EVs with higher carbon emissions than conventional internal combustion engine vehicles (ICEVs) before rolling off the assembly line [6–11].

Furthermore, in exploring the deep decarbonization potential of EVs, the emerging Vehicle-to-Grid (V2G) technology is becoming a critical variable in reshaping life-cycle carbon emissions. The profound impact of V2G on carbon emissions lies in its ability to transform EVs from isolated energy-consuming terminals into distributed mobile energy storage units. Within a power grid characterized by a high penetration of renewable energy, V2G enables vehicles to absorb and store surplus electricity during peak wind and solar generation periods (typically low-carbon intervals), thereby mitigating renewable energy curtailment. Conversely, during periods of peak grid demand, EVs can discharge energy back to the grid, substituting the need for carbon-intensive fossil fuel peaking units [12]. This bidirectional interaction not only optimizes the energy structure of the grid but also fundamentally enhances the decarbonization benefits during the full operational life-cycle.

A substantial body of the literature has conducted in-depth investigations into single life-cycle stages or specific technologies of EVs, evaluating aspects like battery manufacturing footprints [13], V2G decarbonization scenarios [12], and recycling offset effects [4]. However, these existing methodologies predominantly rely on static, isolated emission accounting. Comprehensive reviews that systematically correlate emerging mitigation technologies like V2G with the evolutionary characteristics of all life-cycle stages from a dynamic industry perspective remain scarce.

Therefore, this study adopts a structured narrative review supplemented by a brief bibliometric analysis. The bibliometric dataset comprised 1180 unique records retrieved from the Web of Science Core Collection and was used only to map the broad keyword structure of the field. Separately, 121 core references were identified through topic-oriented reading and were used for the qualitative and quantitative synthesis of EV life-cycle carbon accounting methods, manufacturing emissions, use-phase emissions, V2G interactions, battery recycling, second-life utilization, and carbon-neutrality pathways. As illustrated in Figure 1, the logical framework of this review is structured into three primary components: The first section delineates the carbon emission accounting system for EVs, focusing on the boundary definition of Life Cycle Assessment (LCA) and mainstream accounting models to establish the methodological foundation for subsequent analyses. The second section focuses on the critical phases of the life-cycle, providing an in-depth dissection of the current carbon emission status, key influencing factors, and future development trends across the manufacturing, use, and recycling phases. Based on the above research findings, the third section summarizes the key conclusions regarding the life-cycle carbon emissions of electric vehicles. From the dual perspectives of enterprise technological innovation and national policy guidance, this section further proposes feasible pathways and development suggestions for reducing EV carbon emissions.

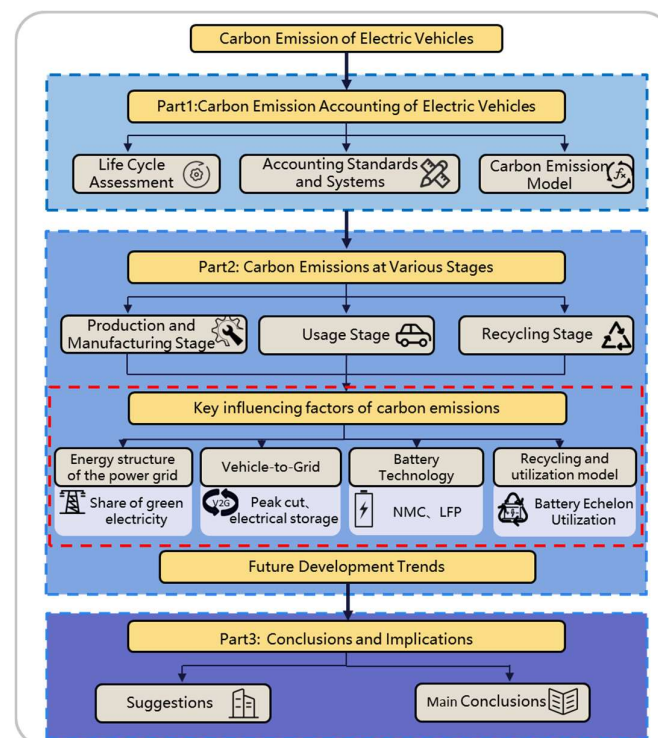


Figure 1. Framework of this review.

2. EV Carbon Emission Accounting

Following the establishment of the strategic role of EVs as a pivotal pathway for transportation decarbonization, scientifically and accurately quantifying their carbon mitigation benefits becomes a primary research prerequisite. Unlike conventional ICEVs that rely primarily on tailpipe emission monitoring, the zero-tailpipe nature of EVs during their use phase shifts the carbon burden upstream to electricity generation, dictating that their true carbon footprint be traced across the entire life-cycle. Therefore, constructing a standardized, multi-dimensional carbon emission accounting framework encompassing the full life-cycle is fundamental to identifying high-emission hotspots and formulating targeted decarbonization strategies. This chapter systematically reviews current mainstream accounting models, standards, and methods, establishing a robust methodological foundation for subsequent in-depth analyses across all life-cycle stages.

2.1. Carbon Accounting Standards

To ensure the scientific rigor and consistency of LCA results, the International Organization for Standardization (ISO) and various regional institutions have established a comprehensive suite of carbon emission accounting standards. Among these, ISO 14040 [14] and ISO 14044 [15] serve as the most widely adopted foundational frameworks globally [16]. ISO 14040 defines the principles and structural framework of LCA, delineating it into four phases: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation. Complementing this, ISO 14044 provides explicit technical requirements and operational guidelines for executing these phases.

To address regional requirements, more specific institutional regulations have emerged. The Product Environmental Footprint (PEF) guide, initiated by the European Commission, aims to create a harmonized environmental labeling scheme across the European market. More stringently, Regulation (EU) 2023/1542 [17] on batteries and waste batteries represents a major regulatory framework governing the sustainability and carbon footprint requirements of batteries placed on the EU market. This regulation mandates a compulsory declaration of carbon footprints for all EV power batteries entering the EU market. It enforces granular computational methodologies, including strict stipulations on secondary datasets and power grid modeling, signaling a paradigm shift in battery carbon accounting from academic discourse to mandatory market-access criteria [18].

Recognizing that international standards often exhibit geographical limitations when applied to specific industrial contexts, regional adaptations have been formulated. The T/CSAE 91-2018 standard [19], promulgated by the China Society of Automotive Engineers (China SAE), provides tailor-made computational guidelines optimized for China's specific fuel and vehicle cycles. For instance, this standard distinctly specifies the accounting methods for the Chinese power grid and incorporates localized emission factors for key manufacturing inputs like steel and aluminum, thereby enhancing the contextual fidelity of carbon emission evaluations under domestic industrial conditions [4,20]. A comparative analysis of these mainstream carbon accounting standards is systematically summarized in Table 1.

Although the aforementioned standards establish a baseline for the carbon accounting of EVs, significant theoretical gaps remain regarding the extension of life-cycle boundaries. First, the existing framework fails to provide unified carbon quota allocation and multi-objective partitioning rules for power batteries in second-life utilization scenarios. Second, current directives such as the EU Battery Regulation explicitly exclude the use phase of vehicles, focusing solely on carbon footprint regulations within the upstream supply chain. This static partitioning of system boundaries forcibly decouples the dynamic decarbonization benefits of V2G technology—such as peak shaving, valley filling, and

renewable energy integration—from the accounting framework, thereby severely underestimating the grid-level carbon emission reduction contributions of EVs as distributed energy storage units.

Table 1. Comparison of mainstream carbon emission accounting standards.

Standard System	Core Content	Key Differences	Scope of Application
ISO 14040/44 [14,15]	Standard LCA four-step framework (Goal, Inventory, Assessment, Interpretation)	Provides principles without specific calculation parameters; results across studies are difficult to compare directly	Academic research; General product design
Regulation (EU) 2023/1542 [17]	Introduces Circular Footprint Formula (CFF) for recycling; sets strict hierarchy for electricity data	Market barrier; serves as a prerequisite for trade compliance	Market access; Carbon tariff declaration
T/CSAE 91-2018 [19]	Clarifies Chinese grid factors; defines boundaries for fuel/vehicle cycles	Resolves data deviations of international standards in China; reflects the reality of the domestic supply chain	Local policy formulation; Supply chain management

From the perspective of future industry demands, a fundamental contradiction exists between the static attributes of the current accounting system and the dynamic evolution of EV technology. Existing standards rely heavily on historical average static emission factors, rendering them incapable of accurately quantifying real-time grid carbon intensity fluctuations induced by a high penetration of renewable energy. Therefore, the iteration of accounting standards must break through existing static life-cycle boundaries to establish a methodological system with high-frequency dynamic responsiveness and international mutual recognition mechanisms. This not only requires legitimizing the carbon offset benefits of interactive scenarios like V2G within regulatory codes, but also mandates the formulation of rigorous cross-regional data traceability baselines to address the deep constraints of transnational mechanisms such as the CBAM.

2.2. Accounting Methodology

During the practical execution of EV LCA, the acquisition and calculation of carbon emission data primarily rely on three core methodologies: the emission factor method, the mass balance method, and the measurement-based method. These three methodologies complement each other, collectively constructing an accounting framework that spans from macro-level estimation to micro-level verification.

The emission factor method is currently the most widely adopted mainstream approach, suitable for rapid macro-level evaluations. The core logic of this method involves multiplying activity data by the corresponding carbon emission factors. As the critical parameter determining accounting accuracy, emission factors are typically derived from authoritative life-cycle databases. For instance, the globally utilized Ecoinvent and GaBi databases provide comprehensive background data for materials (such as steel, aluminum, and lithium) and energy production [4]. Conversely, tailored to the Chinese context, the

China Automobile Life Cycle Database (CALCD) offers localized emission factors that better reflect the domestic power structure and industrial standards. Numerous studies have applied the emission factor method when constructing intelligent EV LCA models, calculating manufacturing phase emissions by multiplying the mass of individual vehicle components by the carbon emission equivalent factors of the respective materials, and determining use phase emissions by multiplying electricity consumption by regional grid emission factors [21].

The mass balance method is primarily applied to the accounting of complex industrial production and recycling processes. This approach is rooted in the law of conservation of mass, which dictates that the total mass entering a system must equal the total mass leaving the system plus the mass accumulated within it. When direct measurement of specific gaseous emissions is unfeasible—such as in complex hydrometallurgical processes—this method calculates material losses and potential carbon emissions retrospectively by precisely measuring the material flows at both the input and output terminals. In the field of battery recycling, this methodology is particularly critical; it enables researchers to elucidate the ultimate flow of carbon elements amid complex chemical reagent consumption and metal extraction processes, thereby filling data gaps within generic databases for specific recycling technologies [22,23].

The measurement-based method focuses on acquiring real-world data through direct monitoring and is frequently employed to validate or calibrate theoretical models. In the vehicle use phase, by installing portable emissions measurement systems (PEMS) or retrieving data from on-board diagnostic (OBD) systems, researchers can directly record instantaneous energy consumption and driving parameters under real-world operating conditions, rather than relying on laboratory driving cycles [24]. For EVs, directly obtaining real-world electricity consumption via high-precision electric meters or charging pile data, combined with real-time grid emission factors to calculate the carbon footprint, can more accurately reflect the impacts of driving behavior and ambient temperature on carbon emissions. A detailed comparison of these three methodologies is systematically summarized in Table 2.

Table 2. Comparison of core carbon emission accounting methodologies.

Accounting Method	Core Logic	Advantages	Disadvantages	Stage/Scenario
Emission Factor Method	Linear Superposition (Activity Data × Factor)	1. High Standardization: Easy to operate, facilitates horizontal comparison. 2. Easier Data Acquisition: Relies on mature databases, no field measurement needed. 3. Full Coverage: Suitable for macroscopic LCA	1. Database Lag: Citations of outdated factors may not reflect the latest processes. 2. Regional Bias: Using European/US databases for Chinese vehicles causes large errors. 3. Dynamic Response Difficulty: Lower accuracy in specific dynamic scenarios.	Full Life Cycle
Mass Balance Method	Mass Conservation	1. High Precision: Suitable for analyzing specific elemental flows and losses. 2. Rigorous Logic: Based on physical/chemical laws, strong data self-consistency.	1. Extremely High Data Requirements: Requires detailed factory-level input/output data. 2. Cumbersome Calculation: Difficult to apply to large-scale accounting at the vehicle level	Recycling Stage

Table 2. Cont.

Accounting Method	Core Logic	Advantages	Disadvantages	Stage/Scenario
Measurement-based Method	Direct Measurement	1. High Authenticity: Reflects the impact of real road conditions, driving behavior, and temperature	1. High Cost: Expensive equipment, long testing cycles. 2. Limited Sample Size: Usually tests only a few vehicles, hard to represent large fleets. 3. Environmental Interference: Large data fluctuations require complex data cleaning	Use Stage

2.3. Accounting Models

The quantitative assessment of EV carbon emissions relies on two distinct yet complementary modeling paradigms: kinetic models focusing on the underlying operational logic of a single life-cycle stage, and LCA models encompassing cross-stage, full-industry-chain boundaries. Fundamental differences exist between these two paradigms regarding their system boundaries and core logics (Table 3).

Table 3. Comparison of mainstream accounting models for EV carbon emissions and energy consumption.

Model Name	Assessment Scope	Core Logic
COPERT/MOVES	Use-phase dynamics	Non-linear statistical fitting of “average speed-emission factor” based on massive dynamometer tests
CMEM	Use-phase dynamics	Transient emission estimation based on the physical parameters of internal combustion engines
VT-CPEM	Use-phase dynamics	Deep coupling of electrochemistry and vehicle dynamics; finely simulates discharge efficiency and regenerative braking logic
REET	Life-cycle	Full-chain material and energy flow modeling of the “fuel cycle” and “vehicle cycle”
GaBi/SimaPro	Life-cycle	Based on the network topology analysis of complex industrial processes and LCI aggregation
CALCD/CALCM	Life-cycle	Anchored to the characteristics of China-specific industrial scenarios

In kinetic-based carbon emission modeling during the use phase, a fundamental difference in underlying logic exists between EV and ICEV emission models: the former features zero tailpipe emissions and essentially evolves into an energy consumption model coupling electrochemistry with vehicle dynamics. Traditional average-speed models, such as the Computer Programme to calculate Emissions from Road Transport (COPERT) and the Motor Vehicle Emission Simulator (MOVES), exhibit significant underlying flaws when evaluating the decarbonization benefits of specific traffic management strategies due to their omission of transient acceleration and deceleration processes [25]. To capture transient operating conditions, micro-physical models centered on vehicle specific power (VSP) have become the current mainstream [26]. Unlike micro-models for conventional vehicles, such as the Comprehensive Modal Emission Model (CMEM) [27], EV-specific energy consumption models, such as the Virginia Tech Comprehensive Power-Based EV Energy Consumption Model (VT-CPEM) developed by Fiori et al., must incorporate motor efficiency maps, the nonlinear response of battery state of charge (SOC), and the braking

logic of regenerative braking systems [28]. Consequently, the core of accurately measuring EV operational carbon emissions has shifted from fitting fuel combustion efficiency to calculating the dynamic losses within the “grid-to-battery-to-wheel” energy flow.

At the macro-evaluation level spanning the full life-cycle, several mainstream LCA model camps have formed internationally, yet their applicability remains constrained by the spatiotemporal heterogeneity of the underlying databases. The Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model developed by Argonne National Laboratory serves as the industry benchmark, with its core advantage lying in its high-resolution fuel cycle (Well-to-Wheels) analysis and dynamic grid tracking capabilities localized to the United States [29]. European models, such as GaBi and SimaPro, primarily rely on the Ecoinvent database, featuring strong traceability for industrial process baseline data [30]. However, because the power battery supply chain is highly concentrated in Asia and manufacturing technologies iterate rapidly, directly applying the background datasets of static Western models to evaluate Chinese supply chains introduces intolerable spatiotemporal inconsistencies. To fill this data vacuum, the CALCM and the CALCD, constructed by the CATARC, explicitly anchor the power grid structures of various Chinese provinces and localized emission factors for key metal smelting, establishing an accounting benchmark aligned with China’s specific industrial geopolitical characteristics [4,31].

Within the existing modeling framework, the primary methodological dilemma lies in the fragmentation between micro-level energy consumption models and macro-level LCA models. Current LCA platforms (e.g., GREET and GaBi) predominantly adopt static, linear assumptions regarding vehicle lifetimes, rendering them incapable of capturing battery capacity degradation induced by extreme ambient temperatures [32] or high-frequency fast charging under real-world operating conditions. Such micro-level physical degradation directly precipitates premature battery retirement or replacement, thereby substantially amplifying supplementary carbon emissions from the upstream manufacturing phase over the vehicle’s life-cycle. Therefore, dismantling the silo effect of existing static models and developing dynamically coupled frameworks that integrate micro-level transient energy consumption with macro-level LCA are critical theoretical gaps urgently requiring resolution in this field.

Based on the standards, accounting methods, and models reviewed above, EV life-cycle carbon accounting generally adopts a cradle-to-grave system boundary, as illustrated in Figure 2. Within this boundary, carbon emissions can be organized into three principal stages: vehicle and battery manufacturing, vehicle use, and end-of-life battery treatment, including second-life utilization and material recycling. These three stages provide the organizing framework for the subsequent analysis.

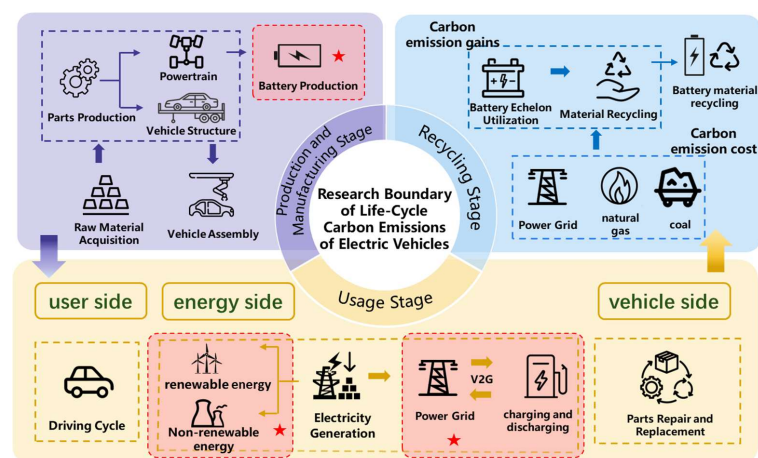


Figure 2. System boundary of EV life-cycle carbon emissions (The red five-pointed stars indicate key processes with significant carbon-emission or carbon-reduction implications).

3. Analysis of EV Life-Cycle Carbon Emission

Based on the life-cycle boundary shown in Figure 2, EV carbon emissions are classified into manufacturing, use, and recycling. Table 4 summarizes the main emission sources, mitigation strategies, and accounting challenges associated with each stage. A brief keyword co-occurrence analysis was also conducted to provide an overview of the main research themes in this field.

Table 4. Stage-based framework for EV life-cycle carbon emissions.

Life-Cycle Stage	Main Emission Sources	Mitigation Strategies	Accounting Challenges
Manufacturing	Material production, battery manufacturing, and vehicle assembly	Clean electricity, low-carbon materials, and process improvement	System boundaries, data quality, and regional emission factors
Use	Electricity generation, charging losses, and vehicle energy consumption	Grid decarbonization, energy-efficiency improvement, and smart charging/V2G	Dynamic grid emission factors and real-world energy consumption
Recycling	Battery collection, second-life preparation, and material recycling	Second-life utilization and closed-loop recycling	Carbon allocation and avoided-emission credits

To provide a concise overview of the main research themes in the field, a supplementary keyword co-occurrence analysis was conducted. A topic search was performed in the Web of Science Core Collection that using the query TS = (“electric vehicle” AND “carbon emission”), with the publication timespan set to 2010–2026. No restrictions were imposed on document type or language. The retrieved records were sorted by relevance for export management, and 1180 unique records were retained after duplicate records were removed.

The records contained 3959 distinct author keywords and Keywords Plus terms before thesaurus normalization. Variants involving singular and plural forms, hyphenation, spelling, abbreviations, and full terms were merged using a thesaurus file, resulting in 3762 normalized keywords. A keyword co-occurrence network was then generated in VOSviewer version 1.6.20 using all keywords and a minimum occurrence threshold of five. Node size represents keyword occurrence, link thickness represents co-occurrence strength, and node color indicates cluster membership.

As shown in Figure 3, the keyword network broadly reflects four interconnected research themes: life-cycle and environmental assessment, vehicle energy consumption and carbon emissions, battery and powertrain technologies, and grid interaction and renewable-energy optimization. The network is used only to contextualize the subsequent structured discussion rather than to provide an independent comprehensive bibliometric assessment.

Following this framework, the three life-cycle stages are discussed separately below, beginning with the manufacturing stage.

Within the manufacturing phase of EVs, power battery production is widely recognized as a high-emission segment [13]. The carbon emissions of power batteries primarily originate from raw material extraction and processing, battery cell manufacturing, and battery pack assembly [39–41]. With the ongoing iteration of battery technologies, different chemical pathways exhibit distinct carbon footprint profiles during the manufacturing phase. Therefore, this review synthesizes and compares the literature concerning the manufacturing carbon emissions of LFP and NCM batteries. As illustrated in Figure 4e, the carbon emissions per unit capacity of different chemical pathways exhibit a distinct stepped distribution during the manufacturing phase. Quantitative analysis indicates that LFP batteries, by avoiding the environmentally intensive extraction and complex purification processes of nickel and cobalt ores, exhibit a median manufacturing carbon emission value (approximately 80 kg CO₂-eq/kWh) significantly lower than that of NCM systems [8,42] (approximately 100 kg CO₂-eq/kWh). Within NCM systems, as the nickel content increases (evolving from NCM111 to NCM811), the greenhouse gas emissions per unit capacity exhibit a downward trend of approximately 7.5%. This mitigation effect is primarily driven by the enhanced energy density associated with high-nickel chemistry, which physically reduces the active material consumption per kWh and diminishes the fixed energy loads during manufacturing [13,43]. However, the wide distribution range of carbon emissions for NCM811 (approximately 60–120 kg CO₂-eq/kWh) underscores that the ultimate carbon footprint of high-nickel systems remains highly sensitive to energy efficiency management during the manufacturing process and other life-cycle influencing factors [44].

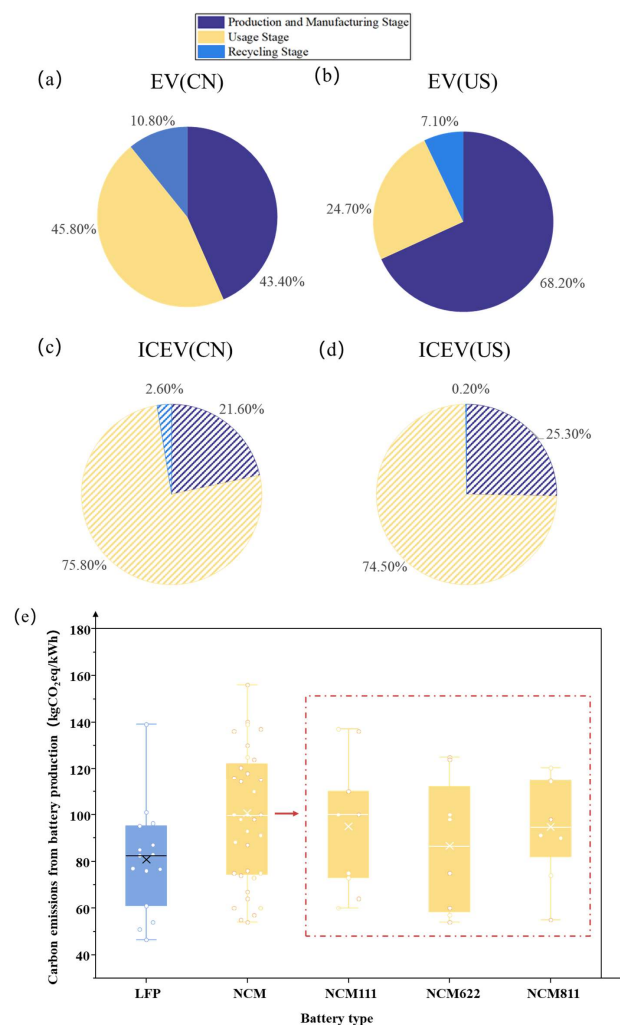


Figure 4. (a) Chinese BEVs; (b) U.S. BEVs; (c) Chinese ICEVs; and (d) U.S. ICEVs. Panels (a–d) show

unweighted means of within-case stage shares (two vehicle cases per panel). The Chinese passenger-car cases are derived from two studies [4,45], whereas the U.S. commercial-van cases are derived from two vehicle comparisons in one study [46]. Yellow denotes production, blue denotes use, and purple denotes recycling. (e) Comparison of carbon emissions per unit capacity during the manufacturing phase for mainstream power batteries, the red dashed box highlights the NCM battery chemistries [7,8,13,21,23,34,40,42,43,46,47].

3.1.2. Future Emission Trends

With the global transition of energy structures and the rapid iteration of EV technologies, the status of the manufacturing phase within life-cycle carbon emissions will undergo a fundamental paradigm shift. Future carbon emission trends will primarily be dictated by the pace of grid decarbonization, the selection of battery technology pathways, and the implementation level of a circular economy.

As power systems decarbonize, emissions during the EV use phase will decline substantially, causing the manufacturing phase (particularly battery production) to progressively dominate life-cycle emissions [41,48,49]. Scenario projections for China's road transport fleet from 2020 to 2050 indicate that, under rapid renewable energy expansion and EV deployment, vehicle and battery production could become the dominant emission sources, accounting for 89–96% of total emissions by 2050. This signifies a complete upward shift in future EV emission pressures toward the upstream manufacturing supply chain [50].

Research on emerging battery technologies demonstrates immense decarbonization potential, though these technologies also face challenges regarding manufacturing process maturity. Among them, lithium–sulfur (Li-S) batteries, as a representative next-generation high-energy-density technology, possess significant resource and environmental advantages by eliminating the reliance on scarce metals such as nickel and cobalt. Comparative life-cycle assessment results indicate that the abundant availability and relatively low extraction-energy requirements of sulfur can give Li-S batteries a lower raw-material acquisition carbon footprint than conventional NCM batteries [7]. However, constrained by current cycle life and electrolyte consumption, their comprehensive life-cycle decarbonization benefits require further unlocking through enhanced energy density and extended operational lifespans.

Concurrently, sodium-ion batteries (NIBs), serving as a low-cost alternative to lithium resources, exhibit inherent advantages in resource availability, yet their carbon emission performance remains subject to multiple variables. A comparative assessment of sodium-ion and LFP batteries indicates that sodium-ion batteries have potential advantages in raw-material availability, cost, and carbon footprint. However, their current emissions from cathode manufacturing, battery management system matching, and pack assembly remain higher than those of mature LFP batteries because of the relatively immature supply chain [51]. This underscores that for NIBs to become a truly low-carbon alternative, urgent breakthroughs in process scaling and energy efficiency optimization are required. The future development of these two emerging battery technologies necessitates accelerated R&D and industrialization, with a strategic focus on mitigating the shortcomings of novel chemical systems regarding manufacturing energy consumption and cycle life. This is essential to minimize the embodied carbon emissions of EVs in a future where the manufacturing phase dominates the life-cycle carbon footprint.

3.2. Carbon Emissions in the EV Use Phase

3.2.1. Current Status of Carbon Emissions

Although the use phase of EVs features zero tailpipe emissions, its carbon footprint primarily originates from indirect emissions during electricity generation. Carbon emissions in the use phase are dictated by the regional grid carbon intensity on the supply side, and the actual operational energy consumption of the vehicle on the demand side [52,53]. Furthermore, this energy consumption is influenced by a multiplicity of factors, including driving mileage, driving behavior, and autonomous driving technologies.

At present, constrained by the high coal-fired baseload of the Chinese power grid, the proportion of carbon emissions in the EV use phase remains as high as 30–40% over the full life-cycle. However, with the deep decarbonization of the novel power system and the escalating penetration of renewable energy sources such as wind and solar, when the share of renewable electricity surpasses 90% in the future, the carbon emissions per unit mileage during this phase will drop to approximately 40 g CO₂-eq/km, achieving an absolute reduction of over 80% compared to current levels. Recent life-cycle assessment results indicate that the use phase accounts for more than 70% of the life-cycle emissions of ICEVs, whereas EV emissions are distributed more evenly between the manufacturing and use phases [54]. A comparative analysis covering 32 countries confirms that grid decarbonization is a major determinant of EV use-phase carbon emissions [40] (the specific impacts of grid carbon intensity will be detailed in Section 3.2.2).

Regarding the impact of driving mileage on carbon emissions, significant discrepancies in carbon footprints exist across different driving ranges. Notably, the EV carbon footprint does not scale linearly with driving range; instead, it exhibits a non-linear U-shaped trajectory of “initial decline followed by subsequent increase.” Studies contextualized in China indicate that within a driving range of 100–850 km, for a full life-cycle mileage of 100,000 km, vehicles with a 200–300 km range yield the lowest carbon footprint, whereas when the life-cycle mileage reaches 200,000 km, vehicles with a 300–400 km range demonstrate optimal performance [40]. This is fundamentally because vehicles with shorter ranges require higher-frequency charge–discharge cycles, precipitating reduced cyclic efficiency and accelerated battery aging, while ultra-long-range vehicles incur escalated energy consumption due to excessive battery weight. Although this overarching trend possesses universal applicability, this “optimal range interval” is not static but manifests significant regional heterogeneity.

To explore the impact of intelligent vehicles on use-phase carbon emissions, it is prerequisite to define the core mechanism of eco-driving. Eco-driving is fundamentally a control strategy that proactively curtails redundant operational energy consumption through multi-scale energy management and dynamic trajectory planning. However, constrained by human perception latency and operational stochasticity, the emission reduction dividends of conventional eco-driving are easily dissipated in complex traffic flows, necessitating a leap toward an algorithmic and connectivity-driven intelligent paradigm. Recent empirical LCA studies verify that relying solely on isolated autonomous vehicles (AVs) without vehicular connectivity cannot achieve eco-driving; paradoxically, the additional load from newly integrated ICT hardware (e.g., radars, high-computing units) and conservative car-following logic leads to a net increase in operational energy consumption [55]. Therefore, the true decarbonization potential must be unlocked through connected and automated vehicles (CAVs). CAVs are capable of strictly executing dynamic eco-routing, speed harmonization, and vehicle platooning. Quantitative studies indicate that in urban road scenarios, L2–L3 intelligent EVs can reduce carbon emissions by approximately 20–22% compared to L1 counterparts, while in highway scenarios, this mitigation ratio is about 12–14% [21,56]. After offsetting the incremental energy consumption of hardware,

this connected eco-driving can further realize an absolute energy consumption reduction of 2–25% (up to 40% under extremely optimized conditions), ultimately accomplishing a low-carbon transition toward “algorithm-driven decarbonization” [57].

3.2.2. Dynamic Decarbonization Mechanism of V2G

In smart-city energy systems, EV charging infrastructure can be integrated with distributed renewable generation and hybrid AC/DC microgrids [58]. At the urban microgrid level, coordinated charging and V2G can align vehicle charging demand with local electricity supply and provide flexibility for low-carbon grid operation [59]. The variable output of wind and solar power makes charging time an important determinant of EV emissions [60]. Under coordinated grid-to-vehicle (G2V) operation, charging can be shifted toward periods of surplus renewable generation or lower grid carbon intensity [61]. Bidirectional V2G further allows connected EVs to discharge during periods of high demand, potentially reducing the need for thermal generation [62]. The net carbon effect nevertheless depends on the electricity used for charging and the generation displaced during discharge [62,63]. An idealized macro-energy model indicated that in wind- and solar-dominated systems, V2G can significantly curtail renewable energy curtailment rates. Compared to unidirectional charging, V2G reduces the curtailment rate by over 50%; particularly in “solar plus storage” systems, V2G is capable of reducing renewable energy curtailment by up to 95% [64]. The contribution of EV batteries to grid flexibility can extend beyond their automotive service life. During vehicle operation, V2G uses onboard batteries to provide flexible storage for the grid. After retirement from automotive use, suitable batteries can be repurposed as stationary storage at charging stations or within local grids to buffer peak charging loads and store surplus renewable electricity [65]. Thus, V2G and second-life battery use provide related grid-flexibility services at different stages of battery life. They can complement each other in practice, but may also compete as V2G participation expands and demand for stationary storage changes [58].

Beyond shifting charging demand, V2G can store electricity during periods of renewable-energy surplus and return it to the grid when demand rises, thereby reducing renewable-energy curtailment and potentially displacing fossil-fuel generation. In a power-system simulation involving 100,000 EVs, enabling V2G reduced annual wind curtailment from 23 to 20 GWh relative to the corresponding scenario without V2G [66]. A separate study projected that V2G could increase the renewable share of electricity used for EV charging from less than 4% to 66% and reduce charging-related greenhouse gas emissions by 20.6% compared with uncoordinated charging [62]. The magnitude of these benefits depends on vehicle availability, charging and discharging schedules, and the local electricity mix.

Although V2G theoretically exhibits substantial decarbonization potential, its actual efficacy is subject to the complex influence of multiple variables. We reviewed 20 studies concerning the impact of V2G on EV carbon emissions, the results of which are synthesized in Figure 5. Through a sensitivity analysis of V2G penetration, grid cleanliness, infrastructure scale, power load, seasonal factors, and peak-to-valley electricity price differentials, the boundary conditions for V2G to exert its environmental benefits can be more distinctly delineated. As V2G penetration increases from 0% to 100%, total annualized carbon emissions exhibit a stable downward trend, decreasing from approximately 2.87 billion tons to 2.82 billion tons (Figure 5a) [67]. Under the V2G system expansion mode, when the grid carbon emission factor decreases to a certain threshold (e.g., below 64 g CO₂-eq/kWh), the system carbon intensity of EVs transitions to a negative value (i.e., achieving negative emissions) (Figure 5b) [68]. Furthermore, a nearly linear positive correlation exists between the number of charging piles participating in V2G and the volume of carbon mitigation

(Figure 5c) [69]. This underscores that V2G can only truly become an emission reduction mechanism when the penetration of renewable energy is sufficiently high. Concurrently, the decarbonization potential of V2G demonstrates strong seasonal characteristics. During the summer, owing to the matching demand between peak air-conditioning loads and photovoltaic generation, the relative carbon mitigation volume of V2G is significantly higher than in the winter (Figure 5d) [62].

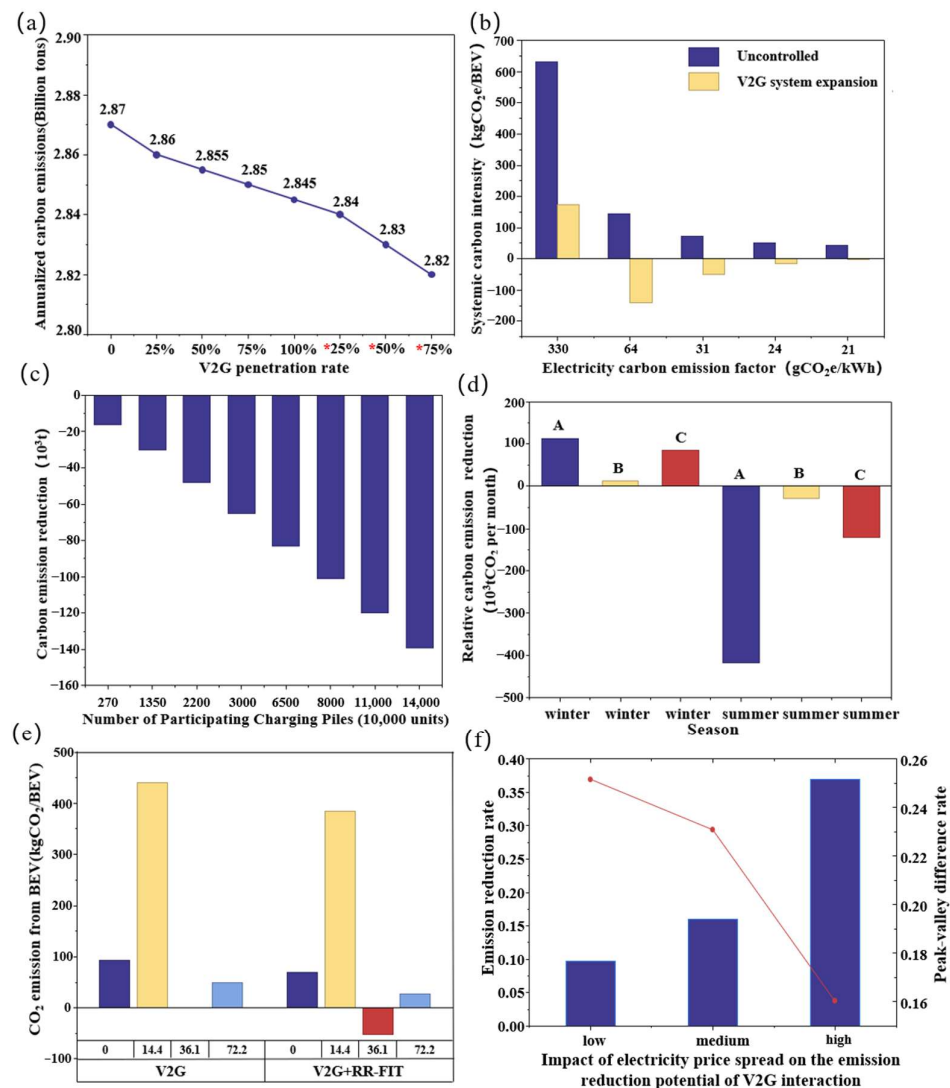


Figure 5. Impact of V2G on the carbon emission of EVs. (a) V2G Penetration Rate (Percentages without an asterisk denote unidirectional coordinated charging, while * denotes 25% unidirectional coordinated charging plus the indicated proportion of bidirectional V2G operation); (b) Grid Carbon Emission Factor; (c) Number of Participating Charging Piles; (d) Seasonal Factors (A–C and the corresponding colors denote Group A (daily commuters), Group B (weekend long travelers), and Group C (frequent long travelers), respectively); (e) Carbon Price (Different colors represent different carbon price levels (0, 14.4, 32.1, and 72.2 USD/tCO₂); (f) Peak–Valley Electricity Price Spread [64–83].

It is noteworthy that under specific carbon price levels (e.g., 14.4 USD/t CO₂), the flexibility provided by V2G may allow cheap coal-fired power—which would otherwise be constrained by a lack of regulation capacity—to be increasingly absorbed by EVs. This subsequently crowds out the share of cleaner but costlier liquefied natural gas (LNG) generation, paradoxically leading to an increase in total system emissions. Empirical surveys reveal that a carbon price of 36.1 USD/t CO₂ is more conducive to stimulating the emission reduction potential of V2G (Figure 5e) [63]. Furthermore, the electricity

pricing mechanism (particularly the peak-to-valley differential) serves as the core driver motivating users to alter their charge–discharge behaviors. A significant positive correlation exists between the magnitude of the price differential and the carbon mitigation rate. Under varying levels of peak-to-valley price differentials, the V2G carbon mitigation rates approximate 10%, 16%, and 37%, respectively, indicating substantial variance (Figure 5f).

Moreover, with the advancement of bidirectional charging technologies, vehicle–grid interaction is no longer confined to peak shaving and valley filling at the grid level, but extends to user-side Vehicle-to-Home (V2H) applications. Detailed modeling of 432 regions in the United States demonstrated that the mitigation potential of V2H is remarkable. Compared to uncoordinated charging, V2H strategies can reduce the life-cycle greenhouse gas emissions of a baseline household vehicle by 89% (a median lifetime reduction of 38.0 t CO₂-eq) [70].

However, some of the literature presents a contrasting perspective: in transitional power grids dominated by coal or characterized by the coexistence of coal and renewable energy, V2G dispatch driven solely by economic costs may paradoxically precipitate an increase rather than a decrease in carbon emissions. A partial market equilibrium model revealed that prior to the deep substitution of coal power phase, although V2G can reduce system costs through arbitrage between off-peak charging and peak discharging, off-peak electricity prices often correspond to high-carbon coal power, whereas peak prices might be marginally set by relatively lower-carbon natural gas generation. Consequently, EVs absorb substantial amounts of high-carbon electricity during the night [12]. Overall, the mitigation potential of V2G exhibits a strong nonlinear coupling with the cleanliness of the regional power structure. In the initial transitional phase dominated by coal, V2G dispatch guided solely by economic arbitrage may inadvertently increase carbon emissions by amplifying the utilization of baseload coal power. Only when the grid carbon intensity drops to a specific critical threshold can V2G truly achieve high-intensity emission reductions.

In addition, the practical deployment of V2G is constrained by several technical factors. Bidirectional charging introduces additional power-conversion equipment and energy losses, while repeated charge–discharge operation may accelerate battery aging depending on the depth of discharge, charging rate, temperature, and dispatch frequency [80–82]. Although infrequent grid services may impose only a limited incremental degradation burden, battery-aging costs and warranty implications must be incorporated into V2G scheduling and life-cycle assessments [84–87]. V2G operation requires coordination among the vehicle, bidirectional charger, aggregator, and grid operator. The incomplete and inconsistent implementation of communication standards, including ISO 15118-20, currently limits interoperability across vehicle and charger manufacturers [88]. User mobility requirements, minimum state-of-charge constraints, uncertain economic returns, and cybersecurity risks further reduce the availability and scalability of V2G resources [89]. Therefore, the carbon benefits of V2G depend not only on renewable-energy penetration but also on battery-management strategies, charger efficiency, interoperable control systems, and reliable user participation.

In summary, the emission reduction benefits of V2G technology are neither static nor linear. Inherently, V2G presents a dual environmental impact: during the initial grid transition phase with high-carbon thermal power as the baseload, economically driven V2G strictly adhering to “peak-to-valley price arbitrage” often induces vehicles to excessively absorb high-carbon coal power during nighttime off-peak periods, thereby generating a high carbon footprint. Conversely, in the deep decarbonization phase dominated by wind and solar, V2G transforms into an indispensable flexibility resource, achieving its mitigation effects by smoothing the volatility of renewable energy. Therefore, to circumvent the risk of carbon lock-in during the transition period, future V2G dispatch strategies must

evolve from a singular “price-driven” paradigm to a “carbon-price co-driven” framework to optimize the ultimate emission reduction efficacy of V2G.

3.2.3. Future Emission Trends

Inherently, carbon emissions during the EV use phase originate from the electricity generation process. Existing LCA studies, integrated with future energy scenario projections, reveal a profound correlation between renewable energy penetration and the carbon mitigation potential of EVs; as the share of renewable energy escalates, the decarbonization dividends of EVs will be further amplified.

Driven by the global energy transition, the power grid structure is undergoing a profound low-carbon transformation, fundamentally reducing operational emissions from EVs. According to the IEA report (Figure 6a), global renewable power generation is projected to expand significantly from 2024 to 2030, with solar photovoltaics (PV) and wind acting as the primary catalysts. Consequently, the share of variable renewable energy (VRE) is expected to climb from 15% in 2024 to 28% by 2030, raising the total renewable energy share to 43%.

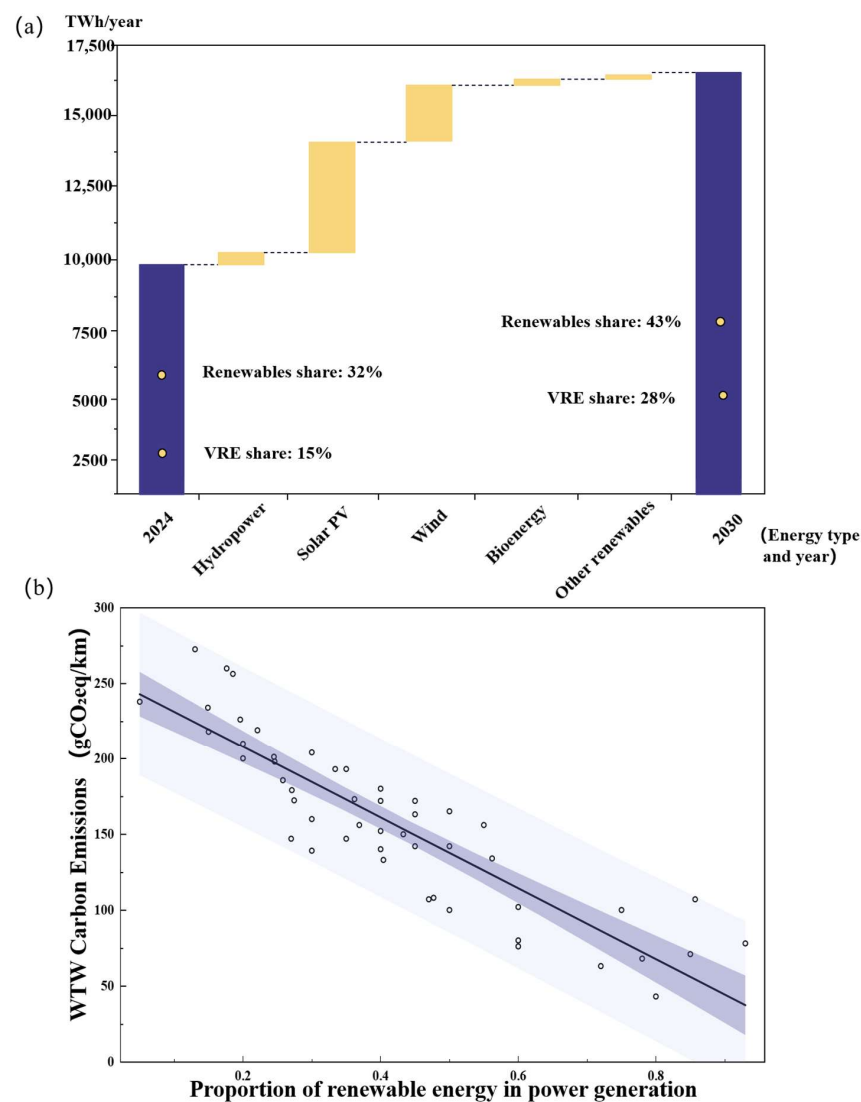


Figure 6. (a) Installed capacity and generation share of renewable energy [1]; (b) impact of renewable energy generation share on EV use-phase carbon emissions (The dark shaded area represents the 95% confidence band of the fitted regression line, while the light shaded area represents the 95% prediction interval) [39,40,50,54,56,63,90–97].

As established in the preceding sections, renewable energy exerts a decisive impact on the use-phase carbon emissions of EVs. A targeted regression analysis elucidating the relationship between the grid's renewable energy proportion and EV use-phase emissions reveals a prominent linear downward trend (Figure 6b). When the renewable energy share is extremely low (approximately 5–10%)—implying a grid heavily reliant on fossil fuels such as coal or natural gas—the WTW carbon emissions of EVs remain elevated at approximately 240–250 g CO₂-eq/km. This emission level is comparable to, or even exceeds, that of highly efficient internal combustion engine vehicles (ICEVs), thereby marginalizing the environmental advantages of EVs. Conversely, when the renewable energy penetration reaches a high level (approximately 90%), the EV WTW carbon emissions drop sharply to around 40 g CO₂-eq/km, signifying that an absolute reduction of over 80% in operational emissions can be achieved under a clean grid framework. Nevertheless, noticeable fluctuations in carbon emissions persist even at identical renewable energy shares, which can be attributed to variances in thermal power generation efficiencies, grid transmission losses, or climate-induced energy consumption discrepancies. Based on the survey findings, the renewable energy share is projected to reach approximately 43% by 2030, which will correspondingly lower EV use-phase carbon emissions to around 150 g CO₂-eq/km. This empirical evidence validates the imperative that transport electrification must be advanced synergistically with grid decarbonization.

3.3. Carbon Emissions in the EV Recycling Phase

Current Status of Carbon Emissions

As the closed-loop segment of the EV life-cycle, the recycling phase primarily relies on two pathways: second-life utilization and material recycling. The essence of these pathways lies in offsetting the embodied carbon footprint of the upstream manufacturing phase by extending service lifespans or substituting virgin materials [98]. A synthesis of current studies on the impacts of recycling on EV carbon emissions indicates that on the material recycling front, compared with the manufacturing of virgin cathode materials, the direct physical recycling (DPR) process can circumvent high-energy-intensive smelting segments, thereby depressing battery greenhouse gas (GHG) emissions by 30–40%. Concurrently, on the second-life utilization front, reconfiguring retired power batteries for integration into energy storage stations can contribute an absolute carbon mitigation of approximately 250 kg CO₂-eq /kWh during their secondary service period.

Existing battery recycling technologies predominantly encompass pyrometallurgy, hydrometallurgy, and DPR, with different technological routes exhibiting significant discrepancies in their carbon mitigation potentials. Material recycling technologies can be broadly classified into pyrometallurgical, hydrometallurgical, and direct recycling routes. Their differences in operating temperature, chemical requirements, material-recovery pathways, and technology maturity lead to substantially different carbon profiles [99]. A concise comparison is provided in Table 5 [22,47,91]. Overall, direct recycling shows the greatest potential for reducing process-related emissions, whereas hydrometallurgical and pyrometallurgical routes currently offer higher technological maturity and feedstock tolerance. The actual environmental performance nevertheless depends on battery chemistry, recovery efficiency, electricity mix, and process configuration.

Second-life utilization refers to the practice of reconfiguring retired power batteries that still retain a certain capacity (typically 70–80%) [100] for applications in energy storage systems or low-speed vehicles, thereby amortizing the carbon emissions of the manufacturing phase by extending the battery's full life-cycle service duration. To visually quantify the decarbonization potential of second-life utilization across diverse application scenarios, Table 6 summarizes key findings from the recent literature. Research gener-

ally indicates that the emission reduction efficacy of second-life power battery utilization exhibits distinct scenario-specific heterogeneity and scale effects. At the micro-level of buildings and localized grids (e.g., residential photovoltaics [101] and microgrid pairings), second-life utilization can achieve a 15–25% reduction in the system’s full life-cycle global warming potential (GWP) by avoiding the manufacturing of virgin batteries. Conversely, in macro-scale utility-grid energy storage deployments, the absolute carbon mitigation contribution of retired batteries reaches 242.65 kg CO₂-eq/kWh, and the system-level cumulative mitigation potential (55.8 Mt) even surpasses the direct physical recycling baseline (48.3 Mt). In essence, the ultimate net environmental benefit of second-life utilization is not a static constant; rather, it is heavily dependent on the baseline carbon intensity of the target grid scenario and the boundary energy losses incurred during the remanufacturing and reassembly processes [102]. Facing the imminent wave of large-scale battery retirements, second-life utilization will serve as a pivotal low-carbon bridge connecting the automotive industry with renewable power grids [47].

Table 5. Comparison of major battery-recycling technologies.

Technology	Main Principle	Main Advantage	Main Limitation	Carbon-Emission Implication
Pyrometallurgy	High-temperature smelting to recover metals	Robust and suitable for mixed or contaminated batteries	High energy demand; lithium recovery is limited	Usually has relatively high process emissions
Hydrometallurgy	Leaching and chemical separation of metals	High recovery efficiency and good selectivity	Chemical consumption and wastewater treatment are required	Emissions depend strongly on chemicals ; electricity,
DPR	Recycling	Preserves material structure and reduces energy demand	Sensitive to battery chemistry and feedstock quality	Potentially the lowest carbon emissions, but technology is less mature

Table 6. Carbon mitigation benefits of second-life battery utilization.

Battery Type	Second-Life Scenario	Key Emission Reduction Conclusion	Reference
NCM	Residential PV Storage	Life cycle climate change impact reduced by approx. 16%	[47]
EVs Batteries	Stationary Energy Storage	Benefit varies: depends on the substituted technology	[100]
EVs Batteries	Regional Grid Storage	Second-life reduction (55.8 Mt) > DPR (48.3 Mt)	[103]
LFP & NCM	Microgrid/Renewable Support	Annualized carbon emission reduction 2.8–18.5%	[104]
NCM111	Remanufacturing	GHG emissions reduced by approx. 38.15%	[105]
NCM	Residential PV	Life cycle GWP reduced by 15–25%	[106]
NCM & LFP	Peak Shaving	Economic ROI highly dependent on aging model	[107]
NCM & LFP	Energy Storage Stations	Every 1 kWh of second-life battery reduces 242.652 kg CO ₂ -eq	[108]

For retired EV batteries repurposed for stationary energy storage, the allocation of life-cycle carbon burdens between the first automotive life and the subsequent stationary-storage life is a critical methodological issue. Several approaches have been adopted in previous LCA studies. Under the cut-off approach, the battery manufacturing burdens are fully assigned to the first-life vehicle, while the second-life system accounts only for additional impacts from testing, disassembly, transportation, repackaging, operation, and final recycling [109,110]. The 50/50 approach distributes the manufacturing and recycling burdens equally between the two applications. Physical allocation assigns the burdens according to remaining capacity, state of health, module retention, or the energy-storage service delivered during each life. Economic allocation distributes the burdens according to the relative economic value of the battery in the automotive and stationary-storage applications. Alternatively, system expansion can be applied by crediting the second-life system for the avoided production of an equivalent new stationary-storage battery. Because these approaches can substantially affect the estimated carbon benefits of second-life batteries, the system boundary, functional unit, allocation factor, and substituted reference technology should be explicitly reported, and double counting of manufacturing burdens or recycling credits should be avoided [111–113].

In summary, the recycling phase constitutes the critical closed-loop for the life-cycle carbon mitigation of EVs. The selection of technological routes directly dictates whether the recycling segment yields net emission reductions or incurs high energy consumption. Research demonstrates that DPR possesses the highest mitigation potential, as it preserves the crystal structure of cathode materials and circumvents the necessity for extreme temperatures or massive chemical reagent consumption. Furthermore, the marginal benefits of recycling are highly correlated with the intrinsic value of battery materials. For NCM batteries rich in nickel and cobalt, recycling not only presents substantial economic viability but also circumvents high-carbon-intensity metal extraction, thereby yielding pronounced environmental benefits. Concurrently, second-life utilization amortizes manufacturing emissions by prolonging battery lifespans, serving as a pivotal mitigation bridge connecting the automotive and energy systems. As delineated in the investigative analysis in Section 3.1, the battery manufacturing phase constitutes a core emission source within the EV life-cycle. Therefore, prior to terminal recycling, prolonging the battery service lifespan via second-life utilization can effectively amortize the elevated manufacturing carbon footprint, thereby maximizing the life-cycle environmental dividends of EVs.

4. Discussion

The preceding analysis indicates that the life-cycle carbon emissions of EVs depend not only on vehicle, battery, and recycling technologies, but also on the electricity mix, charging infrastructure, and coordination between the transport and energy systems.

4.1. Evolutionary Trajectory of EV Carbon Emissions in China

This review synthesizes evidence on carbon accounting and mitigation across the manufacturing, use, and recycling stages of EVs in China. Figure 7 depicts the evolution trajectory of carbon emissions of China's EVs. The decarbonization trajectory of China's EV industry is not a static linear optimization; rather, it has undergone a three-stage evolutionary path: from passive constraint by the energy structure, to active propulsion by underlying technologies, and ultimately toward system-level synergy between the transportation and energy networks. During the nascent stage prior to 2010, constrained by a coal-dominated power structure, the carbon mitigation advantages of EVs were not pronounced, with their carbon dioxide emissions per unit distance even exceeding those of hybrid electric vehicles (HEVs) [3].

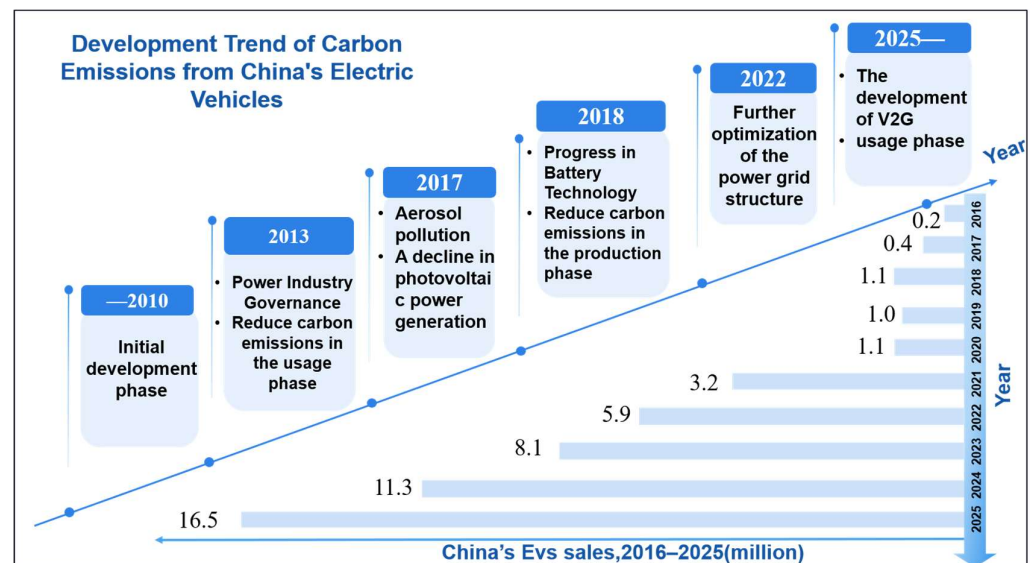


Figure 7. Evolutionary trajectory of EV carbon emissions in China [3,105,114–125].

A crucial turning point emerged in 2013 with the deep governance of the power sector triggered by the Air Pollution Prevention and Control Action Plan. The widespread deployment of desulfurization and denitrification facilities drastically reduced both pollutant and carbon emission intensities on the charging supply side [3,114]. Post-2017, the indirect dividends of aerosol pollution mitigation materialized; enhanced solar radiation boosted photovoltaic generation efficiency by 11–15%, thereby optimizing the charging carbon footprint of EVs from the energy supply end [115]. By around 2018, the epicenter of emission reduction shifted toward the manufacturing phase. Breakthroughs in battery technologies, such as all-weather fast charging, not only miniaturized battery pack volumes but also significantly lowered the manufacturing energy consumption per kWh [116].

Looking toward 2025 and beyond, this low-carbon transition will enter a phase of rapid acceleration. Driven by the large-scale application of V2G technologies, EVs will transform from passive electrical loads into flexible energy storage resources. By absorbing variable renewable energy (VRE) at high frequencies and executing grid peak shaving and valley filling, this paradigm shift catalyzes the profound integration of the transportation and energy systems. Ultimately, it firmly establishes EVs as the core pillar for achieving life-cycle carbon neutrality within the transportation sector [117].

4.2. System-Level Perspectives and Future Research

The life-cycle decarbonization of EVs should also be assessed within a broader multi-source energy system integrating renewable generation, stationary energy storage, charging infrastructure, and the power grid. Coordinated grid-to-vehicle (G2V) charging can shift electricity demand to periods of surplus renewable generation or lower grid carbon intensity, while V2G and stationary storage can provide additional flexibility during peak-load periods [54–58,64,66]. However, continued growth in the EV fleet without corresponding expansion of distribution-grid capacity may result in local congestion, transformer overloading, and additional peak-generation demand. The deployment of charging infrastructure should therefore be coordinated with local grid hosting capacity, renewable-energy availability, and energy-storage planning. Such coordination can improve renewable-energy utilization and reduce charging-related emissions, although its net mitigation benefit remains dependent on the electricity mix, charging efficiency, and the generation sources displaced by V2G discharge.

Digital technologies associated with Industry 4.0 and Industry 5.0 provide practical tools for achieving such system-level coordination. Real-time sensing, multiphysics modelling, and intelligent optimization have been applied to improve the design and operational performance of renewable-energy systems, as exemplified by recent smart optimization approaches for wind turbines [126]. For EV applications, future research should integrate vehicle-level life-cycle assessment with time-resolved grid carbon intensity and charging-network constraints to enable the joint optimization of renewable generation, G2V charging, V2G discharging, and stationary energy storage. Such optimization should consider carbon emissions alongside grid reliability, battery degradation, economic costs, and users' mobility requirements.

4.3. Practical Implications

Based on the preceding life-cycle and system-level analyses, several practical implications can be identified for Chinese enterprises and policymakers. Battery and vehicle manufacturers should reduce emissions from material processing and cell production, improve the traceability of product-level carbon footprint data, and consider repair, second-life use, and recycling at the design stage. Policy priorities include improving China-specific life-cycle data and region- and time-resolved electricity emission factors; piloting carbon-aware charging and V2G with appropriate incentives and emissions verification; and strengthening battery traceability and extended producer responsibility. Clear carbon allocation rules for second-life batteries are also needed. In response to emerging green trade requirements, including the EU Battery Regulation and the CBAM, developing a frequently updated, China-specific LCA reference database that facilitates international comparability and mutual recognition has become an important priority.

5. Conclusions

This review demonstrates that achieving deep decarbonization across the full life cycle of EVs requires coordinated mitigation across the manufacturing, use, and end-of-life stages. Technological improvements targeting any single stage are unlikely to deliver life-cycle carbon neutrality because emissions and mitigation benefits are transferred and interconnected across battery production, electricity generation, vehicle operation, second-life use, and material recycling.

The manufacturing stage generates substantial embodied emissions, although its contribution varies with battery capacity and chemistry, production electricity, vehicle lifetime mileage, system boundaries, and use-phase grid carbon intensity. During vehicle use phases, grid decarbonization remains the primary determinant of emission reductions. Coordinated V2G discharging can facilitate renewable-energy integration when they reduce curtailment or displace high-carbon generation, but their net benefits depend on charging efficiency, battery degradation, vehicle availability, user participation, and local grid conditions. At the recycling phases, battery second-life use can extend the service provided by previously manufactured batteries, while recycling can reduce demand for virgin materials. However, their estimated environmental benefits remain sensitive to recovery technologies, substituted products, system boundaries, and the allocation of emissions and credits between first-life and second-life applications. Overall, the life-cycle decarbonization of EVs in China depends on the combined progress of low-carbon battery manufacturing, power-sector decarbonization, carbon-aware vehicle-grid coordination, and transparent accounting for battery second-life use and recycling.

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L.Z., H.W. and F.G.; visualization, F.L.; supervision, L.Z. and H.W.; project administration, J.F. and F.G.; funding acquisition, X.H. All authors have read and agreed to the published version of the manuscript.

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References

1. The International Energy Agency (IEA). *Global EV Outlook 2025*; The International Energy Agency (IEA): Paris, France, 2025.
2. Cano, A.; Arévalo, P.; Benavides, D.; Jurado, F. Sustainable tramway, techno-economic analysis and environmental effects in an urban public transport: A comparative study. *Sustain. Energy Grids Netw.* **2021**, *26*, 100462. [\[CrossRef\]](#)
3. Huo, H.; Zhang, Q.; Wang, M.Q.; Streets, D.G.; He, K. Environmental Implication of Electric Vehicles in China. *Environ. Sci. Technol.* **2010**, *44*, 4856–4861. [\[CrossRef\]](#)
4. Qiao, Q.; Zhao, F.; Liu, Z.; He, X.; Hao, H. Life cycle greenhouse gas emissions of Electric Vehicles in China: Combining the vehicle cycle and fuel cycle. *Energy* **2019**, *177*, 222–233. [\[CrossRef\]](#)
5. Huo, H.; Cai, H.; Zhang, Q.; Liu, F.; He, K. Life-cycle assessment of greenhouse gas and air emissions of electric vehicles: A comparison between China and the U.S. *Atmos. Environ.* **2015**, *108*, 107–116. [\[CrossRef\]](#)
6. Khanna, D.; Gemechu, E.; Mahbub, N.; Joy, J.; Kumar, A. Assessment of life cycle environmental impacts of materials, driving pattern, and climatic conditions on battery electric and hydrogen fuel cell vehicles in a cold region. *Environ. Impact Assess. Rev.* **2025**, *110*, 107680. [\[CrossRef\]](#)
7. Benveniste, G.; Sánchez, A.; Rallo, H.; Corchero, C.; Amante, B. Comparative life cycle assessment of Li-Sulphur and Li-ion batteries for electric vehicles. *Resour. Conserv. Recycl. Adv.* **2022**, *15*, 200086. [\[CrossRef\]](#)
8. Feng, T.; Guo, W.; Li, Q.; Meng, Z.; Liang, W. Life cycle assessment of lithium nickel cobalt manganese oxide batteries and lithium iron phosphate batteries for electric vehicles in China. *J. Energy Storage* **2022**, *52*, 104767. [\[CrossRef\]](#)
9. Wu, Z.; Wang, M.; Zheng, J.; Sun, X.; Zhao, M.; Wang, X. Life cycle greenhouse gas emission reduction potential of battery electric vehicle. *J. Clean. Prod.* **2018**, *190*, 462–470. [\[CrossRef\]](#)
10. Tao, Y.; Rahn, C.D.; Tao, Y.; Archer, L.A.; You, F. Second life and recycling: Energy and environmental sustainability perspectives for high-performance lithium-ion batteries. *Sci. Adv.* **2021**, *7*, eabi7633. [\[CrossRef\]](#)
11. Huang, J.; Boles, S.T.; Tarascon, J.-M. Sensing as the key to battery lifetime and sustainability. *Nat. Sustain.* **2022**, *5*, 194–204. [\[CrossRef\]](#)
12. Yang, K.; Zhang, Q.; Wang, G.; Li, H.; McLellan, B. A new model for comprehensively evaluating the economic and environmental effects of vehicle-to-grid (V2G) towards carbon neutrality. *J. Energy Storage* **2024**, *98*, 113067. [\[CrossRef\]](#)
13. Winjobi, O.; Kelly, J.C.; Dai, Q. Life-cycle analysis, by global region, of automotive lithium-ion nickel manganese cobalt batteries of varying nickel content. *Sustain. Mater. Technol.* **2022**, *32*, e00415. [\[CrossRef\]](#)
14. ISO 14040:2006; Environmental Management—Life Cycle Assessment—Principles and Framework. International Organization for Standardization: Geneva, Switzerland, 2006.
15. ISO 14044:2006; Environmental Management—Life Cycle Assessment—Requirements and Guidelines. International Organization for Standardization: Geneva, Switzerland, 2006.
16. Rebitzer, G.; Ekvall, T.; Frischknecht, R.; Hunkeler, D.; Norris, G.; Rydberg, T.; Schmidt, W.-P.; Suh, S.; Weidema, B.P.; Pennington, D.W. Life cycle assessment. *Environ. Int.* **2004**, *30*, 701–720. [\[CrossRef\]](#)
17. Regulation (EU) 2023/1542; Regulation of the European Parliament and of the Council of 12 July 2023 Concerning Batteries and Waste Batteries, Amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and Repealing Directive 2006/66/EC. European Union: Brussels, Belgium, 2023.
18. Temporelli, A.; Carvalho, M.L.; Girardi, P. Life Cycle Assessment of Electric Vehicle Batteries: An Overview of Recent Literature. *Energies* **2020**, *13*, 2864. [\[CrossRef\]](#)

19. T/CSAE 91-2018; Method of Life Cycle Assessment for Vehicle Greenhouse Gas and Air Pollutant Emissions. China Society of Automotive Engineers: Beijing, China, 2018.
20. Hao, H.; Mu, Z.; Jiang, S.; Liu, Z.; Zhao, F. GHG Emissions from the Production of Lithium-Ion Batteries for Electric Vehicles in China. *Sustainability* **2017**, *9*, 504. [\[CrossRef\]](#)
21. Liu, Y.; Zhang, C.; Hao, Z.; Cai, X.; Liu, C.; Zhang, J.; Wang, S.; Chen, Y. Study on the Life Cycle Assessment of Automotive Power Batteries Considering Multi-Cycle Utilization. *Energies* **2023**, *16*, 6859. [\[CrossRef\]](#)
22. Fahimi, A.; Ducoli, S.; Federici, S.; Ye, G.; Mousa, E.; Frontera, P.; Bontempi, E. Evaluation of the sustainability of technologies to recycle spent lithium-ion batteries, based on embodied energy and carbon footprint. *J. Clean. Prod.* **2022**, *338*, 130493. [\[CrossRef\]](#)
23. Quan, J.; Zhao, S.; Song, D.; Wang, T.; He, W.; Li, G. Comparative life cycle assessment of LFP and NCM batteries including the secondary use and different recycling technologies. *Sci. Total Environ.* **2022**, *819*, 153105. [\[CrossRef\]](#)
24. Bishop, J.D.K.; Molden, N.; Boies, A.M. Using portable emissions measurement systems (PEMS) to derive more accurate estimates of fuel use and nitrogen oxides emissions from modern Euro 6 passenger cars under real-world driving conditions. *Appl. Energy* **2019**, *242*, 942–973. [\[CrossRef\]](#)
25. Perugu, H. Emission modelling of light-duty vehicles in India using the revamped VSP-based MOVES model: The case study of Hyderabad. *Transp. Res. Part Transp. Environ.* **2019**, *68*, 150–163. [\[CrossRef\]](#)
26. Jimenez-Palacios, J.L. Understanding and Quantifying Motor Vehicle Emissions with Vehicle Specific Power and TILDAS Remote Sensing. Ph.D. Thesis, Massachusetts Institute of Technology, Cambridge, MA, USA, 1999.
27. Zhang, J.; Wang, Z.; Liu, P.; Zhang, Z. Energy consumption analysis and prediction of electric vehicles based on real-world driving data. *Appl. Energy* **2020**, *275*, 115408. [\[CrossRef\]](#)
28. Fiori, C.; Ahn, K.; Rakha, H.A. Power-based electric vehicle energy consumption model: Model development and validation. *Appl. Energy* **2016**, *168*, 257–268. [\[CrossRef\]](#)
29. Kelly, J.C.; Dai, Q.; Wang, M. Globally regional life cycle analysis of automotive lithium-ion nickel manganese cobalt batteries. *Mitig. Adapt. Strateg. Glob. Change* **2020**, *25*, 371–396. [\[CrossRef\]](#)
30. Tagliaferri, C.; Evangelisti, S.; Acconcia, F.; Domenech, T.; Ekins, P.; Barletta, D.; Lettieri, P. Life cycle assessment of future electric and hybrid vehicles: A cradle-to-grave systems engineering approach. *Chem. Eng. Res. Des.* **2016**, *112*, 298–309. [\[CrossRef\]](#)
31. Qiao, Q.; Zhao, F.; Liu, Z.; Jiang, S.; Hao, H. Cradle-to-gate greenhouse gas emissions of battery electric and internal combustion engine vehicles in China. *Appl. Energy* **2017**, *204*, 1399–1411. [\[CrossRef\]](#)
32. Karimi, G.; Li, X. Thermal management of lithium-ion batteries for electric vehicles: Thermal management of Li-ion battery packs. *Int. J. Energy Res.* **2013**, *37*, 13–24. [\[CrossRef\]](#)
33. Ellingsen, L.A.-W.; Singh, B.; Strømman, A.H. The size and range effect: Lifecycle greenhouse gas emissions of electric vehicles. *Environ. Res. Lett.* **2016**, *11*, 054010. [\[CrossRef\]](#)
34. Yu, M.; Bai, B.; Xiong, S.; Liao, X. Evaluating environmental impacts and economic performance of remanufacturing electric vehicle lithium-ion batteries. *J. Clean. Prod.* **2021**, *321*, 128935. [\[CrossRef\]](#)
35. Lu, Y.; Liu, Q.; Zhu, J.; Zhao, Z.; Li, Z.; Li, Q. Effects of lightweighting on emissions of vehicles with different powertrains: Insights from dynamic and interpretable life cycle assessment. *J. Clean. Prod.* **2025**, *524*, 146500. [\[CrossRef\]](#)
36. Sun, X.; Meng, F.; Liu, J.; McKechnie, J.; Yang, J. Life cycle energy use and greenhouse gas emission of lightweight vehicle—A body-in-white design. *J. Clean. Prod.* **2019**, *220*, 1–8. [\[CrossRef\]](#)
37. Ahmadzadeh, O.; Rodriguez, R.; Getz, J.; Panneerselvam, S.; Soudbakhsh, D. The impact of lightweighting and battery technologies on the sustainability of electric vehicles: A comprehensive life cycle assessment. *Environ. Impact Assess. Rev.* **2025**, *110*, 107668. [\[CrossRef\]](#)
38. Yang, L.; Yu, B.; Yang, B.; Chen, H.; Malima, G.; Wei, Y.-M. Life cycle environmental assessment of electric and internal combustion engine vehicles in China. *J. Clean. Prod.* **2021**, *285*, 124899. [\[CrossRef\]](#)
39. Lai, X.; Chen, J.; Chen, Q.; Tang, B.; Zheng, Y.; Cheng, E. Investigating the impact of electric vehicle range on use-phase carbon footprint: A life cycle assessment approach. *Process Saf. Environ. Prot.* **2025**, *197*, 107044. [\[CrossRef\]](#)
40. Crenna, E.; Gauch, M.; Widmer, R.; Wäger, P.; Hirschier, R. Towards more flexibility and transparency in life cycle inventories for Lithium-ion batteries. *Resour. Conserv. Recycl.* **2021**, *170*, 105619. [\[CrossRef\]](#)
41. Koroma, M.S.; Costa, D.; Philippot, M.; Cardellini, G.; Hosen, M.S.; Coosemans, T.; Messagie, M. Life cycle assessment of battery electric vehicles: Implications of future electricity mix and different battery end-of-life management. *Sci. Total Environ.* **2022**, *831*, 154859. [\[CrossRef\]](#)
42. Wang, Y.; Yu, Y.; Huang, K.; Chen, B.; Deng, W.; Yao, Y. Quantifying the environmental impact of a Li-rich high-capacity cathode material in electric vehicles via life cycle assessment. *Environ. Sci. Pollut. Res.* **2017**, *24*, 1251–1260. [\[CrossRef\]](#)
43. Wu, H.; Hu, Y.; Yu, Y.; Huang, K.; Wang, L. The environmental footprint of electric vehicle battery packs during the production and use phases with different functional units. *Int. J. Life Cycle Assess.* **2021**, *26*, 97–113. [\[CrossRef\]](#)
44. Zhang, H.; Zhao, F.; Hao, H.; Liu, Z. Life cycle emissions of passenger vehicles in China: A sensitivity analysis of multiple influencing factors. *Sustainability* **2023**, *15*, 4854. [\[CrossRef\]](#)

45. Farzaneh, F.; Jung, S. Lifecycle carbon footprint comparison between internal combustion engine versus electric transit vehicle: A case study in the U.S. *J. Clean. Prod.* **2023**, *390*, 136111. [\[CrossRef\]](#)
46. Philippot, M.; Costa, D.; Hosen, S.; Senécat, A.; Brouwers, E.; Nanini-Maury, E.; Van Mierlo, J.; Messagie, M. Environmental impact of the second life of an automotive battery: Reuse and repurpose based on ageing tests. *J. Clean. Prod.* **2022**, *366*, 132872. [\[CrossRef\]](#)
47. Botejara-Antúnez, M.; Prieto-Fernández, A.; González-Domínguez, J.; Sánchez-Barroso, G.; García-Sanz-Calcedo, J. Life cycle assessment of a LiFePO. *Environ. Sci. Pollut. Res.* **2024**, *31*, 57242–57258. [\[CrossRef\]](#)
48. Scrucca, F.; Presciutti, A.; Baldinelli, G.; Barberio, G.; Postrioti, L.; Karaca, C. Life cycle assessment of Li-ion batteries for electric vehicles: A review focused on the production phase impact. *J. Power Sources* **2025**, *639*, 236703. [\[CrossRef\]](#)
49. Lu, Y.; Liu, Q.; Li, B.; Jiang, Q.; Li, Q. Energy mix-driven dynamic life cycle assessment on greenhouse gas emissions of passenger cars in China. *J. Clean. Prod.* **2024**, *466*, 142817. [\[CrossRef\]](#)
50. Li, X.; Liu, Y.; Qu, Y.; Ding, L.; Yan, X. Effect of electric vehicles and renewable electricity on future life cycle air emissions from China's road transport fleet. *Energy* **2025**, *318*, 134969. [\[CrossRef\]](#)
51. Guo, W.; Feng, T.; Li, W.; Hua, L.; Meng, Z.; Li, K. Comparative life cycle assessment of sodium-ion and lithium iron phosphate batteries in the context of carbon neutrality. *J. Energy Storage* **2023**, *72*, 108589. [\[CrossRef\]](#)
52. Wu, Z.; Wang, C.; Wolfram, P.; Zhang, Y.; Sun, X.; Hertwich, E.G. Assessing electric vehicle policy with region-specific carbon footprints. *Appl. Energy* **2019**, *256*, 113923. [\[CrossRef\]](#)
53. Knobloch, F.; Hanssen, S.V.; Lam, A.; Pollitt, H.; Salas, P.; Chewprecha, U.; Huijbregts, M.A.J.; Mercure, J.-F. Net emission reductions from electric cars and heat pumps in 59 world regions over time. *Nat. Sustain.* **2020**, *3*, 437–447. [\[CrossRef\]](#)
54. Liu, Y.; Liu, Q.; Gao, L.; Xing, Y.; Chen, Y.; Zhang, S. The life cycle assessment and scenario simulation prediction of intelligent electric vehicles. *Energy Rep.* **2024**, *12*, 6046–6071. [\[CrossRef\]](#)
55. Qu, X.; Zhong, L.; Zeng, Z.; Tu, H.; Li, X. Automation and connectivity of electric vehicles: Energy boon or bane? *Cell Rep. Phys. Sci.* **2022**, *3*, 101002. [\[CrossRef\]](#)
56. Huang, K.; Zhang, Z.; Wang, X.; Tao, Y.; Liu, Z. Life-cycle carbon emissions of autonomous electric vehicles in varying traffic situations. *Transp. Res. Part Transp. Environ.* **2025**, *146*, 104871. [\[CrossRef\]](#)
57. Taiebat, M.; Brown, A.L.; Safford, H.R.; Qu, S.; Xu, M. A Review on Energy, Environmental, and Sustainability Implications of Connected and Automated Vehicles. *Environ. Sci. Technol.* **2018**, *52*, 11449–11465. [\[CrossRef\]](#)
58. Kazerani, M.; Arab Tehrani, K. Grid of Hybrid AC/DC Microgrids: A New Paradigm for Smart City of Tomorrow. In Proceedings of the 2020 IEEE 15th International Conference of System of Systems Engineering, Budapest, Hungary, 2–4 June 2020; pp. 175–180.
59. Wu, Y.; Lau, Y.-Y.; Wu, J.-A. Integration of Electric Vehicles into Microgrids: Policy Implication for the Industrial Application of Carbon Neutralisation in China. *World Electr. Veh. J.* **2022**, *13*, 96. [\[CrossRef\]](#)
60. Zhong, Z.; Yu, Y.; Zhao, X. Revisiting electric vehicle life cycle greenhouse gas emissions in China: A marginal emission perspective. *iScience* **2023**, *26*, 106565. [\[CrossRef\]](#)
61. Dixon, J.; Bukhsh, W.; Edmunds, C.; Bell, K. Scheduling electric vehicle charging to minimise carbon emissions and wind curtailment. *Renew. Energy* **2020**, *161*, 1072–1091. [\[CrossRef\]](#)
62. Xu, J.; Chen, J.; Wei, H.; Zhao, Y.; Tian, B.; Wen, Y.; Jiang, H.; Zhang, N.; Zhang, S.; Wu, Y. Emissions reduction potential and feasibility of vehicle-to-grid for Beijing's future electric vehicles. *Cell Rep. Phys. Sci.* **2025**, *6*, 102616. [\[CrossRef\]](#)
63. Kataoka, R.; Ogimoto, K.; Iwafune, Y.; Nishi, T. Does BEV always help to reduce CO2 emission? impact of charging strategy. *Transp. Res. Part Transp. Environ.* **2024**, *129*, 104124. [\[CrossRef\]](#)
64. Dioha, M.O.; Ruggles, T.H.; Ashfaq, S.; Caldeira, K. Idealized analysis of relative values of bidirectional versus unidirectional electric vehicle charging in deeply decarbonized electricity systems. *iScience* **2022**, *25*, 104906. [\[CrossRef\]](#)
65. Aguilar Lopez, F.; Lauinger, D.; Vuille, F.; Müller, D.B. On the potential of vehicle-to-grid and second-life batteries to provide energy and material security. *Nat. Commun.* **2024**, *15*, 4179. [\[CrossRef\]](#)
66. Ramos, A.; Latorre, J.M.; Báñez, F.; Hernández, Á.; Morales-España, G.; Dietrich, K.; Olmos, L. Modeling the Operation of Electric Vehicles in an Operation Planning Model. In Proceedings of the 17th Power Systems Computation Conference, Stockholm, Sweden, 22–26 August 2011; pp. 987–994.
67. Ma, S.-C.; Fan, Y.; Yao, X.; Fang, H.; Xu, C. Cost and environmental impacts assessment of electric vehicles and power systems synergy: The role of vehicle-to-grid technology. *Environ. Impact Assess. Rev.* **2025**, *114*, 107899. [\[CrossRef\]](#)
68. Wohlschlager, D.; Kigle, S.; Schindler, V.; Neitz-Regett, A.; Fröhling, M. Environmental effects of vehicle-to-grid charging in future energy systems—A prospective life cycle assessment. *Appl. Energy* **2024**, *370*, 123618. [\[CrossRef\]](#)
69. Tian, X.; Zha, H.; Tian, Z.; Lang, G.; Li, L. Carbon emission reduction capability assessment based on synergistic optimization control of electric vehicle V2G and multiple types power supply. *Energy Rep.* **2024**, *11*, 1191–1198. [\[CrossRef\]](#)
70. Chen, J.; Craig, M.T.; Michalek, J.; Bruchon, M.; Vaishnav, P. Negative Electric Vehicle Emissions: Vehicle-to-Grid Can Incentivize Enough Wind and Solar Investment to Reverse EV Charging Emissions. *Environ. Sci. Technol.* **2025**, *59*, 21090–21101. [\[CrossRef\]](#)

71. Yao, S.; Bian, Z.; Hasan, M.K.; Ding, R.; Li, S.; Wang, Y.; Song, S. A bibliometric review on electric vehicle (EV) energy efficiency and emission effect research. *Environ. Sci. Pollut. Res.* **2023**, *30*, 95172–95196. [\[CrossRef\]](#)
72. Li, Y.; Huang, Y.; Liang, Y.; Song, C.; Liao, S. Economic and carbon reduction potential assessment of vehicle-to-grid development in guangdong province. *Energy* **2024**, *302*, 131742. [\[CrossRef\]](#)
73. Du, P.; Liu, T.; Chen, T.; Jiang, M.; Zhu, H.; Shang, Y.; Goh, H.H.; Zhao, H.; Huang, C.; Kong, F.; et al. Enhancing green mobility through vehicle-to-grid technology: Potential, technological barriers, and policy implications. *Energy Environ. Sci.* **2025**, *18*, 4496–4520. [\[CrossRef\]](#)
74. Fang, C.; Li, W.; Wang, H.; Zhou, Y.; Shi, S.; Feng, D. Estimation of Urban V2G Carbon Emission Reduction Potential. In *Proceedings of the 2023 IEEE 7th Conference on Energy Internet and Energy System Integration EI2, Hangzhou, China, 15–18 December 2023*; IEEE: New York, NY, USA, 2023; pp. 135–141. [\[CrossRef\]](#)
75. Gunkel, P.A.; Bergaentzle, C.; Jensen, I.G.; Scheller, F. From passive to active: Flexibility from electric vehicles in the context of transmission system development. *Appl. Energy* **2020**, *277*, 115526. [\[CrossRef\]](#)
76. Wu, Y.; Huang, S.; Alharthi, Y.Z.; Wang, Y. Market scheduling of emission-aware smart prosumers in smart grids: A multi-objective bi-level approach. *Appl. Energy* **2025**, *389*, 125745. [\[CrossRef\]](#)
77. Yu, S.; Huang, Y.; Chen, Y. Optimization of Orderly Charging/Discharging Strategy for Electric Vehicles Considering Incremental Cost of V2G. *E3S Web Conf.* **2023**, *466*, 02011. [\[CrossRef\]](#)
78. Tian, B.; Shen, W.; Zhang, C.; Anderson, J.E.; Degner, M.W.; Lu, X.; Zhao, S.; Wu, Y.; Zhang, S. Optimizing the charging behaviors of private BEVs to enhance coordinated charging and V2G in Beijing. *eTransportation* **2025**, *26*, 100470. [\[CrossRef\]](#)
79. Wei, Y.; Pang, K.; Li, Y.; Wang, H.; Lu, L.; Ouyang, M. Potential Benefits of Vehicle-to-grid (V2G) to Decarbonization Pathways toward Carbon Neutrality. In *Proceedings of the 2024 9th Asia Conference on Power and Electrical Engineering ACPEE, Shanghai, China, 11–13 April 2024*; IEEE: New York, NY, USA, 2023; Volume 2024, pp. 2749–2753. [\[CrossRef\]](#)
80. Vollmuth, P.; Wohlschlager, D.; Wasmeier, L.; Kern, T. Prospects of electric vehicle V2G multi-use: Profitability and GHG emissions for use case combinations of smart and bidirectional charging today and 2030. *Appl. Energy* **2024**, *371*, 123679. [\[CrossRef\]](#)
81. Li, J.; Wang, G.; Wang, X.; Du, Y. Smart charging strategy for electric vehicles based on marginal carbon emission factors and time-of-use price. *Sustain. Cities Soc.* **2023**, *96*, 104708. [\[CrossRef\]](#)
82. Zhong, C.-Y.; Cai, Q.; Creutzig, F.; Qing, J.; Xu, Q.; Liang, Q.-M. Techno-environmental and economic impacts of EV charging strategies on urban power systems under fleet heterogeneity and electrification uncertainty. *Energy* **2025**, *336*, 138497. [\[CrossRef\]](#)
83. Yu, B.; Lei, X.; Shao, Z.; Jian, L. V2G Carbon Accounting and Revenue Allocation: Balancing EV Contributions in Distribution Systems. *Electronics* **2024**, *13*, 1063. [\[CrossRef\]](#)
84. Peterson, S.B.; Apt, J.; Whitacre, J.F. Lithium-ion battery cell degradation resulting from realistic vehicle and vehicle-to-grid utilization. *J. Power Sources* **2010**, *195*, 2385–2392. [\[CrossRef\]](#)
85. Dubarry, M.; Devie, A.; McKenzie, K. Durability and reliability of electric vehicle batteries under electric utility grid operations: Bidirectional charging impact analysis. *J. Power Sources* **2017**, *358*, 39–49. [\[CrossRef\]](#)
86. Harnischmacher, C.; Markefke, L.; Brendel, A.B.; Kolbe, L. Two-sided sustainability: Simulating battery degradation in vehicle to grid applications within autonomous electric port transportation. *J. Clean. Prod.* **2023**, *384*, 135598. [\[CrossRef\]](#)
87. Zhao, G.; Baker, J. Effects on environmental impacts of introducing electric vehicle batteries as storage—A case study of the United Kingdom. *Energy Strategy Rev.* **2022**, *40*, 100819. [\[CrossRef\]](#)
88. International Energy Agency. *Vehicle-to-Grid Technology*; IEA: Paris, France, 2026. Available online: <https://www.iea.org/reports/vehicle-to-grid-technology> (accessed on 8 September 2026).
89. Goncencar, A.; De Cauwer, C.; Sapountzoglou, N.; Van Krieking, G.; Huber, D.; Messagie, M.; Coosemans, T. The barriers to widespread adoption of vehicle-to-grid: A comprehensive review. *Energy Rep.* **2024**, *12*, 27–41. [\[CrossRef\]](#)
90. Petrauskienė, K.; Skvarnavičiūtė, M.; Dvarionienė, J. Comparative environmental life cycle assessment of electric and conventional vehicles in Lithuania. *J. Clean. Prod.* **2020**, *246*, 119042. [\[CrossRef\]](#)
91. Maselli, M.; Pelegrina, J.; Marotti De Mello, A.; Ribeiro Souza, J.V.; Marx, R.; Priarone, P.C. Electric or internal combustion vehicles? A Life Cycle Assessment in São Paulo, Renew. *Sustain. Energy Rev.* **2025**, *212*, 115431. [\[CrossRef\]](#)
92. Jenn, A. Emissions of electric vehicles in California's transition to carbon neutrality. *Appl. Energy* **2023**, *339*, 120974. [\[CrossRef\]](#)
93. Burchart-Korol, D.; Jursova, S.; Folega, P.; Korol, J.; Pustejovska, P.; Blaut, A. Environmental life cycle assessment of electric vehicles in Poland and the Czech Republic. *J. Clean. Prod.* **2018**, *202*, 476–487. [\[CrossRef\]](#)
94. Du, B.; Jia, H.; Zhang, B.; Li, Y.; Wang, H.; Yan, J.; Du, E.; Zhang, N. Evaluating the carbon-emission reduction potential of employing low-carbon demand response to guide electric-vehicle charging: A Chinese case study. *Appl. Energy* **2025**, *397*, 126196. [\[CrossRef\]](#)
95. Rüdisüli, M.; Bach, C.; Bauer, C.; Beloin-Saint-Pierre, D.; Elber, U.; Georges, G.; Limpach, R.; Pareschi, G.; Kannan, R.; Teske, S.L. Prospective life-cycle assessment of greenhouse gas emissions of electricity-based mobility options. *Appl. Energy* **2022**, *306*, 118065. [\[CrossRef\]](#)

96. Hu, D.; Zhou, K.; Hu, R.; Yang, J. Provincial inequalities in life cycle carbon dioxide emissions and air pollutants from electric vehicles in China. *Commun. Earth Environ.* **2024**, *5*, 726. [\[CrossRef\]](#)
97. Li, Y.; Ha, N.; Li, T. Research on Carbon Emissions of Electric Vehicles throughout the Life Cycle Assessment Taking into Vehicle Weight and Grid Mix Composition. *Energies* **2019**, *12*, 3612. [\[CrossRef\]](#)
98. Dunn, J.B.; Gaines, L.; Sullivan, J.; Wang, M.Q. Impact of recycling on cradle-to-gate energy consumption and greenhouse gas emissions of automotive lithium-ion batteries. *Environ. Sci. Technol.* **2012**, *46*, 12704–12710. [\[CrossRef\]](#)
99. Ciez, R.E.; Whitacre, J.F. Examining different recycling processes for lithium-ion batteries. *Nat. Sustain.* **2019**, *2*, 148–156. [\[CrossRef\]](#)
100. Casals, L.C.; García, B.A.; Canal, C. Second life batteries lifespan: Rest of useful life and environmental analysis. *J. Environ. Manag.* **2019**, *232*, 354–363. [\[CrossRef\]](#)
101. Li, X.; Zhang, L.; Liu, Y.; Pan, A.; Liao, Q.; Yang, X. A fast classification method of retired electric vehicle battery modules and their energy storage application in photovoltaic generation. *Int. J. Energy Res.* **2020**, *44*, 2337–2344. [\[CrossRef\]](#)
102. Faria, R.; Marques, P.; Garcia, R.; Moura, P.; Freire, F.; Delgado, J.; de Almeida, A.T. Primary and secondary use of electric mobility batteries from a life cycle perspective. *J. Power Sources* **2014**, *262*, 169–177. [\[CrossRef\]](#)
103. Wesselkämper, J.; Hendrickson, T.P.; Lux, S.; Von Delft, S. Recycling or Second Use? Supply Potentials and Climate Effects of End-of-Life Electric Vehicle Batteries. *Environ. Sci. Technol.* **2025**, *59*, 15751–15765. [\[CrossRef\]](#)
104. Akram, M.N.; Abdul-Kader, W. Supporting Sustainable Development Goals with Second-Life Electric Vehicle Battery: A Case Study. *Sustainability* **2025**, *17*, 6307. [\[CrossRef\]](#)
105. Orsi, F.; Muratori, M.; Rocco, M.; Colombo, E.; Rizzoni, G. A multi-dimensional well-to-wheels analysis of passenger vehicles in different regions: Primary energy consumption, CO₂ emissions, and economic cost. *Appl. Energy* **2016**, *169*, 197–209. [\[CrossRef\]](#)
106. Cusenza, M.A.; Guarino, F.; Longo, S.; Mistretta, M.; Cellura, M. Reuse of electric vehicle batteries in buildings: An integrated load match analysis and life cycle assessment approach. *Energy Build.* **2019**, *186*, 339–354. [\[CrossRef\]](#)
107. Rallo, H.; Canals Casals, L.; De La Torre, D.; Reinhardt, R.; Marchante, C.; Amante, B. Lithium-ion battery 2nd life used as a stationary energy storage system: Ageing and economic analysis in two real cases. *J. Clean. Prod.* **2020**, *272*, 122584. [\[CrossRef\]](#)
108. Yu, W.; Zheng, Y.; Zhang, Y. Carbon Emission Reduction by Echelon Utilization of Retired Vehicle Power Batteries in Energy Storage Power Stations. *World Electr. Veh. J.* **2022**, *13*, 144. [\[CrossRef\]](#)
109. Wilson, N.; Meiklejohn, E.; Overton, B.; Robinson, F.; Farjana, S.H.; Li, W.; Staines, J. A physical allocation method for comparative life cycle assessment: A case study of repurposing Australian electric vehicle batteries. *Resour. Conserv. Recycl.* **2021**, *174*, 105759. [\[CrossRef\]](#)
110. Ahmadi, L.; Young, S.B.; Fowler, M.; Fraser, R.A.; Achachlouei, M.A. A cascaded life cycle: Reuse of electric vehicle lithium-ion battery packs in energy storage systems. *Int. J. Life Cycle Assess.* **2017**, *22*, 111–124. [\[CrossRef\]](#)
111. Bobba, S.; Mathieux, F.; Blengini, G.A. How will second-use of batteries affect stocks and flows in the EU? A model for assessing environmental impacts. *Resour. Conserv. Recycl.* **2019**, *145*, 279–291.
112. Dong, Q.; Liang, S.; Li, J.; Kim, H.C.; Shen, W.; Wallington, T.J. Cost, energy, and carbon footprint benefits of second-life electric vehicle battery use. *iScience* **2023**, *26*, 107195. [\[CrossRef\]](#)
113. Spindlegger, A.; Slotyuk, L.; Jandric, A.; De Souza, R.G.; Prenner, S.; Part, F. Environmental performance of second-life lithium-ion batteries repurposed from electric vehicles for household storage systems. *Sustain. Prod. Consum.* **2025**, *54*, 227–240. [\[CrossRef\]](#)
114. Karplus, V.J.; Zhang, S.; Almond, D. Quantifying coal power plant responses to tighter SO₂ emissions standards in China. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, 7004–7009. [\[CrossRef\]](#)
115. Li, X.; Wagner, F.; Peng, W.; Yang, J.; Mauzerall, D.L. Reduction of solar photovoltaic resources due to air pollution in China. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 11867–11872. [\[CrossRef\]](#)
116. Yang, X.-G.; Zhang, G.; Ge, S.; Wang, C.-Y. Fast charging of lithium-ion batteries at all temperatures. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, 7266–7271. [\[CrossRef\]](#)
117. Ma, Y.; Ke, R.-Y.; Han, R.; Tang, B.-J. The analysis of the battery electric vehicle's potentiality of environmental effect: A case study of Beijing from 2016 to 2020. *J. Clean. Prod.* **2017**, *145*, 395–406. [\[CrossRef\]](#)
118. Fang, J.; Yu, G.; Liu, L.; Hu, S.; Chapin, F.S. Climate change, human impacts, and carbon sequestration in China. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, 4015–4020. [\[CrossRef\]](#)
119. Guo, S.; Hu, M.; Zamora, M.L.; Peng, J.; Shang, D.; Zheng, J.; Du, Z.; Wu, Z.; Shao, M.; Zeng, L.; et al. Elucidating severe urban haze formation in China. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 17373–17378. [\[CrossRef\]](#)
120. Tessum, C.W.; Hill, J.D.; Marshall, J.D. Life cycle air quality impacts of conventional and alternative light-duty transportation in the United States. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 18490–18495. [\[CrossRef\]](#)
121. Zhao, Y.; Saleh, R.; Saliba, G.; Presto, A.A.; Gordon, T.D.; Drozd, G.T.; Goldstein, A.H.; Donahue, N.M.; Robinson, A.L. Reducing secondary organic aerosol formation from gasoline vehicle exhaust. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 6984–6989. [\[CrossRef\]](#)
122. Soret, A.; Guevara, M.; Baldasano, J.M. The potential impacts of electric vehicles on air quality in the urban areas of Barcelona and Madrid (Spain). *Atmos. Environ.* **2014**, *99*, 51–63. [\[CrossRef\]](#)

123. Michalek, J.J.; Chester, M.; Jaramillo, P.; Samaras, C.; Shiau, C.-S.N.; Lave, L.B. Valuation of plug-in vehicle life-cycle air emissions and oil displacement benefits. *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 16554–16558. [[CrossRef](#)]
124. Woo, J.; Choi, H.; Ahn, J. Well-to-wheel analysis of greenhouse gas emissions for electric vehicles based on electricity generation mix: A global perspective. *Transp. Res. Part Transp. Environ.* **2017**, *51*, 340–350. [[CrossRef](#)]
125. Ke, W.; Zhang, S.; He, X.; Wu, Y.; Hao, J. Well-to-wheels energy consumption and emissions of electric vehicles: Mid-term implications from real-world features and air pollution control progress. *Appl. Energy* **2017**, *188*, 367–377. [[CrossRef](#)]
126. Tehrani, K.; Beikbabaie, M.; Mehrizi-Sani, A.; Jamshidi, M. A smart multiphysics approach for wind turbines design in Industry 5.0. *J. Ind. Inf. Integr.* **2024**, *42*, 100704. [[CrossRef](#)]

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