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Systematic Review

Electric Vehicle Adoption: A Comprehensive Systematic Review of Technological, Environmental, Organizational and Policy Impacts

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Abstract: This comprehensive systematic review explores the multifaceted impacts of electric vehicle (EV) adoption across technological, environmental, organizational, and policy dimensions. Drawing from 88 peer-reviewed articles, the study addresses a critical gap in the existing literature, which often isolates the impact of EV adoption without considering holistic effects. Technological advancements include innovations in the battery technology and energy storage systems, enhancing EV performance and mitigating range anxiety. The environmental analysis reveals substantial reductions in greenhouse gas emissions, with lifecycle assessments showing significant reductions for EVs compared to internal combustion engine vehicles, particularly when charged with renewable energy sources. Key comparisons include lifecycle emissions between mid-size battery electric vehicles (BEVs) and internal combustion engine vehicles (ICEVs), and global average lifecycle emissions by powertrain under various policy scenarios. The organizational implications are evident, as businesses adopt new models for fleet management and logistics, leveraging EVs for operational efficiency and sustainability. Policy analysis underscores the crucial role of government incentives, regulatory measures, and infrastructure investments in accelerating EV adoption. The review identifies future research areas such as efficient battery recycling methods, the potential impact of EVs on grid stability, and long-term economic implications. This study offers insights for stakeholders aiming to foster sustainable transportation and achieve global climate goals.

Keywords: electric vehicles; sustainability; environment; organizations; technology; sustainable infrastructure; policy frameworks; energy efficiency

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1. Introduction

Electric vehicles (EVs) are cars and trucks that run on electricity instead of gasoline or diesel. Adopting EVs refers to the increased choice of electric vehicles over traditional fossil fuel-powered vehicles by individuals and companies. Over the past decade, interest in EVs has grown, as more consumers and businesses recognize the benefits of cleaner, more efficient transportation [1]. According to [2], this shift is supported by significant advancements in EV technology and infrastructure, which have helped alleviate some of the early concerns such as battery life and the availability of charging stations. Policy and fiscal incentives are crucial in driving EV adoption. Strategies such as stricter fuel economy and CO_2 standards, alongside EV sales mandates, have stimulated the initial uptake and subsequent expansion of the EV market. With the International Energy Agency (IEA) projecting a 35% global market share for electric cars by 2030, with China, the United States, and Europe leading the charge [3], these policies not only lower financial barriers but also strengthen the commitment to sustainable mobility. Such governmental support boosts consumer and manufacturer confidence in EVs, fostering a more robust market environment. Additionally, such policy-driven efforts shape broader market dynamics and have direct implications for organizational strategies, as companies must adapt and innovate in response to these evolving regulatory landscapes. This adaptation requires enhancing EV designs [4], expanding charging infrastructure, and implementing more efficient operational practices to meet new standards and consumer expectations [5].

In the evolving landscape of transportation and energy management, the adoption of EVs presents significant changes. These innovations not only enhance energy efficiency but also drive economic restructuring and market trend shifts. The authors in [6] explored the behavioral factors driving this adoption in China's Jiangsu Province, shedding light on how perceptions and technology acceptance influence EV integration strategies. Similarly, the authors in [7] extended the dialogue to operational efficiencies, introducing a model that integrates EV routing with battery health, emphasizing the longevity and cost-effectiveness of fleet operations. Building on this, the studies in [8,9] offer computational models that balance travel time and battery degradation costs, and maximize profitability within electric taxi fleets, respectively. These insights collectively underscore a shift toward more sustainable and economically viable transportation solutions, prompting organizations to reconsider their strategic approaches in light of these technological advancements.

Figure 1 shows an exponential rise in scholarly publications from 2019 to August 2024, highlighting the importance and timeliness of this systematic study. The statistics show how important EV adoption is for advancing sustainable practices, as acknowledged by the academic community. They also show how important EVs are becoming to business and policymaking. Figure 1 illustrates a noteworthy upsurge in publications between 2023 to June 2024.

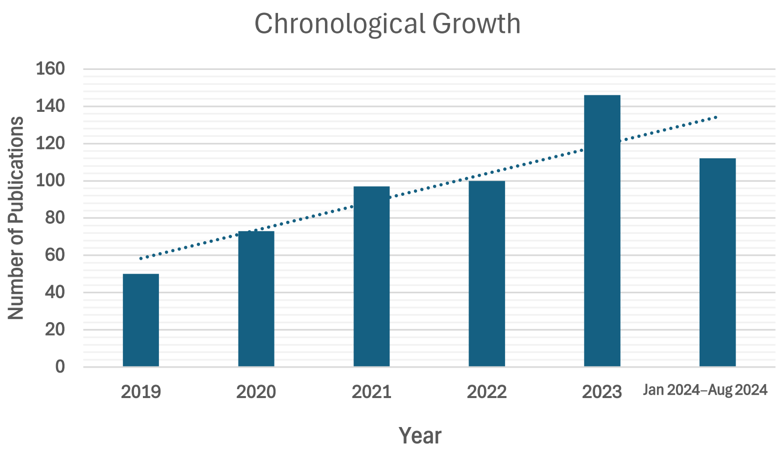

Figure 1. Chronological growth of publications on EV adoption and its multifaceted impacts (2019—August 2024)—Scopus.

In the realm of environmental sustainability, adopting EVs plays a pivotal role in mitigating climate change impacts through significant reductions in greenhouse gas (GHG) emissions [1,10,11]. According to the U.S. Department of Energy [11], electric motors in EVs are highly efficient, converting over 77% of the electrical energy from the grid to power at the wheels. In contrast, conventional gasoline vehicles only convert about 12–30% of the energy stored in gasoline to power at the wheels [11]. This higher efficiency means that even when the electricity used to charge EVs is generated from fossil fuels, the total emissions are still lower than those from traditional gasoline or diesel vehicles.

According to the IEA [1,3], the lifecycle emissions of a medium-size battery electric vehicle (BEV) are about half of those of an equivalent internal combustion engine vehicle (ICEV). The IEA reports that net avoided well-to-wheel (WTW) GHG emissions from EV deployment are substantial, with significant reductions projected from 2023 to 2035 across various scenarios [1]. Figure 2 illustrates that under the Stated Policies Scenario (STEPS), the net GHG emissions avoided will reach nearly 700 million tonnes of CO_2-equivalent by 2030. In the Announced Pledges Scenario (APS) and the Net Zero Emissions by 2050

Scenario (NZE), even greater reductions are projected, showcasing the potential for EVs to drive substantial emissions savings as electricity grids continue to decarbonize.

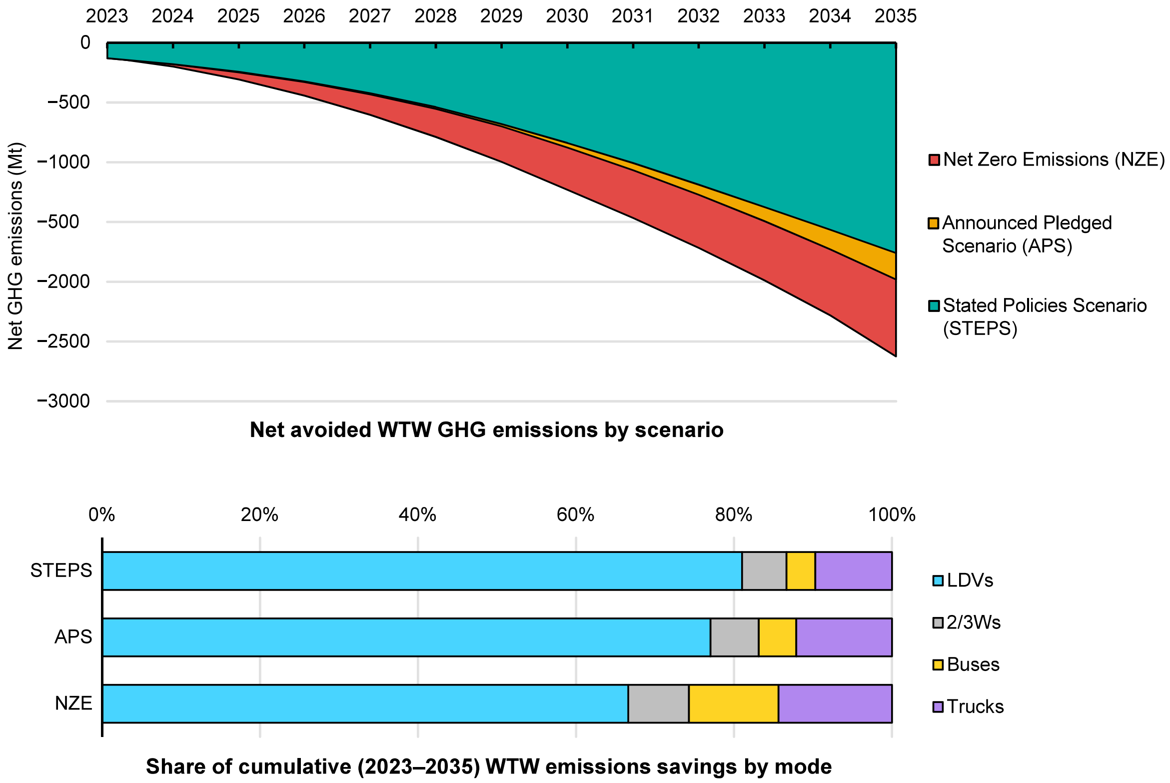

Figure 2. Net reduction in well-to-wheel GHG emissions from EV implementation, detailing the proportion of emissions avoided by mode, from 2023 to 2035—adapted from [1].

Moreover, as highlighted by Sergey Paltsev, Deputy Director of the MIT Joint Program on the Science and Policy of Global Change, while EVs are more carbon-intensive to manufacture due to their large lithium-ion batteries, they compensate by operating much more cleanly under nearly any condition. For instance, a study from MIT showed that gasoline cars emit more than 350 grams of CO_2 per mile driven over their lifetimes, while fully battery-electric vehicles create just 200 g. Even in regions heavily reliant on coal for electricity, EVs tend to emit less carbon than gasoline cars over their lifetime [10]. These findings reinforce the significant long-term climate benefits of EVs.

In the STEPS scenario, for example, net GHG emissions avoided by 2035 are significant, underscoring the effectiveness of current policies. The APS scenario, which includes announced pledges, shows further reductions, and the NZE scenario highlights the impact of achieving net-zero emissions by 2050. These scenarios collectively demonstrate that EV adoption, coupled with grid decarbonization, can result in substantial GHG emissions savings. These benefits underscore the necessity of adopting EVs in urban planning and policy-making to foster a sustainable transport model that aligns with climate targets [1].

At the intersection of technology and operational efficiency, the integration of EVs into transportation networks introduces complex challenges and innovative solutions. Advances in battery technology, smart charging infrastructures, and software management systems are crucial for optimizing the operational efficiency and reliability of EVs. These technological innovations not only enhance the functionality and range of EVs but also support the scalability of electric mobility solutions. As the sector evolves, continuous technological enhancements will be vital in addressing the infrastructural demands and energy management needs of a growing EV market, ensuring that the transition to electric mobility is both efficient and sustainable.

The current body of literature on EV adoption tends to focus on specific aspects, often overlooking the multifaceted impacts of EVs. For instance, environmental studies have primarily concentrated on the effects of EVs on air pollution and health, energy consumption, carbon emissions, and comparisons with diesel vehicles [12–14]. Technological research has delved into areas such as charging infrastructure, power management, and control techniques, and the impact of national culture on technology acceptance [15,16]. Organizational studies have provided decision-makers with perspectives on passenger EV adoption at the country level and suggested policy, societal, and managerial implications of EV adoption [17]. However, while valuable, these studies do not provide a holistic view of the impacts of EV adoption on the environment, technology, and organizations. This gap in the literature could hinder stakeholders, decision-makers, and governments from making informed decisions about EV adoption. Therefore, there is a pressing need for comprehensive research that examines the holistic impact of EV adoption across these three dimensions. Such research could provide invaluable insights and guide policy-making in this critical area.

Building on the existing body of knowledge, this paper employs a systematic approach to holistically examine the multifaceted impacts of EV adoption, addressing significant gaps in the current research. While studies to date have explored various dimensions of EVs—from environmental effects to technological infrastructure and organizational strategies—there remains a crucial need for an integrated analysis that encapsulates these interconnected aspects. By employing the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology, this research aims to comprehensively map out the existing literature and identify critical areas lacking thorough investigation. The results of this systematic review will not only inform different stakeholders but also outline key areas where further research is needed, potentially guiding future investigations into the sustainable integration of EVs across various sectors.

The rest of this paper will therefore discuss the PRISMA methodology employed in this research, detailing the systematic review process to evaluate the organizational, technological, and environmental impacts of EV adoption, as reported by the body of knowledge. As such, this paper presents a bibliometric analysis of the existing studies and their mapping in the field to identify key trends and contributions to the body of knowledge. In addition, this study delves into a detailed content analysis systematically organized into thematic areas, providing insights into the multifaceted impacts of EV adoption. Finally, the study draws conclusions from the findings and suggests directions for future research, with emphases on areas that require further exploration to enhance the understanding and implementation of EV strategies in both policy and practice.

2. Methodology

This systematic review adheres to the PRISMA 2020 guidelines, with a detailed PRISMA flow diagram (Figure 3) visually summarizing the study selection process. This process includes identification through the Scopus database, a screening of titles and abstracts, an assessment of full-text article eligibility, and final study inclusion. Our predefined search strategy, selection criteria, and analytical methods are documented below to ensure reproducibility and transparency.

a. Literature Retrieval: We conducted a comprehensive search in the Scopus database using a specific set of keywords to identify publications relevant to EV adoption. The search, adhering to PRISMA 2020 guidelines, was completed in August 2024.
   The search strategy was designed to cover the literature on EV adoption comprehensively, using a targeted query in the Scopus database. Our search string was: ("electric vehicle*" OR "EV" OR "EVs") AND ("fleet electrification" OR "fleet management" OR "fleet operations" OR "Emission Reductions" OR "Adoption of EVs") AND ("sustainability" OR "organizational performance" OR "Key Performance Indicators" OR "KPI" OR "energy consumption" OR "cost savings" OR "renewable energy utilization"). We restricted our search to English-language, peer-reviewed

journal articles published from 2019 to 2024, ensuring a focus on the most recent and relevant research.

The keywords were carefully selected to cover the complex dimensions of EV adoption research. "Electric vehicle*" and its variants broadly define the scope, while terms like "fleet electrification", "management", and "operations" delve into organizational impacts. Environmental effects are captured by "Emission Reductions" and "sustainability", whereas "Organizational performance", "KPI", and similar phrases focus on the technological and performance-related aspects essential for understanding EV adoption's broader implications. We chose Scopus as our primary database due to its comprehensive coverage across diverse research fields such as engineering, environmental science, and business. This strategy led to the retrieval of 802 papers, reflecting current trends and significant interest in the multifaceted impacts of EV adoption.

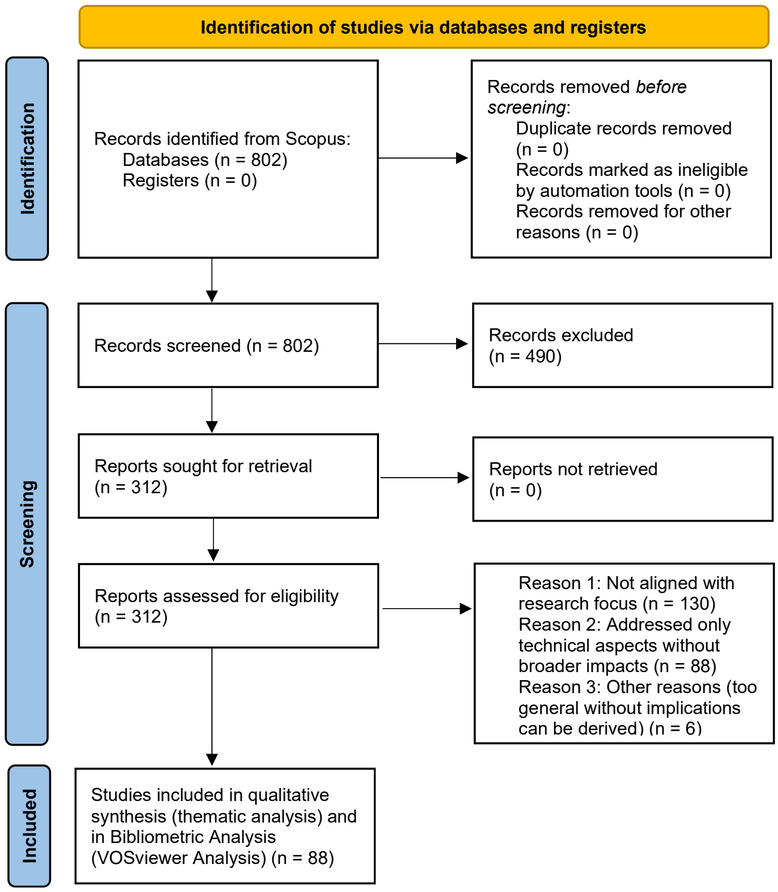

Figure 3. PRISMA flow diagram.

b. Literature Screening: Adhering to PRISMA 2020 guidelines, we meticulously reviewed the retrieved literature to ensure relevance and quality. Initial filtering based on publication year (2019–2024) reduced the pool to 498 papers, reflecting a surge in EV adoption research. Further refinement to include only English-language journal articles narrowed it down to 312 papers.

Next, we reviewed the titles and abstracts of the remaining papers, narrowing our selection to 130 studies closely aligned with our focus on the integration of EVs with sustainability and organizational strategy. We applied strict exclusion criteria to ensure the included studies comprehensively addressed the impact of EV adoption on organizational performance, technological innovation, and sustainable infrastructure, excluding those that solely focused on the technical aspects of EVs without considering these broader impacts. The flow diagram of the search and selection process is shown in Figure 3.

2.1. Selection Process

Two independent reviewers screened the titles and abstracts of the retrieved articles using an Excel spreadsheet, marking each study as ’relevant’ or ’not relevant’ with color codes (green for relevant, red for not relevant). Discrepancies were resolved through consensus in joint review sessions, ensuring no disagreements escalated. This manual approach, without the use of automated tools, enhanced the rigor and reproducibility of our selection process, in compliance with the PRISMA 2020 guidelines.

2.2. Data Collection Process

Data from each included study were independently extracted by two reviewers using a structured Excel spreadsheet designed to capture essential information, such as the year of publication, the main focus, key findings, and the study’s objectives. This approach ensured consistency and comprehensiveness.

The reviewers operated independently to minimize bias, planning to resolve any discrepancies through consensus. No significant discrepancies occurred. However, any disagreements were to be resolved through consultation with the second author, who also served as the advisor, to provide final guidance.

This meticulous, manual process ensured the accuracy and reliability of our data, adhering to the transparency and replicability standards set by the PRISMA guidelines.

2.3. Data Items and Outcomes Sought

Data collection targeted four primary outcome dimensions to assess the comprehensive impacts of EV adoption: environment, organizations, technology, and policy.

- Environment: Focus on GHG emissions, air quality improvements, and lifecycle environmental impacts.
- Organizations: Examination of economic viability, energy efficiency, and market dynamics affected by EV adoption.
- Technology: Analysis of advancements in battery technologies, energy storage solutions, and smart charging strategies.
- Policy: Assessment of policy frameworks, regulatory impacts, and strategic recommendations to encourage EV adoption.

We employed VOSviewer software for bibliometric analysis to create co-occurrence maps of key terms from the titles and abstracts of the selected articles, refining terms based on frequency and relevance and removing duplicates with a thesaurus file.

For content analysis, data on methodological approaches, key findings, and implications within the outlined outcome dimensions were collected. Each reviewer independently verified details such as the publication year, main focus, key findings, and objectives of each study. Discrepancies were discussed and resolved in consultation with the second author, ensuring a thorough and unbiased analysis without the use of automated tools.

Additional Variables Sought: We collected specific data on:

- Participant Characteristics: Information about the organizations and sectors involved in adopting EVs, focusing on the scope of adoption and types of fleets, such as public transport and commercial fleets.
- Intervention Characteristics: Details concerning technological and operational interventions, including the use of specific EV models, charging infrastructures, and battery management strategies.
- Geographical Distribution: Analysis of regional data to understand the geographical spread and contextual impacts of EV adoption.

Assumptions Made: In conducting this review, we assumed:

- Data Completeness: The bibliometric data from Scopus were assumed to be complete and accurate.
- Software Reliability: VOSviewer software was assumed to be reliable in producing precise visualization maps and identifying key terms.
- Impact of Missing Data: Missing or unclear information was assumed not to significantly affect the overall analysis, with efforts made to clarify or supplement such data as needed.

c. Bibliometric Analysis: We conducted a bibliometric analysis using VOSviewer to map the field of EV adoption research. This analysis highlights significant contributions, identifies new developments, and pinpoints geographical focuses in the academic landscape, helping us understand where global research efforts concentrate.

d. Content Analysis: We performed a detailed content analysis of selected studies to capture and synthesize the main ideas concerning EV adoption's impacts on organizational performance, innovation, and sustainability. This process involved a systematic examination of the studies to identify key recurring themes, insights, and trends.

This systematic review is registered on the Open Science Framework (OSF), enhancing transparency and reproducibility. Details of the registration can be accessed on the OSF platform [18], demonstrating our adherence to open science principles and PRISMA guidelines. Following this section, the paper continues with detailed bibliometric and content analyses, as outlined in our methodology.

3. Bibliometric Analysis

This bibliometric analysis establishes the foundational scientific landscape for EV adoption. Drawing from a comprehensive dataset sourced from the Scopus database, this section seeks to uncover critical data and emerging trends that will inform the key areas of our detailed examination in the content analysis. The objective is to map out the broad-ranging effects of EV adoption across multiple sectors, highlighting key intersections between multiple dimensions, such as technology, policy, and market dynamics that warrant deeper investigation.

Utilizing VOSviewer, we have generated a series of visualization maps to graphically represent these dimensions. Each map uses variably sized circles to depict entities such as concepts, authors, or studies, with the size and proximity of circles indicating the level of research activity and thematic relationships, respectively. Larger, closely positioned circles denote strong research presence and closely related themes, which guide the thematic selection for the content analysis. This strategic use of bibliometric data ensures that our subsequent in-depth analysis is directly influenced by the most prominently discussed topics in the current academic discourse on EV adoption, thereby setting a structured and data-driven agenda for exploring specific themes, such as environmental impact, technological challenges, and policy strategies.

3.1. Co-Occurrence Map Based on Text Data

In this subsection, we conduct a bibliometric analysis to quantitatively map the scholarly landscape, guiding the thematic focus of our subsequent content analysis section. By analyzing the titles and abstracts of the selected articles, we conducted a co-occurrence analysis to extract significant terms, forming a network of thematic connections. This method allows us to identify the core themes that are most prevalent in the literature. Out of the 2977 terms generated, 51 met the threshold of at least 10 occurrences. Through VOSviewer's relevance scoring, the top 60% of these terms were further refined, yielding 31 key terms that are depicted in Figure 4. These terms, selected for their pertinence, directly influence the specific dimensions we explore in the content analysis, ensuring our discussion is grounded in the most current and impactful facets of EV adoption research.

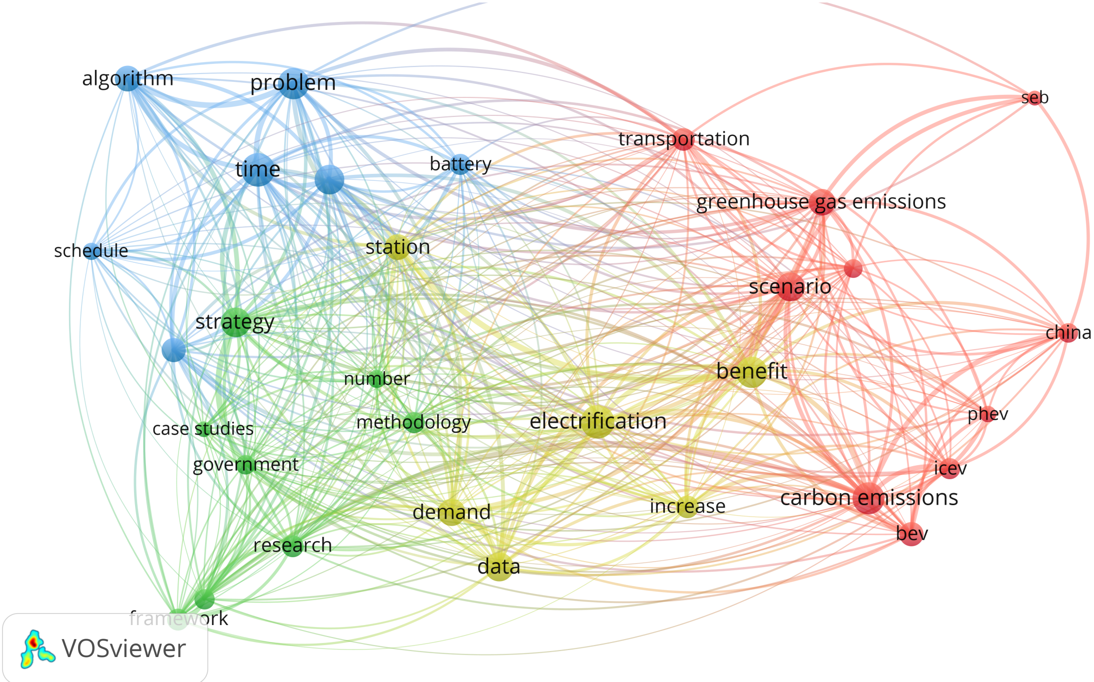

Figure 4. Co-occurrence map of text data.

Dominant terms identified through this analysis, such as 'emission', 'strategy', and 'government', directly inform the themes of our content analysis. These terms reflect critical aspects of EV adoption, emission reduction, strategic adaptations within organizations, and policy developments, that catalyze the transition to electric mobility. The visualization in Figure 4 highlights the prevalence of these terms and underscores their centrality in the discourse, shaping our subsequent examination of how these factors influence the broader adoption and integration of EVs.

The focus on terms such as 'station', 'battery', and 'time' underscores the technological challenges and operational considerations pivotal to EV integration, themes that we delve into in the content analysis. Similarly, the prominence of 'China' in the network highlights its role in the global EV market, both in terms of policy innovation and market dynamics. These insights guide our in-depth exploration of technological advancements and policy frameworks, critical elements for understanding the pace and direction of EV adoption.

In summary, Figure 4 offers a visual synopsis of the critical themes identified, setting the stage for our content analysis by underscoring the academic community's focus on overcoming challenges through innovation and proactive policy-making. This visualization not only confirms the research narrative's trajectory but also justifies our selection of key areas for deeper examination, particularly in how technological innovations and policies are shaping the future of EV adoption.

Figure 5 focuses on 'electrification' and its pivotal role in advancing sustainable transportation, connecting crucial elements like 'transportation', 'framework', 'infrastructure', and 'government'. This visualization underpins the comprehensive approach reviewed in the subsequent Content Analysis section. It strategically determines the focus areas that emerged from the bibliometric analysis, serving as a precursor to a more detailed exploration of how these elements interplay in the broader context of EV adoption.

The co-occurrence network shown in Figure 5 places 'electrification' at the heart of sustainable transportation discussions, highlighting its fundamental role. It is intricately linked to 'transportation', emphasizing how the future of mobility is shaped by EVs. This connection highlights the transformations within transport infrastructures necessary to support this shift. Furthermore, 'electrification' is closely tied to 'framework' and 'infrastructure', underlining the essential policy frameworks and practical implementations required for a successful electric transition. These insights form the basis of the subsequent content analysis, guiding our exploration into how technological, policy, and infrastructural strategies must align to support the broader adoption of EVs. The proximity of 'electrification' to 'strategy' underscores the necessity for a cohesive approach that combines technological innovation with strategic long-term planning to navigate the complexities of EV integration.

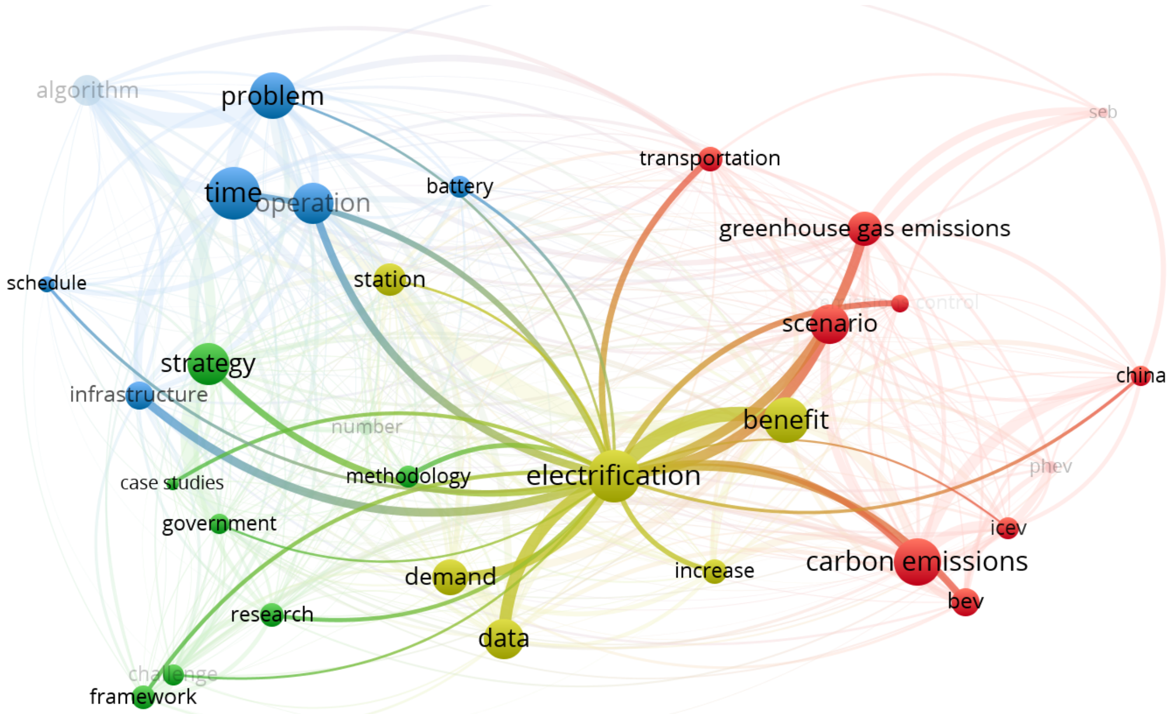

Figure 5. Terms directly connected with "Electrification".

Table 1 provides a quantitative overview of the most prominent themes within the EV adoption literature. It identifies the ten most significant terms using VOSviewer, along with their frequency and relevance scores. These scores, calculated through a comparison of the distribution of second-order co-occurrences against the broader co-occurrence dataset using the Kullback–Leibler distance, denote each term's significance within the EV research landscape. The larger the difference between the two distributions, the higher the relevance of a term [19]. The term 'SEB', referring to shared electric bicycles, tops the list with the highest relevance, indicating a significant focus within the research community on micro-mobility solutions. 'China' follows, reflecting the country's prominent role in EV research and adoption, while 'PHEV' (plug-in hybrid electric vehicles) and 'ICEV' (internal combustion engine vehicles) show the comparative analysis within different vehicle technologies. The term 'government' underscores the importance of policy and regulation in the adoption of EVs, highlighting how governmental actions influence the EV market. 'Carbon emissions' is a central environmental term, pointing to the considerable attention on EVs' impact on carbon footprint reduction.

The prominence of terms like 'algorithm' and 'strategy' emphasizes the technological and strategic dimensions of EV research, highlighting advancements in EV-related software and strategic approaches for EV integration. Lastly, 'framework' and 'challenge' suggest a focus on structural and systematic obstacles within the field. These insights directly inform the content analysis, guiding our exploration into the impacts of EV adoption on energy, economy, market dynamics, environmental sustainability, technological challenges, and policy recommendations. This interconnected web of technical, environmental, policy, and strategic concerns frames our detailed examination in the Content Analysis section.

Table 1. Top 10 terms by occurrences and relevance in EV adoption literature.

Rank	Term	Occurrences	Relevance
1	Shared Electric Bicycles (SEB)	10	2.63
2	China	18	2.51
3	Plug-in Hybrid Electric Vehicles (PHEV)	12	1.99
4	Internal Combustion Engine Vehicles (ICEV)	20	1.67
5	Government	18	1.67
6	Carbon Emissions	45	1.57
7	Algorithm	30	1.36
8	Strategy	40	1.31
9	Framework	22	1.29
10	Challenge	19	1.24

Note: This table provides a quantitative overview of the most prominent themes identified using VOSviewer. Terms are ranked by their frequency of occurrence and relevance, highlighting key focuses such as SEB, China, and the comparative analysis of PHEVs and ICEVs. Higher relevance scores indicate greater significance within the EV research landscape. The ranking is based on the Kullback–Leibler distance method [19].

3.2. Co-Occurrences Map Based on Keywords

In this analysis, we identified frequently occurring keywords from 88 publications, a foundational step in framing the subsequent content analysis. Out of 1146 keywords, 44 were selected with a minimum occurrence of five, as shown in Figure 6.

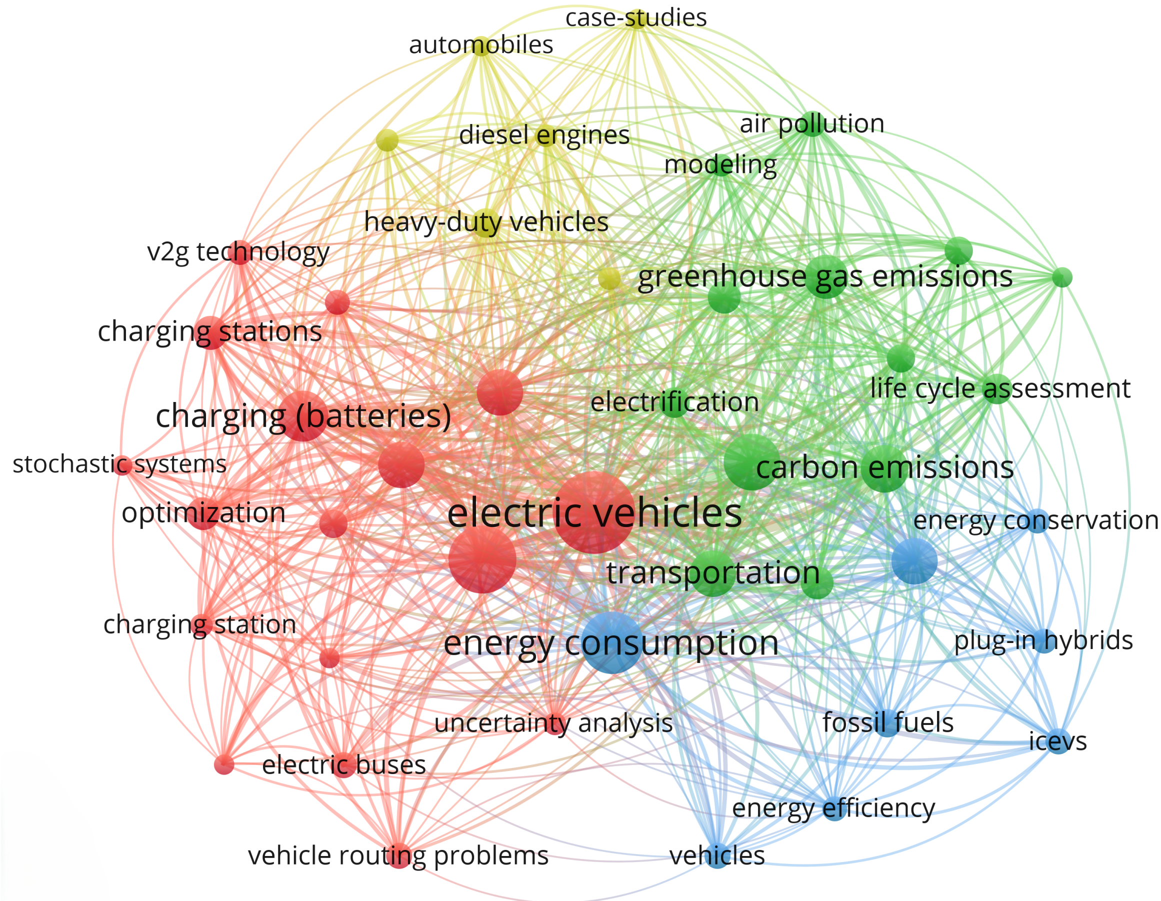

Figure 6. Co-occurrence map of all keywords.

Using VOSviewer (VOSviewer 1.6.20) along with a thesaurus, we standardized these keywords and eliminated redundancies [20], ensuring a focused and precise dataset. This refined selection includes both author keywords, which represent the core concepts emphasized by the researchers, and index keywords, used by databases for categorization and retrieval. The chosen keywords serve as a direct indicator of prevalent themes and trends within the scholarly discourse on EV adoption, guiding our in-depth examination of specific aspects such as technological challenges, policy frameworks, and environmental impacts in the subsequent section of content analysis.

The term 'Electric Vehicles' occupies a central node in our analysis, underscoring its fundamental importance across all facets of EV research. This central positioning is surrounded by clusters of interconnected terms that depict the scope of our review. Notably, the term 'Fleet Operations' emerges prominently, emphasizing the significant role of operational management in electric fleet integration. This prominence guides our subsequent analysis of organizational impacts and operational challenges in EV adoption, highlighting areas such as fleet optimization and management practices that are crucial for effective EV implementation.

Clusters adjacent to 'Electric Vehicles' outline additional core themes directly shaping the scope of our content analysis. The terms 'Sustainability' and 'Emissions Control' are pivotal, highlighting the environmental impacts that EV adoption fosters, which we explore in depth in the subsequent environmental impact analysis. Similarly, 'Charging (Batteries)' signals the technical challenges and infrastructure needs essential for EV integration, setting the stage for our discussion on technological and operational challenges. Financial implications are spotlighted by terms like 'Economic Analysis' and 'Cost Benefit Analysis', informing our examination of market dynamics. Furthermore, 'Plug-in Hybrids' and 'ICEVs' (internal combustion engine vehicles), alongside 'Life Cycle Assessment' and 'Environmental Impact', provide a framework for contrasting various vehicle technologies and assessing comprehensive environmental effects, underscoring the multifaceted nature of EV adoption.

This interconnected map underscores the comprehensive nature of the research landscape, encompassing technological innovation, policy implications, environmental benefits, and operational challenges in market integration. Each keyword's connectivity highlights the interdisciplinary collaboration inherent in the EV research domain. This map not only charts the prevalent discussions but also directly informs the thematic areas our content analysis will delve into, exemplifying the complex interdependencies within the EV ecosystem. The detailed exploration of these terms and their interrelations is cataloged in Table 2, where the total link strength quantifies the depth of connections between keywords [21], reinforcing the selected themes for detailed exploration in subsequent sections.

Table 2. Top 10 keywords by occurrences.

Rank	Keyword	Occurrences	Total Link Strength
1	Electric vehicles	76	497
2	Fleet operations	53	358
3	Energy consumption	44	286
4	Sustainability	36	228
5	Charging (batteries)	29	206
6	Transportation	25	205
7	Carbon emissions	26	199
8	Economic analysis	24	197
9	Secondary batteries	25	191
10	Emissions control	24	176

Note: The table lists keywords identified in the research analysis along with the number of occurrences and the total strength of their associative links.

The keyword 'Electric vehicles' stands out with the highest occurrences and total link strength, underscoring its central role in scholarly discussions and affirming its selection as a core theme for deeper exploration. Following closely are 'Fleet operations', addressing operational management challenges; 'energy consumption' and 'sustainability', highlighting eco-efficiency; and 'charging (batteries)' and 'transportation', which detail the practical aspects of EV integration. The presence of terms like 'carbon emissions', 'economic analysis', 'secondary batteries', and 'emissions control' further broadens the scope, showcasing a spectrum that spans technological, environmental, and economic dimensions. These keywords not only reflect the critical topics within the EV dialogue but also frame our content analysis sections, focusing on the corresponding impacts of EV adoption as derived from the bibliometric insights.

To enhance our understanding of the thematic focus in the field of EV adoption, two additional keyword maps were generated to offer a more granified perspective. The first map displays the most common author keywords, with a threshold set at five occurrences, showcasing eight crucial terms that have guided author contributions within the scholarly community (Figure 7). The second map presents the most common index keywords, with forty-four terms highlighted, demonstrating the broad indexing categories used by databases to organize the literature (Figure 8). These maps further refine our selection of themes for the content analysis by providing a visual representation of the prevailing topics and their interconnections, underscoring the relevance of these key areas in current and future EV research.

Collectively, this keyword analysis not only provides a clear understanding of how EV adoption is framed within contemporary research but also lays the groundwork for the focused themes in our content analysis. It highlights the role of EVs in promoting sustainable practices, combating climate change, and shaping urban and energy strategies. This analysis underscores the essential interplay between technological innovation, policy formation, environmental stewardship, and organizational management. The findings direct our subsequent exploration of these key areas, ensuring a coherent transition into the detailed discussions on the technological, environmental, organizational, and policy-related impacts of EV adoption. The visualization maps serve as a foundational tool, illuminating the interconnected research landscape and the diverse expertise that drives the electric mobility transition.

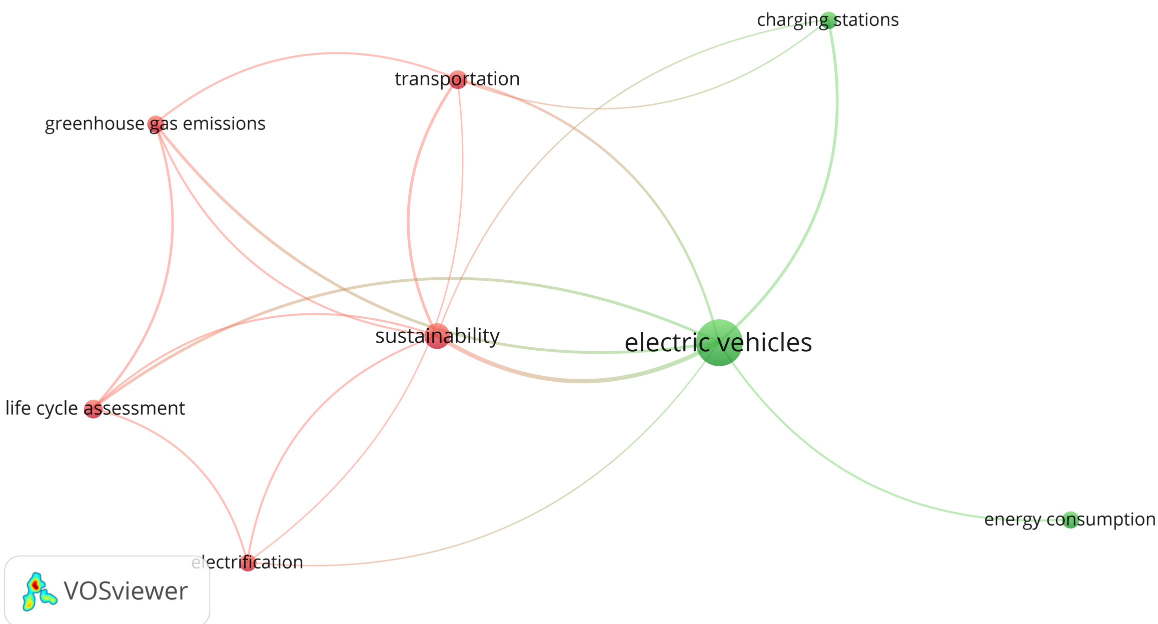

Figure 7. Co-occurrence map of author keywords.

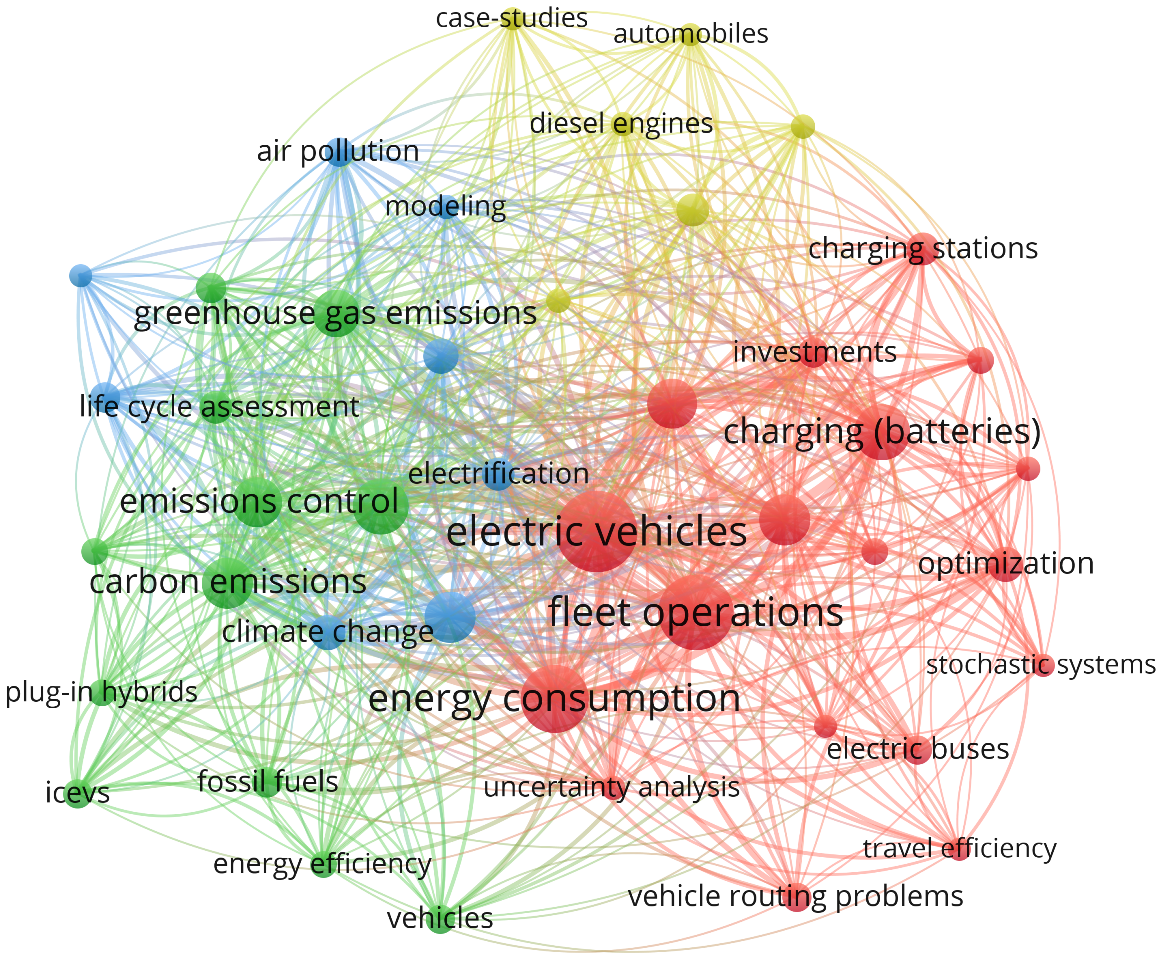

Figure 8. Co-occurrence map of index keywords.

3.3. *Co-Occurrence Map Based on Country of Co-Authorship*

In this subsection, we examine the geographic distribution of publications to highlight the global collaboration and interest in EV adoption.

This analysis utilizes a visualization map generated for countries of co-authorship, with the criterion that a country must be represented in at least four documents to be included. Among the thirty-nine countries analyzed, only ten countries met this threshold.

The results, depicted in Figure 9, highlight the international scale of research and lay the groundwork for understanding how regional collaborations and developments contribute to the overarching themes of EV adoption that are explored in more depth in the subsequent Content Analysis section.

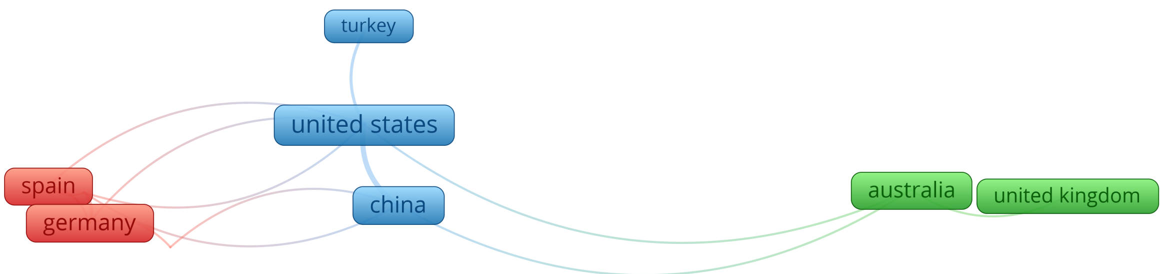

Figure 9. Countries of co-authorships.

Table 3 presents the leading countries in EV adoption research, ranked by document count, citations, and total link strength, a metric reflecting the intensity of co-authorship connections. This table highlights the international dimension of EV research and also identifies the key contributors: China, with its leading volume of research and citations, indicates a significant thrust in EV development; the United States, with the highest link strength, underscores its role as a central node in global collaborations. Germany and the Netherlands also contribute prominently, each bringing unique regional insights into the field. Other countries, including Australia, Spain, Poland, Turkey, the United Kingdom, and Italy, also play essential roles, showcasing a diverse range of perspectives and expertise. The geographic diversity here directly informs our analysis of environmental, technological, and policy-driven themes in EV adoption, showcasing how regional experiences shape global advancements and collaborative efforts in electric mobility.

Table 3. Top countries by document count, citation per document, and associated link strength.

Rank	Country	Documents	Citations	Total Link Strength
1	United States	24	272	12
2	China	24	325	9
3	Germany	8	166	5
4	Netherlands	4	74	5
5	Australia	5	108	3
6	Spain	4	98	3
7	Poland	4	61	3
8	Turkey	4	48	2
9	United Kingdom	4	109	2
10	Italy	4	131	1

Note: The table ranks the top countries based on the total link strength of documents.

3.4. Co-Occurrence Map Based on Authorship

Upon examining the co-occurrence map based on authorship, we found that each author is linked to a single document, indicating a lack of substantial collaboration in this field. This fragmented landscape highlights diverse, independent approaches, explored further in our content analysis on technological innovation, policy formation, and environmental impact. Notably, ten authors with high citation counts (91 each) made significant yet isolated contributions, suggesting the need for greater interdisciplinary collaboration, as shown in Table 4.

Table 4. Top 10 authors by citations.

Rank	Author	Documents	Citations	Total Link Strength
1	Bie, Yiming	1	91	0
2	Chen, Wen	1	91	0
3	Hong, Jichao	1	91	0
4	Ji, Jinhua	1	91	0
5	Lin, Peng	1	91	0
6	Qu, Changhui	1	91	0
7	Qu, Xiaobo	1	91	0
8	Wang, Leyi	1	91	0
9	Wang, Xiangyu	1	91	0
10	Wang, Zhenpo	1	91	0

Note: This table lists authors ranked by the number of citations. Each listed author has contributed to one document, which has received 91 citations.

The observed citation levels signify the substantial influence of the discussed research, forming a robust foundation for the thematic explorations in our content analysis. Despite the independence of these authors, their notable contributions highlight key areas ripe for further investigation and integration into broader thematic contexts, such as technological advances and policy impacts on EV adoption.

3.5. Data Analysis on Article Sources

In this analysis, we analyze the distribution of the 88 publications across different journals to identify where the most significant conversations on EV adoption are taking place. We cataloged 44 unique sources, with 'Energies' leading at nine publications, followed by 'Transportation Research Part D: Transport and Environment' with seven. This distribution, depicted in a bar graph (Figure 10), not only highlights the journals most engaged with EV topics but also underscores the thematic concentrations within these outlets. By examining these sources, we frame our content analysis to focus on the most influential themes and discussions in the field, ensuring our review is aligned with the primary forums of scholarly debate on EV adoption.

Figure 10. A bar chart of the top 10 sources by number of publications used in this paper. The sources were identified based on the search strategy detailed in the Methodology section using the Scopus database, including the main criteria of English-language, peer-reviewed journal articles, published between 2019 and 2024.

The diversity of journals from which these studies are sourced emphasizes the interdisciplinary approach required to fully understand EV adoption. This range, covering engineering, environmental science, and policy studies, not only reflects the collaborative nature of this research area but also prepares the groundwork for our content analysis. The varied perspectives gathered across these sectors enrich our understanding and highlight crucial aspects such as technological advancements, policy evolution, and sustainability practices. This preparation allows for a comprehensive exploration of how these domains interact within the broader narrative of electric mobility, guiding our focus on key areas of impact and development in subsequent analyses.

4. Content Analysis

This section provides a thematic analysis of 88 papers on the multifaceted impacts of EV adoption. To ensure comprehensive coverage, we conducted targeted searches within our original methodology to include additional relevant studies. This section offers stakeholders, decision-makers, and organizations a holistic view of the EV landscape and its impacts. This section is divided into five subsections, each addressing critical topics. The first subsection examines the impact of EV adoption on organizations, focusing on energy, economy, and market dynamics. The second subsection discusses the impact on the energy sector, particularly the petroleum industry. The third subsection addresses the environmental impact, including regional carbon reduction, vehicle type, and lifecycle assessment (LCA). The fourth subsection covers technological and operational challenges in EV integration, including advanced battery technologies, EV charging strategies and management, and the optimization of the EV charging infrastructure. Finally, the fifth subsection presents framework and policy recommendations. This comprehensive analysis informs organizational strategies and infrastructure planning, essential for transitioning to sustainable mobility.

4.1. Impacts of EV Adoption on Energy, Economy, and Market Dynamics

As countries and corporations pivot toward more sustainable transportation solutions, EVs stand at the forefront of this transformative shift, promising to significantly alter energy consumption patterns, economic landscapes, and market dynamics. This subsection explores the multi-dimensional impacts of EV adoption, focusing on direct effects on energy efficiency and economic viability, as well as broader market responses. Through the exploration of empirical studies and theoretical analyses, we aim to uncover how EVs influence the economic dynamics of industries, dictate new market trends, and redefine energy utilization parameters. The ensuing discussions and tables encapsulate the complexity of these interactions, offering strategic insights into the efficient integration and optimal utilization of EVs across different sectors.

4.1.1. Energy Efficiency and Consumption

Energy efficiency remains a critical focus in the adoption of EVs, reflecting a central aspect of sustainable mobility. The studies summarized in Table 5 examine various aspects of energy efficiency and consumption in EVs compared to internal combustion engine vehicles (ICEVs). Using advanced modeling tools, real-world operational data, and innovative vehicle operation strategies, these studies highlight the substantial energy efficiency gains achievable through EV adoption.

Table 5. Overview on energy efficiency and consumption of EVs.

Ref.	Focus	Key Findings	Implications
[22]	Modeling and analyzing energy efficiency of EVs vs. ICEVs in Malaysia using AIMSUN software.	Significant energy savings and cost efficiencies with EVs.	Strategic advantage for fleet electrification, reducing operational costs and environmental impact.
[23]	Analyzed a year's worth of data from an electrified transit fleet, focusing on bus speed and seasonal energy consumption changes.	Bus speed and seasonal changes significantly influence BEV energy consumption.	Optimizing energy costs by adapting operations to seasonal variations enhances fleet electrification's economic viability.
[25]	Explored driver behavior patterns and route optimization for long-haul electric trucking.	Potential reductions in energy consumption and range anxiety.	Enhancing operational efficiency of electric trucks, paving the way for sustainable long-distance transportation.
[24]	Investigated battery electric trucks for day trips in a department of transportation fleet.	High feasibility for completing day trips with battery electric trucks.	Potential for DOT fleet electrification, supporting sustainability goals without sacrificing operational efficiency.
[26]	Developed an energy-optimized adaptive cruise control strategy for EVs at intersections.	Improved energy efficiency and traffic flow.	Technological advancements can reduce operational energy costs and contribute to sustainability objectives.

Table 5 outlines the main focus, key findings, and broader implications for the transportation sector, providing strategic insights for organizations to leverage in fleet electrification. The findings underscore the profound impact that targeted innovations in EV technology and management can have on energy efficiency. The analysis of EVs, especially in fleet settings, indicates potential cost savings and significant environmental benefits from reduced energy consumption. For instance, the use of AIMSUN software to model vehicle routes in Malaysia highlights how contextual factors like route diversity can influence energy efficiency outcomes [22]. Similarly, the adaptations to seasonal variations in bus operations suggest a dynamic approach to fleet management that aligns energy use with operational needs throughout the year [23].

Moreover, the evidence pointing to the feasibility of using battery electric trucks for departmental operations without compromising on operational efficiency marks a pivotal shift towards more sustainable governmental fleet management practices [24]. These findings collectively advocate for a strategic rethinking of how vehicles are integrated into fleets, suggesting that a move towards electric mobility can achieve multiple objectives: lowering operational costs, reducing carbon footprints, and enhancing the adaptability of transportation infrastructures to future energy landscapes [25,26].

In light of these insights, it becomes evident that transitioning to electric mobility requires not just an investment in new technologies but also a commitment to the continuous optimization of operational strategies. This approach will ensure that the potential of EVs to contribute to sustainable development goals is fully realized. Future research should continue to explore these dynamics, particularly focusing on long-term operational data and cross-regional studies, to validate and expand upon these findings. Building on this overview, we delve deeper into the specifics of how EV adoption enhances energy efficiency across different vehicle segments, providing a detailed comparison with ICEVs.

4.1.2. Analysis of Energy Efficiency and Consumption

EVs are recognized for their superior operating efficiency compared to ICEVs, resulting in substantial energy savings. This sub-subsection provides a detailed analysis of energy efficiency and consumption across various EV segments, supported by numerical data highlighting the magnitude of savings achieved by EVs. The analysis covers two-wheelers, three-wheelers, passenger cars, light commercial vehicles (LCVs), and heavy commercial vehicles (HCVs).

- **Well-to-Wheel Efficiency:** The well-to-wheel efficiency of BEVs is significantly higher than that of ICEVs. BEVs have a well-to-wheel efficiency ranging from 21% to 39%, with an average of 32%, compared to ICEVs' maximum overall energy efficiency of 28% [27]. Table 6 shows details on energy consumption and savings by vehicle type.

Table 6. Energy consumption and savings by vehicle type.

Vehicle Type	Energy Consumption (Wh/pkm or MJ/km)	Conventional Vehicle Energy Consumption	Energy Savings (%)
Electric Two-Wheeler	28.67 Wh/pkm [28]	Scooter: 139.26 Wh/pkm, Motorcycle: 155.93 Wh/pkm [28]	80–85%
Electric Three-Wheeler	43.25 Wh/pkm [28]	LPG Auto: 230.21 Wh/pkm, Diesel Auto: 181.40 Wh/pkm [28]	76–81%
Full EVs (Four-Wheelers)	166 Wh/km (Nissan Leaf) [29]	2024 Nissan Sentra: around 264 Wh/km (34 miles per gallon) [30]	around 37%
LCVs	Mercedes-Benz eVito Tourer Long 90 kWh: 194–391 Wh/km (depends on weather and driving conditions) [31]	Mercedes-Benz Vito 119 CDI: 660 Wh/km (21.48 liters/100 km) [32]	up to 70%
HCV	Volvo FH Electric: 1.1 kWh/km (1100 Wh/km) [33]	Volvo FH Diesel: 2148 Wh/km (21.48 liters/100 km) [34]	48.8%

- **Impact of Power Generation Mix:** The environmental benefits of EVs, particularly in terms of CO_2 emissions, are significantly influenced by the electricity generation mix. For instance, BEVs in regions with a high proportion of renewable energy sources exhibit lower lifecycle CO_2 ($LCCO_2$) emissions compared to ICEVs. In Norway, where the electricity is predominantly generated from hydropower, BEVs have much lower $LCCO_2$ emissions than ICEVs [35]. Conversely, in China, where coal is a major source of electricity, BEVs may have higher $LCCO_2$ emissions than efficient ICEVs like the Honda Insight [36]. Table 7 presents an illustrative example of $LCCO_2$ emissions by region and vehicle type.

Table 7. $LCCO_2$ emissions by region and vehicle type: an illustrative example—adapted from [36].

Region	ICEV Emissions (Tons)	BEV Emissions (Tons)	Comparison
Beijing	42.237	45.714	Emissions in BEV is **Higher** than ICEV
Yunnan	30.280	11.962	Emissions in BEV is **Lower** than ICEV

- **Analysis of Energy Savings and CO_2 Reduction:** BEVs with an energy consumption rate (ECR) of 10 kWh/100 km can meet the EU 2020 CO_2 regulations if the power generation mix $LCCO_2$ is around 900 g/kWh. For BEVs with an ECR of 20 kWh/100 km, the power generation mix must have $LCCO_2$ below 460 g/kWh to meet the same regulations [37]. Moreover, BEVs in high-mileage applications, such as ride-hailing fleets, could require 1–1.5 battery replacements over a 12-year vehicle life, impacting their overall environmental performance [38].

Overall, EVs across different segments exhibit substantial energy savings over their internal combustion engine counterparts, as shown in Table 6. These savings are most pronounced in smaller vehicle segments such as two-wheelers and three-wheelers, where the percentage savings can exceed 80%. For larger vehicles such as light and heavy commercial vehicles, the savings are still significant, reflecting the inherent efficiency advantages of electric powertrains. These findings underscore the potential for widespread energy savings through the adoption of EVs, particularly as the technology continues to improve and electricity generation becomes cleaner.

4.1.3. Impact of EVs on the Economy

Having established the substantial energy savings of EVs, we now focus on the economic ramifications and market dynamics of EV integration. This part examines how transitioning to electric mobility impacts operational costs, fleet management, and overall market trends.

The adoption of EVs presents an opportunity for significant cost savings and economic benefits across various sectors. Table 8 presents an economic analysis of various studies on EV adoption, highlighting key findings and implications. These studies emphasize the importance of optimizing operations, evaluating economic viability, assessing recharging models, and considering human factors in economic analyses. Strategic insights are provided for fleet managers, policymakers, and organizations to enhance the economic benefits and operational efficiency of EV integration. Optimized scheduling and procurement strategies for electric bus fleets, for example, have not only improved efficiency but also resulted in substantial cost reductions [39]. These strategies reveal the transformative potential of EVs to lower operational expenses. Additionally, the adoption of advanced models for evaluating different electric van powertrains enhances fleet management efficiency [40]. Innovative approaches like dynamic pricing for EV charging have become crucial in aligning charging infrastructure with energy grid capacities, thereby optimizing resource use and maximizing economic returns [41,42]. These findings highlight the role of strategic economic planning and adaptive policies in encouraging widespread adoption of EVs, where addressing economic factors alongside technological advancements can significantly boost market penetration, supporting sustainability and profitability.

Table 8. Economic analysis and cost savings.

Ref.	Focus	Key Findings	Implications
[39]	Optimizing electric bus fleet operations.	Efficiency gains and cost reductions.	Benefits for transit authorities and fleet managers.
[40]	Evaluating electric van powertrains' economic viability.	Cost-effective fleet composition.	Insights for logistics and transportation sectors.

Table 8. *Cont.*

Ref.	Focus	Key Findings	Implications
[43]	Assessing recharging business models for taxi fleets.	Viability of battery swapping and double-shift operations.	Cost benefits for the taxi industry.
[44]	Developing energy consumption estimation models for EV fleets.	Operational cost reductions.	Tools for fleet managers to optimize operations.
[45]	Evaluating BEVs in subarctic conditions.	Cost of ownership and battery performance impacts.	Considerations for EV adoption in various climates.
[46]	Exploring feasibility of long-haul electric trucks.	Challenges and requirements.	Insights for logistics operations.
[47]	Impact of driver behavior on energy consumption and costs.	Significant impact of behavior.	Importance of human factors in economic analysis.
[48]	Analyzing trends in EV charging demand.	Demand for faster charging solutions.	Implications for energy consumption and infrastructure.
[41]	Adaptive pricing strategy for EV charging.	Potential for grid efficiency.	Enhances grid efficiency and economic benefits.
[42]	Dynamic pricing for EV charging.	Benefits of aligning pricing with energy and traffic conditions.	Supports renewable energy integration and traffic management.
[49]	Policy influence on BEV adoption rates.	Critical role of infrastructure support and subsidies.	Importance of comprehensive policy frameworks.

The positive impact of electric mobility extends to job markets, particularly in manufacturing and infrastructure development. In the United States, a surge in EV-related job announcements has linked 195,000 direct jobs to EV manufacturing, fueled by substantial federal investments aimed at domesticating the EV supply chain and establishing states as centers of new opportunities [50]. This job growth necessitates enhanced infrastructure, projected to generate over 160,000 jobs by 2032 in various roles, from installation to maintenance [51]. The economic implications are even more pronounced in developing countries, where enhanced affordability through lower operating and maintenance costs contrasts with high upfront costs.

In nations like India, policy interventions such as the Faster Adoption and Manufacturing of Electric Vehicles (FAME) scheme and the Electric Mobility Promotion Scheme 2024 (EMPS) are crucial for fostering market penetration [52,53]. These initiatives support the adoption of hundreds of thousands of EVs, focusing primarily on electric two-wheelers and three-wheelers. Conversely, Brazil's struggles with EV adoption due to less effective policy measures and a lack of collaborative governance emphasize the need for a comprehensive policy framework that includes both financial and non-financial incentives [54].

Such policies are complemented by infrastructural developments critical for the widespread adoption of EVs. The availability and density of charging stations significantly influence EV adoption rates. Studies by the World Bank and researchers at MIT have shown that strategically placed charging stations and systems to delay charging initiation can manage the increased energy demands from widespread EV adoption [55,56]. Additionally, Vehicle-to-grid (V2G) technology allows EVs to discharge electricity back into the grid, providing a distributed energy storage solution that stabilizes the grid during peak demand periods [57].

Financial incentives also play a pivotal role in promoting EV adoption. Tax breaks and subsidies have significantly narrowed the cost gap between EVs and internal combustion engine vehicles, enhancing consumer adoption rates. In the U.S., the national Plug-In Electric Drive Vehicle Credit offers up to USD 7500, and studies suggest that direct purchase rebates are more effective in boosting EV sales than tax credits [52,58].

These economic and policy drivers align closely with environmental and socio-economic benefits. The transition to electric mobility reduces GHG emissions and air pollution, leading to lower healthcare costs and fostering a cleaner living environment. In regions like China, the adoption of EVs has significantly reduced local PM2.5 levels, a particulate matter linked to respiratory and cardiovascular diseases [59]. The shift also promises long-term economic benefits such as a reduced dependency on imported oil and improved public health [60].

As electric mobility evolves, further studies should focus on long-term economic impacts and renewable energy integration to assess the cost-effectiveness of EV adoption. This comprehensive approach helps stakeholders make informed decisions, enhancing operational viability and sustainability. Integrating EVs into the economy presents opportunities for cost savings, job creation, and environmental benefits, emphasizing the need for strategic planning and infrastructure investment to maximize economic gains.

4.1.4. Strategic Insights and Market Dynamics in EV Adoption

After examining the economic aspects, it is crucial to explore how integrating EVs within existing infrastructures influences both consumer behavior and strategic decisions in mixed vehicle fleets. Table 9 provides a detailed look at market adoption complexities, focusing on the interplay of policy, consumer attitudes, and technological advancements.

Table 9. Strategic insights and market dynamics in EV adoption.

Ref.	Focus	Key Findings	Implications
[61]	Using game theory to study the dynamics between electric and gasoline vehicles in South Korea.	Optimization strategies for taxes and subsidies.	Highlights the need for informed policy design.
[62]	Examining diverse business models for EV commercialization.	Innovation and service orientation drive EV adoption.	Framework for enhancing EV market penetration.
[63]	Investigating consumer attitudes towards EVs.	Digital features, financial incentives, and environmental awareness influence decisions.	Insights for boosting EV adoption through targeted marketing and policies.
[64]	Effects of EV penetration on Thailand's electricity systems.	Interaction between EV adoption and energy consumption patterns.	Implications for national energy planning and GHG emissions strategies.
[65]	Exploring biofuels' role alongside EV adoption in Norway.	Alternative strategies for achieving climate goals.	Advocates a multi-faceted approach including both EVs and biofuels.
[66]	Assessing the sustainability impact of conventional vs. electric fleets in Spain.	Emissions implications of varying levels of EV penetration.	Tool for evaluating fleet transitions for policymakers and fleet managers.
[67]	Operational dynamics of medium-duty EVs in urban delivery fleets.	Economic considerations and technological needs.	Insights for electric mobility transition and leveraging subsidies.
[68]	Stock dynamics model for fleet electrification, shared mobility, and autonomous vehicles.	Impact on energy consumption and emissions in Switzerland.	Strategic planning insights for market adoption and behavioral implications of emerging mobility trends.

This table consolidates strategic insights from key studies on optimization strategies, business models, and operational dynamics, emphasizing the significance of informed policy design, innovation, and targeted marketing. For instance, the work of Yang et al. [67] highlights the challenges in integrating medium-duty EVs into urban delivery fleets, pointing out that technological advancements are essential to fully leverage subsidies, underscoring that subsidies alone are insufficient without concurrent technological support. The table thus provides a comprehensive overview, offering valuable insights for policymakers, fleet managers, and organizations aiming to transition to electric mobility.

RocaPuigros et al. [68] offer a broader perspective with their stock dynamics model, illustrating how electrification combined with shared and autonomous vehicles can reshape energy consumption and emissions patterns in transportation systems. Their findings underscore the importance of a holistic approach to adopting new mobility technologies.

Further insights are provided by Kumar et al. [62], who discuss how diverse business models can facilitate EV commercialization, emphasizing the role of service orientation and innovation in driving market acceptance. Similarly, AL Mansour [63] focuses on consumer attitudes, highlighting how digital features, financial incentives, and environmental awareness significantly influence EV purchasing decisions.

Additional studies like that of Uthathip [64] assess the implications of EV penetration on national energy systems, suggesting that EV adoption impacts energy consumption patterns and GHG emissions strategies. This is complemented by the work of Cavalett Cherubini et al. [65], who advocate for a diversified approach to transportation decarbonization, including both EVs and biofuels.

Collectively, these studies provide a comprehensive view of the factors influencing EV adoption, including consumer behavior, policy impacts, technological innovations, and market strategies. They underscore the necessity of integrating consumer insights, technological readiness, and strategic policy frameworks to facilitate a sustainable transition to electric mobility. Future research should continue to address these interconnected elements, focusing on overcoming barriers to adoption and enhancing the appeal of EVs to a broader audience.

4.2. Impact of Electric Transportation on the Energy Sector: Focus on the Petroleum Industry

The rise of electric transportation is transforming the energy sector, bringing significant implications for the petroleum industry. The increasing adoption of EVs directly reduces the demand for petroleum products. According to the IEA, the global EV fleet is projected to displace approximately six million barrels of oil per day by 2030 [1]. This substantial reduction in petroleum demand presents a significant challenge for the oil industry, traditionally reliant on transportation fuels as a major revenue source [69].

The decline in petroleum demand driven by EV growth is prompting major oil companies to reassess their business models. Companies like BP and Shell are increasingly investing in renewable energy sources and EV charging infrastructure [70]. For instance, Shell aims to operate over 500,000 EV charge points globally by 2025 [71]. These strategic shifts are designed to diversify revenue streams and mitigate the financial impact of reduced oil consumption [72].

Furthermore, the environmental benefits of reduced petroleum consumption are substantial. The shift from internal combustion engine vehicles to EVs results in lower greenhouse gas emissions and decreased air pollution [10]. According to the IEA, by 2035, the widespread adoption of EVs could reduce CO_2 emissions by 1.8 gigatonnes, with further reductions expected through 2040 [1]. This transition supports global efforts to combat climate change and promotes cleaner air in urban areas [73].

Government policies also play a crucial role in accelerating EV adoption and subsequently impacting the petroleum sector. Policies such as subsidies for EV purchases, stringent emission regulations, and investments in charging infrastructure are driving the shift toward electric mobility [52]. For example, the European Union's Green Deal aims to reduce net greenhouse gas emissions by at least 55% by 2030 [74], significantly impacting oil demand in the region.

Additionally, market dynamics are evolving, with oil prices potentially experiencing increased volatility due to fluctuating demand [75]. As more consumers transition to EVs, the traditional correlation between economic growth and oil demand may weaken, leading to new pricing and supply strategies in the petroleum industry [76].

Norway serves as a pertinent case study, exemplifying the impact of EV adoption on the petroleum sector. With EVs accounting for over 54.3% of new car sales in 2020, the country has seen a marked decrease in gasoline and diesel consumption [52]. In response, Norwegian oil companies are investing heavily in offshore wind energy projects and other renewable ventures to adapt to the changing market landscape [77].

Further illustrating the intersection of energy policies and transportation, Durdağ and Şahin [78] examine how energy policies in Turkey impact the road transportation sector, with a particular focus on energy-related costs and their influence on economic and social life. Their research highlights the reliance on petroleum products in Turkish road transport and provides a detailed analysis of energy consumption and cost distribution. The study suggests that adopting alternative fuels, improving energy efficiency, and leveraging combined transport methods can significantly reduce energy costs across the supply chain. These findings underscore the need for strategic energy management in the transport sector to enhance economic efficiency and minimize environmental impact.

Overall, the rise of electric transportation is reshaping the petroleum industry by reducing oil demand, prompting economic shifts, and contributing to environmental sustainability [79]. As the transition to electric mobility accelerates, the petroleum sector must adapt through strategic investments and innovations to remain viable in the evolving energy landscape [80].

4.3. Environmental Impact of EV Adoption

EV adoption is a critical step in mitigating environmental degradation, prominently through the reduction of greenhouse gas (GHG) emissions and other pollutants. This subsection explores the multifaceted environmental impacts of EV adoption, examining how these vehicles influence air quality, carbon footprints, and overall ecological sustainability across various sectors and regions. Through a series of comprehensive tables and studies, we assess the immediate and long-term environmental benefits of electrifying transportation, ranging from individual vehicle emissions to broader global impacts. This analysis highlights the potential of EVs to advance environmental goals while also examining the complexities and challenges inherent in their full lifecycle, providing a balanced view of their sustainable promise and the associated trade-offs.

4.3.1. Overview of Carbon Emissions Reduction in Vehicle Types and Technologies

The adoption of EVs offers a transformative opportunity for substantial reductions in carbon emissions across diverse transportation sectors. This shift is especially impactful in areas such as heavy-duty trucks, taxis, and public buses, where electrification not only reduces emissions but also improves operational efficiency. These benefits highlight the potential of EVs to contribute significantly to sustainability goals.

In Table 10, we provide a detailed overview of studies that quantify these impacts across various vehicle types. The table focuses on the substantial emissions reductions and efficiency gains achieved through electrification in different sectors, offering insights into greening operations and optimizing fleet management. Each study emphasizes the importance of selecting appropriate EV technologies and strategies to maximize environmental benefits.

Table 10. Overview on carbon emissions reduction in vehicle types and technologies.

Ref.	Focus	Key Findings	Implications
[81]	Investigating electric heavy-duty trucks within industrial settings.	Substantial emissions reductions and efficiency gains.	Actionable insights for greening operations through EV integration.
[82]	Evaluating the electrification of app-based taxi fleets in Delhi.	Notable environmental and economic gains.	Compelling case for urban mobility systems to transition towards EVs.
[83]	Comparing vehicle technologies for taxis in Hong Kong.	EVs offer a cost-effective route to reducing carbon emissions.	Importance of selecting the right EV technologies for transport organizations.
[84]	Evaluating the decarbonization potential of electric buses in Turkey's urban transport.	Electrification as a profitable and sustainable approach.	Insights for integrating EVs into public transport systems.
[85]	Analyzing city buses with various energy storage systems.	Finds EVs the most efficient, emphasizing potential for emission reductions.	Importance of EVs for sustainable public transport improvements.
[86]	Introducing an innovative route optimization model for electric garbage trucks in Istanbul.	Valuable insights into reducing energy consumption and environmental impact.	Route optimization as a strategic tool for electric fleet management.
[87]	Evaluating energy consumption and CO_2 emissions of various powertrains under real-world driving conditions in Northern Thailand.	BEVs exhibited superior efficiency.	Significant influence of regional driving characteristics on the environmental benefits of EV adoption.
[88]	Assessing the potential of BEPVs in China for electricity conservation and carbon emissions reduction.	Strong emissions reduction potential of BEPVs.	Compelling argument for integrating EVs into sustainability strategies.
[89]	Developing an urban-scale carbon emissions estimation model based on real-world ride-hailing EV data.	Improves emissions accounting and showcases operational efficiencies.	Methodology for optimizing the environmental performance of EV fleets.

For instance, Dou et al. [81] highlight significant emissions reductions in heavy-duty industrial trucks, emphasizing the role of EVs in enhancing green operations. Similarly, Rajagopal et al. [82] and Mingolla [83] provide insights into the urban context, showcasing how taxis can reduce their carbon footprint and operational costs through electrification.

Further contributions like those from Kumbaroglu et al. [84] and Lebkowski [85] discuss the integration of EVs into public transport systems, pointing out the profitability and sustainability of such initiatives. These studies not only confirm the environmental advantages but also outline the practical aspects of implementing EV technologies in public and commercial transport sectors.

Moreover, innovative approaches like Erdinc's [86] route optimization for electric garbage trucks and Huang's [89] emission estimation models leverage advanced methodologies to enhance the environmental performance of EV fleets, demonstrating how targeted technological solutions can optimize operational efficiencies and sustainability outcomes.

These analyses collectively underscore the critical role of tailored technological adoption in achieving significant environmental improvements. By transitioning to electric powertrains, different sectors can not only meet regulatory emissions targets but also foster a sustainable operational model that aligns with global environmental objectives. Future research should continue to focus on overcoming barriers to adoption, optimizing technology integration, and expanding the scope of EV benefits to more vehicle types and operational scenarios.

4.3.2. Regional and Global Impacts of EV Adoption

Building on vehicle-specific emission reductions, this section shifts to examining the regional and global impacts of EV adoption. This perspective is crucial for highlighting both the localized benefits and broader implications for global carbon reduction strategies.

Table 11 presents studies exploring the effectiveness of EVs in different geographical contexts, showing how varied regional strategies can significantly influence the success of global environmental goals and highlighting diverse findings that illustrate the critical role of EVs in mitigating environmental impacts on both regional and global scales.

Table 11. Regional and global impacts of EV adoption.

Ref.	Focus	Key Findings	Implications
[90]	CO_2 mitigation in China's Yangtze River Delta.	Significant CO_2 and health benefits.	Supports region-specific sustainable practices.
[91]	Carbon footprint reductions in Qatar's gas-based grid.	Substantial transportation carbon footprint cuts.	Stresses the role of government incentives in similar contexts.
[92]	Fleet electrification in Greek urban areas.	Notable environmental and social benefits.	Advocates electrification for urban sustainability.
[93]	Electric vs. fossil-fueled vehicles in urban delivery.	EVs are advantageous in urban delivery.	Highlights EVs' role in urban sustainability.
[94]	Forecasting new energy vehicle ownership in China.	EV adoption impacts the decarbonization of transport.	Necessitates strategic policies for sustainable mobility.
[95]	GLOSA tech in PHEVs.	Technological advancements cut energy use and emissions.	Integrating smart tech with EVs amplifies benefits.
[96]	EV rollout in China via integrated model.	Significant CO_2 reductions with minimal economic impact.	Highlights EV adoption's potential for sectoral emissions cuts.
[97]	Integrating truck–drone delivery systems.	Significant last-mile emissions reductions.	Drones with EVs enhance delivery sustainability.
[98]	Forecasting EV sales in Portugal and grid impact.	Peak power demand challenges.	EV adoption needs careful infrastructure planning.
[99]	EV vans in Great Britain: CO_2/NOx reductions and savings.	Significant emissions cuts and economic savings.	Advocates rapid electric van transition for sustainability.

For instance, the studies by Yijing [90] and Al Buenain [91] discuss the considerable reductions in carbon emissions in China's Yangtze River Delta and Qatar, respectively, highlighting how region-specific policies and energy contexts can shape the effectiveness of EV adoption. Further analysis by Kouridis [92] and Pilati [93] offers insights into the integration of EVs within urban fleets in Greece and the sustainable parcel delivery challenges in urban environments. These studies underscore the potential of EVs to foster urban sustainability and reduce operational carbon footprints through tailored electrification strategies. Additionally, the work of Chen [94] and Guo [96] delves into the broader implications of widespread EV adoption in China, suggesting that comprehensive policy frameworks are essential to support sustainable mobility transitions and achieve significant sectoral emissions reductions. Jia's [95] exploration of GLOSA technology in plug-in hybrid electric vehicles further emphasizes the role of technological advancements in enhancing the environmental benefits of EVs.

Research works of [97,98] introduce innovative concepts such as integrating drone technology with truck deliveries and the infrastructural challenges posed by increasing EV sales in Portugal. These studies highlight how cutting-edge solutions and infrastructure planning are crucial for maximizing the environmental benefits of EVs. Collectively, these findings not only reinforce the necessity of adopting EVs for carbon reduction but also highlight the importance of regional considerations and advanced technological integrations in realizing these environmental benefits.

4.3.3. Analysis of Carbon Emissions Reduction in Vehicle Types and Technologies

EVs have become a pivotal solution for reducing carbon emissions in the transportation sector. This section examines the carbon footprint of EVs compared to internal combustion engine (ICE) vehicles, using the Nissan Leaf and a comparable Nissan ICE vehicle as case studies. The analysis includes both component-wise and vehicle-wise carbon footprint calculations and discusses the methodologies used in these calculations. Previous studies have shown that the environmental impact of EVs, like the Nissan Leaf, is significantly influenced by factors such as battery production, electricity grid composition, and vehicle usage patterns [100].

Lifecycle assessment (LCA) is a comprehensive approach used to evaluate the environmental performance of vehicles from production to end-of-life. This methodology includes stages such as raw material extraction, manufacturing, use phase, and end-of-life. In the raw material extraction phase, the emissions from extracting and processing raw materials are evaluated. The manufacturing phase involves assessing the emissions from vehicle and battery production processes. The use phase measures the emissions during the vehicle's operational life, including fuel or electricity consumption. Finally, the end-of-life stage considers the emissions from vehicle disposal, recycling, and potential second-life applications.

With this methodology in mind, we begin by examining the manufacturing phase emissions of EVs. The manufacturing phase of EVs like the Nissan Leaf typically results in higher GHG emissions compared to ICE vehicles, primarily due to the energy-intensive process of battery production. For instance, the production of a 40 kWh battery for the Nissan Leaf contributes significantly to its initial carbon footprint. According to the IVL Swedish Environmental Research Institute, the emissions from battery production are estimated to be around 61 kg CO_2e/kWh [101], resulting in approximately 2.44 tonnes of CO_2-equivalent emissions for the battery alone. In contrast, the manufacturing emissions for a comparable ICE vehicle, such as a Nissan Sentra, are generally lower due to the absence of a large battery. The International Council on Clean Transportation (ICCT) reports that the total manufacturing emissions for ICE vehicles are significantly less than for EVs [102].

Moving on to the use-phase emissions, EVs like the Nissan Leaf produce zero tailpipe emissions, which is a significant advantage over ICE vehicles. The Carbon Brief analysis shows that the Nissan Leaf can save approximately 2 to 3 tonnes of CO_2-equivalent annually in the UK, assuming the current electricity mix [14]. Conversely, a typical ICE vehicle emits about 4.6 metric tonnes of CO_2 per year based on an average fuel economy of 22 miles per gallon and annual mileage of 11,500 miles, as reported by the U.S. Environmental Protection Agency [103], resulting in approximately 55.2 tonnes of CO_2 over a 12-year lifespan.

Considering the entire lifecycle, including manufacturing, use, and end-of-life phases, EVs generally have lower GHG emissions compared to ICE vehicles. The ICCT conducted a comprehensive LCA and found that medium-sized BEVs registered today have 60–68% lower lifecycle GHG emissions in the United States compared to their gasoline counterparts [104]. For the Nissan Leaf, the cumulative GHG emissions over a 150,000 km (approximately 93,205 miles) lifetime are significantly lower than those of a comparable ICE vehicle. The Carbon Brief [14] estimates that the Nissan Leaf's lifecycle emissions are around 29 tonnes of CO_2-equivalent, whereas a comparable ICE vehicle emits approximately 57 tonnes of CO_2-equivalent over the same distance. Table 12 summarizes the comparative emissions for the Nissan Leaf EV and a comparable Nissan ICE vehicle across different lifecycle stages.

Table 12. Comparative emissions summary, based on [105].

Lifecycle Stage	Nissan Leaf EV	Nissan ICE Vehicle (e.g., Nissan Sentra)	Notes
Production	Higher CO_2, water use, harmful substances, and electric energy.	Lower CO_2, water use, harmful substances, and electric energy.	EV production is more resource-intensive due to battery materials like nickel, manganese, cobalt.
Operation	Higher energy use; 3.21 tons CO_2/year; more harmful substances.	Lower energy use; 3.75 tons CO_2/year; fewer harmful substances.	EVs use more energy due to inefficiencies but emit less CO_2 during use; ICE vehicles are more efficient but emit more CO_2.
Natural Resources	Six times more resources needed.	Significantly fewer resources needed.	EV production demands more natural resources, increasing its environmental footprint.
Waste Products	More industrial waste generated.	Less industrial waste generated.	EVs produce more waste during production due to the use of ores with low metal content.
Overall Environmental	Higher production burden, lower operational burden.	Lower production burden, higher operational burden.	EVs have a higher impact during production but lower during operation; the overall impact depends on the lifecycle stage balance.

Figure 11 illustrates the comparative lifecycle GHG emissions of a mid-size BEV and ICEV under two scenarios, showing significant differences. The chart illustrates the comparative lifecycle GHG emissions of a mid-size BEV and ICEV under two scenarios for BEVs: a base case and a high-GHG minerals case. Emissions are categorized into vehicle manufacturing, battery assembly, battery minerals, electricity, and the fuel cycle (well-to-wheel).

The data highlights that BEVs, even in the high-GHG minerals case, have significantly lower overall emissions compared to ICEVs, primarily due to the absence of fuel cycle emissions. The base case BEV scenario shows total lifecycle emissions of approximately 19. tCO_2e, while the high-GHG minerals case increases this to about 21.1 tCO_2e. In contrast, the ICEV exhibits a much higher total lifecycle emission of 41.9 tCO_2e, driven predominantly by the fuel cycle emissions [106]. This comparison underscores the environmental benefits of BEVs over ICEVs, even when accounting for variations in mineral extraction and processing emissions. The reduction in emissions for BEVs can be further enhanced with cleaner electricity grids and advancements in battery technology, reinforcing the importance of transitioning to EVs for climate mitigation.

As detailed in [1], Figure 12 compares the global average lifecycle emissions for different vehicle powertrains across three scenarios, highlighting the advantages of BEVs. The chart compares the global average lifecycle emissions for different vehicle powertrains (e.g., ICEV, HEV, PHEV, and BEV) across three scenarios: 2023, Stated Policies 2035, and Announced Pledges 2035. The emissions are categorized into car production, battery production, well-to-tank, tank-to-wheel, and grid decarbonization impact.

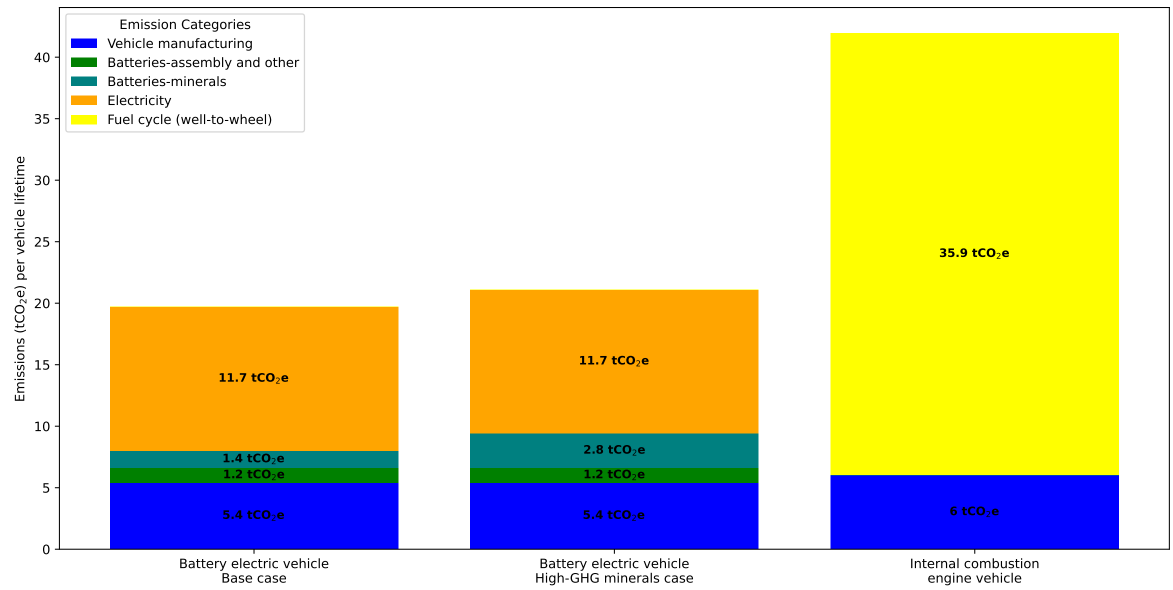

Figure 11. Comparison of LCGHG emissions between a mid-size BEV and ICE vehicle—adapted from [106].

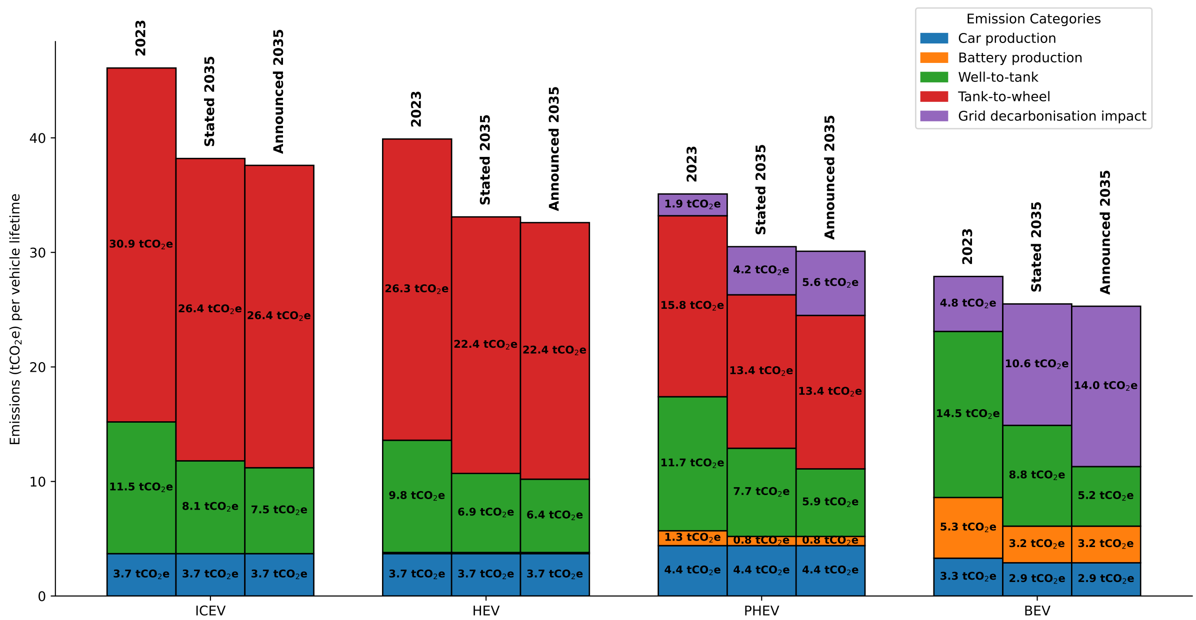

Figure 12. Comparison of worldwide average lifecycle emissions by powertrain under the Stated Policies and Announced Pledges Scenarios from 2023 to 2035—adapted from [1].

The analysis demonstrates that BEVs, sold in 2023, emit roughly half the GHG over their lifetime compared to ICEVs. This trend continues to improve with grid decarbonization, as BEVs are projected to have significantly lower emissions by 2035. In the Stated Policies Scenario, BEVs in 2035 will have emissions about two-and-a-half times lower than ICEVs, and in the Announced Pledges Scenario, the difference increases to over three times. Well-to-tank emissions are expected to decrease significantly, by up to 75% in the Announced Pledges Scenario, due to cleaner electricity generation.

The chart also highlights that larger vehicles, while generally having higher emissions, benefit substantially from electric powertrains, which mitigate much of the impact. This comprehensive lifecycle analysis underscores the importance of continued investment in renewable energy and cleaner electricity to maximize the environmental benefits of EVs, affirming that BEVs offer significant emissions reductions compared to conventional ICEVs and other hybrid powertrains.

4.3.4. Lifecycle Environmental Impacts

In concluding our exploration of EVs' environmental impacts, it is crucial to consider their full lifecycle implications. This holistic perspective assesses everything from production and operational impacts to end-of-life recycling, offering a comprehensive view of EVs' sustainability. Table 13 delves into studies evaluating the total environmental footprint of EVs across various phases of their lifespan, highlighting essential trade-offs and benefits.

Table 13. Lifecycle environmental impacts.

Ref.	Focus	Key Findings	Implications
[107]	Lifecycle energy use and GHG emissions of various vehicle types in China, highlighting EV battery production impacts.	Overall environmental benefits of EVs, especially with cleaner electricity.	Insights on lifecycle impacts and sustainability for China's transport sector.
[108]	Lifecycle environmental impacts of fleet electrification on asphalt concrete pavement in the U.S.	Expands LCA to include infrastructure sustainability.	Highlights the link between vehicle technology and infrastructure sustainability.
[109]	Comparing lifecycle impacts of different bus technologies in Bolzano, Italy.	Electric buses reduce non-renewable energy demand and global warming potential.	Benefits of electric buses for sustainable urban mobility.
[110]	LCA of shared electric bicycles in China.	Significant net GHG reduction benefits, with efficient recycling practices.	Indicates that shared electric bicycles can aid urban sustainability, important for shared mobility ecosystems.
[111]	LCA of various vehicle technologies in India.	Emissions reductions from electrification depend on regional energy grid composition.	Need for strategic EV implementation considering local energy contexts, offering insights for policymakers.
[112]	Assessing emissions impact of various vehicle types in China using LCA.	EVs significantly reduce CO_2 emissions, especially with more renewable energy.	Insights for understanding the environmental benefits of transitioning to electric mobility.
[113]	Comparative analysis of EVs and ICEVs in the US, focusing on battery degradation over time.	Provides a nuanced view of EVs' environmental and economic benefits.	Informs stakeholders about EV performance complexities, aiding data-driven vehicle selection decisions.

Building on this overview, the table includes detailed studies such as those by Peng [107] and Barkh [108], which explore specific aspects of lifecycle impacts. For example, Grazieschi's [109] study on bus technologies in Italy confirms that electric buses significantly reduce global warming potential and non-renewable energy demand, supporting their adoption in public transport. Similarly, Zhu's [110] assessment of electric bicycles emphasizes the role of efficient recycling practices in enhancing the environmental benefits of shared mobility platforms.

Additionally, Peshin's [111] work on vehicle technologies in India emphasizes the importance of aligning EV deployment with local energy grid compositions to optimize emissions reductions. This is echoed by Wang's [112] analysis, which suggests that the integration of EVs with renewable energy sources is pivotal for realizing their full potential in reducing carbon emissions. Yang's [113] comparative analysis further illuminates the long-term sustainability of EVs compared to internal combustion engine vehicles, particularly focusing on battery degradation and its implications for lifecycle environmental performance.

Collectively, these studies underscore the multifaceted nature of EVs' environmental impact, demonstrating that while there are significant benefits, strategic considerations are necessary to maximize these advantages. As we move forward, the continued research and adaptation of policies based on local contexts and technological advancements will be essential to fully harness the potential of EVs for a sustainable future.

4.3.5. Contribution of CO_2 and Energy Consumption in Recycling EV Batteries

Recycling EV batteries, particularly lithium-ion batteries (LIBs), involves a complex, energy-intensive process aimed at reducing GHG emissions and conserving resources. The typical lifespan of these batteries spans 5 to 10 years, undergoing more than 1000 charge/discharge cycles, after which they are retired at around 80% of their original capacity. These retired batteries can be either recycled or repurposed for second-life applications, where they can continue functioning for over a decade with reduced capacity [114].

Recycling processes for EV batteries can be broadly categorized into pyrometallurgical, hydrometallurgical, and direct physical methods, each having distinct environmental impacts. Pyrometallurgical recycling involves high-temperature processing, often exceeding 1000 °C, which is energy-intensive and results in significant CO_2 emissions. Specifically, this method produces approximately 2.17×10^{-11} in overall environmental impact when recycling 1000 kg of batteries, largely due to the fossil fuel energy consumed during the process and the pyrolysis of graphite anodes [115]. Although this method offers high economic value, its ecological value is relatively poor due to its substantial GHG emissions.

In contrast, hydrometallurgical recycling, which uses chemical leaching at lower temperatures, is less energy-intensive and generates fewer emissions. This method has an overall environmental impact of -1.50×10^{-12} when recycling 1000 kg of batteries [115]. However, it does produce a considerable amount of toxic waste and solutions, posing significant environmental challenges. Direct physical recycling, while still in the experimental stage and not yet suitable for large-scale application, shows the highest potential for reducing emissions, with approximately 37.2 kg CO_2-eq/kWh, offering about a 32% reduction in emissions compared to traditional methods [116].

The energy consumption and CO_2 emissions associated with recycling processes are crucial for understanding the environmental footprint of EVs. For instance, the energy required for recycling one battery pack is approximately 7.64 kWh for pyrometallurgical recycling and 7.76 kWh for hydrometallurgical recycling [115]. The CO_2 emissions from these processes are similarly substantial, with each battery pack contributing approximately 0.224 kg CO_2 [115].

Beyond the direct recycling process, the infrastructure for charging EVs also plays a significant role in the overall environmental impact. Charging equipment, particularly DC fast chargers, involves considerable energy use and material consumption during production. While specific emissions data for the manufacturing of chargers alone are scarce, the overall lifecycle emissions, including production, operation, and disposal, highlight their substantial carbon footprint [117]. The operational emissions of charging infrastructure vary significantly depending on the electricity mix. In regions where fossil fuels dominate the energy supply, the associated emissions are higher compared to areas with a greater reliance on renewable energy sources [10].

Charging infrastructure can be categorized into three types: Level 1, Level 2, and DC fast chargers. Level 1 chargers use standard 120V AC outlets and consume about 1 kW of power, taking 40–50 h to charge a battery electric vehicle (BEV) from empty [118]. Level 2 chargers, operating at 240V in residential settings or 208V in commercial applications, provide 3.3–19.2 kW per hour and typically require 4–10 h to fully charge a BEV [119]. DC fast chargers, which use three-phase 480V power, deliver outputs ranging from 50 kW to 350 kW, capable of charging a BEV to 80% in 20 min to an hour [118].

The LCA of charging stations considers various stages, including manufacturing, installation, maintenance, and disposal. These stages involve significant material and energy inputs, contributing to the overall environmental impact [117]. Regular maintenance and eventual disposal further add to this footprint.

To mitigate the environmental impact, advancements in recycling technologies and the integration of renewable energy sources are essential. Using renewable energy to power both recycling facilities and charging infrastructure can significantly reduce the carbon footprint of EVs. Strategies such as solar-powered charging stations are being explored to enhance sustainability and minimize environmental impacts [118].

In conclusion, both the recycling of EV batteries and the infrastructure for charging play pivotal roles in the overall environmental impact of EVs. By improving recycling methods and integrating renewable energy, the industry can support the broader adoption of EVs as a sustainable transportation solution, thereby reducing the carbon footprint and promoting a cleaner environment. Table 14 summarizes the key aspects, including energy consumption, CO_2 emissions, overall environmental impact, advantages, disadvantages, charging times, and environmental mitigation strategies of different recycling methods and charging infrastructure for EV batteries.

Table 14. Summary of energy consumption, CO_2 emissions, and environmental impact of recycling methods and charging infrastructure for EV batteries.

Aspect	Pyrometallurgical	Hydrometallurgical	Direct Physical	Charging Infrastructure
Process	High-temp processing	Chemical leaching	Direct separation	Level 1, 2, DC fast chargers
Energy Use	7.64 kWh/pack [115]	7.76 kWh/pack [115]	Not specified (experimental)	1 kW (L1), 3.3–19.2 kW (L2), 50–350 kW (DC) [118]
CO_2 Emissions	0.224 kg CO_2/pack [115]	Not specified	37.2 kg CO_2-eq/kWh [116]	Varies by energy mix; higher in fossil fuel-dominant regions [10]
Environmental Impact	2.17×10^{-11} (normalized) [115]	-1.50×10^{-12} (normalized) [115]	32% lower than traditional [116]	Significant from manufacturing, operation, disposal [117]
Advantages	High economic value	Less energy-intensive, fewer emissions	High potential for emission reduction	Quick charging (DC)
Disadvantages	High GHG emissions, energy-intensive	Toxic waste	Experimental, not for large-scale	High material and energy inputs
Charging Time	N/A	N/A	N/A	40–50 h (L1), 4–10 h (L2), 20 min–1 h (DC) [118]
Mitigation Strategies	Improve recycling tech, use renewable energy	Renewable energy, better waste management	Tech advancements, scaling up	Solar-powered stations, renewable integration

Note: N/A = Not Applicable.

4.3.6. Impact of Tires on Carbon Footprint in EVs

Building on the broader environmental impacts, the sustainability of EVs extends to the production and use of their components. Tires, as a critical component of EVs, play a significant role in influencing their overall carbon footprint. This part of our analysis delves into the lifecycle emissions of tires, focusing on innovative materials like silica and graphene, and advanced emission control strategies.

Traditional tire production primarily utilizes carbon black, a material known for its durability and performance-enhancing properties. However, its production is energy-intensive and carbon-rich. Studies indicate significant environmental benefits when replacing carbon black with alternative materials such as silica or graphene, which can substantially reduce the carbon footprint associated with tire manufacturing.

- Carbon Black vs. Silica: LCAs reveal that silica-based tires emit approximately 11,639.36 kg CO_2 eq per ton, which is a reduction of 526.78 kg CO_2 eq compared to all-carbon black systems. This transition not only reduces the Global Warming Potential (GWP) by about 4.3% but also enhances the performance of tires in terms of lower rolling resistance and better wet grip [120].
- Cumulative Energy Demand (CED): Traditional tires exhibit higher energy consumption due to inefficient material use. Conversely, ecological tires made with silica have a lower energy demand, benefiting from more sustainable manufacturing processes that further contribute to reducing the carbon footprint of EVs [121].

Innovations in tire materials play a critical role in its impact on the carbon footprint of EVs. Graphene, noted for its exceptional strength and conductivity, offers further reductions in lifecycle carbon emissions when used as a replacement for carbon black in tire production.

- Carbon Black vs. Graphene: Integrating graphene into tire production can decrease carbon emissions by up to 23.46% when graphene fully replaces carbon black. This potential reduction is pivotal, considering that the raw material stage of production, where carbon black is heavily used, contributes most significantly to the overall emissions. By substituting carbon black with 25%, 50%, 75%, and 100% graphene, the emissions can be reduced by 5.92%, 11.62%, 17.76%, and 23.46%, respectively. Remarkably, graphene can reduce the emissions of the carbon black component itself by up to 98.81% [122].

While material innovations provide significant reductions in carbon emissions, advancements in vehicle control strategies also play a crucial role in addressing non-exhaust emissions from tires.

- Tire Emission Control: Advanced control strategies have been developed to reduce tire emissions in EVs effectively. For instance, the implementation of tire particle control strategies can decrease particulate emissions by over 90% while ensuring ride comfort. This reduction is critical for mitigating microplastic pollution and reducing the indirect environmental impacts of EVs [123].

The tire industry's impact on the EV carbon footprint is multifaceted, including direct emissions from production and indirect effects from tire wear. Innovations in materials like silica and graphene, along with advanced vehicle control strategies, help mitigate these impacts. As EV adoption grows, optimizing tire production and use becomes essential for achieving environmental sustainability goals. Table 15 shows a summary of innovative tire materials on EV carbon footprint. Addressing the environmental impact of EV tires through innovative materials and advanced control strategies is crucial for enhancing the overall sustainability of EVs.

Table 15. Impact of innovative tire materials on EV carbon footprint.

Material Comparison	Description	GWP of Traditional Tires (kg CO_2 eq)	GWP of Ecological Tires (kg CO_2 eq)	CO_2 Reduction (kg CO_2 eq)	Cumulative Energy Demand	Notes	Source
Carbon Black vs. Silica	Lifecycle comparison of carbon black and silica in tires	12,166.14	11,639.36	526.78	Lower with silica	Silica tires reduce rolling resistance and energy use.	[120]
Carbon Black vs. Graphene	Replacing carbon black with graphene in tire production	Similar to carbon black	Up to 23.46% reduction with full replacement	Depends on replacement level	Lower with graphene	Graphene improves strength, thermal conductivity, and tire performance.	[122]
Tire Emission Control Strategy	Strategy to minimize tire wear emissions in EVs	Not applicable	Not applicable	Over 90% reduction in particulates	Not directly affected	Strategy improves comfort while reducing emissions.	[123]

As these advancements continue to develop, they hold the promise of significantly reducing the carbon footprint associated with tire production and use. Having comprehensively covered the environmental impacts of EV adoption, the next subsection will delve into the technological and operational challenges in EV integration, exploring the complexities and innovative solutions necessary for effective implementation.

4.4. Technological and Operational Challenges in EV Integration

Integrating EVs into transportation networks and energy systems presents a complex array of technological and operational challenges that go beyond simple vehicle deployment. This subsection explores the intricate dynamics involved in the effective implementation of EV technologies, covering the development of advanced battery systems, efficient charging infrastructures, and the optimization of fleet management and software solutions. Innovations in energy storage, smart charging strategies, and digital management tools are crucial for addressing these challenges. Each table and accompanying discussion highlight both the current limitations and forward-thinking approaches that promise to enhance the reliability, efficiency, and overall effectiveness of EV integration, paving the way for a more sustainable automotive future.

4.4.1. Battery Technologies and Energy Storage Solutions

Advancements in battery technology and energy storage solutions play a crucial role in addressing operational challenges. The effective integration of these technologies is critical for enhancing the efficiency, reliability, and overall performance of EVs. Table 16 presents a comprehensive analysis of current advancements in battery swap technology, routing algorithms that consider battery health, and predictive models for battery requirements in diverse operational conditions.

Table 16. Advanced battery technologies and energy storage solutions.

Ref.	Focus	Key Findings	Implications
[6]	Battery swap technology (BST) adoption in China; user attitudes and safety concerns.	BST alleviates range anxiety.	Recommends policies to foster BST adoption for enhanced operational efficiency and user satisfaction.
[7]	EV routing approach incorporating battery health, addressing degradation and state of charge.	Nuanced solution to routing by considering battery health.	Supports fleet longevity and reliability, aligning with sustainable operational goals.
[124]	Predictive model for battery electric bus energy consumption; vehicular, operational, topological, and external parameters.	Optimized routing and operational strategies for greater energy efficiency.	Assists transit planners and fleet managers in designing sustainable and efficient urban transit networks.
[125]	Deep learning for precise battery State of Health estimation under varying conditions.	Enhances safety and reliability of EV usage.	Vital for maintaining EV performance and lifecycle sustainability.
[126]	Viability of electric heavy-duty vehicles in Icelandic conditions.	Insights into infrastructural needs for wide-scale adoption.	Highlights tailored solutions for cold climates to promote EV integration.

The studies outlined in Table 16 collectively shed light on the transformative impact of advanced battery technologies and energy storage solutions on the operational dynamics of EVs. Adu-Gyamfi et al. [6] emphasize the critical role of battery swap technology in mitigating range anxiety, highlighting the necessity for supportive policies that encourage widespread adoption and address user concerns related to safety and convenience. This technology not only enhances user satisfaction but also improves vehicle uptime and operational efficiency.

Longhitano's [7] innovative routing algorithm integrates considerations of battery health, such as degradation and state of charge, which underpins the sustainability of EV operations by extending battery life and ensuring efficient energy use. Similarly, the predictive model presented in Abdelaty and Mohamed's study [124] for the energy needs of battery electric buses incorporates environmental and operational variables to optimize routing and charging strategies, thereby supporting fleet managers in achieving more sustainable urban mobility.

Moreover, Hong's [125] application of deep learning for estimating the State of Health of batteries enhances the safety and operational reliability of EVs, ensuring that the vehicles operate within their optimal battery capacity and contribute to the longevity of the vehicle's life cycle. Alonso-Villar's [126] study further illustrates the need for EV technologies to be adaptable to various environmental conditions, particularly in challenging climates like Iceland, underscoring the importance of developing region-specific solutions to foster the broader integration of EVs across different sectors.

In addition to battery advancements, supercapacitors (SCs) have emerged as a complementary energy storage solution with unique advantages and applications. Şahin et al. [127] provide a comprehensive review of supercapacitor technology, emphasizing its high power density, rapid charge–discharge cycles, and long lifecycle, which make SCs particularly well-suited for applications requiring quick bursts of energy, such as regenerative braking in EVs. The integration of SCs with traditional batteries in hybrid energy storage systems (HESSs) offers a promising solution for optimizing both power and energy density in EVs, enhancing performance, and extending battery life.

Building on these advancements, Ting and Şahin [128] introduce a novel DC-DC boost converter designed for EVs, featuring dual inputs supported by an ultracapacitor. This design is particularly effective in managing high current demands during sudden acceleration, thereby reducing strain on the battery and potentially extending its lifespan. The converter operates in three modes—conventional boost, ultracapacitor-assisted, and recharging mode—ensuring stable power distribution across various driving conditions. The results demonstrate the converter's potential to enhance EV performance and reliability, especially in urban environments with frequent stop-and-go traffic.

These collective insights not only highlight the crucial role of advanced battery and supercapacitor technologies in facilitating the widespread adoption of EVs but also underscore the need for continuous innovation in this field to meet the growing demands of an electrified transportation future.

4.4.2. Strategies for Recycling Batteries and Recovering Cobalt and Lithium

The increasing adoption of EVs has led to a surge in the production and disposal of lithium-ion batteries. Effective recycling strategies are crucial for recovering valuable materials such as cobalt and lithium, which are essential for battery production. This sub-subsection examines current practices, technologies, and future directions for battery recycling and material recovery.

Battery recycling involves the collection, disassembly, and processing of spent batteries to recover valuable materials. The process is complex due to the varied chemistry of batteries, which includes lithium, cobalt, nickel, manganese, and other materials [129]. Current recycling practices face challenges such as the high cost of recycling, safety concerns, and the need for efficient and environmentally friendly methods [130]. Several technologies are employed to recover cobalt and lithium from spent batteries.

Hydrometallurgical processes involve the use of aqueous solutions to extract metals from batteries. It is known for its high recovery rates and lower energy consumption compared to traditional methods. Hydrometallurgy is particularly effective in recovering lithium and cobalt with minimal environmental impact [131]. Pyrometallurgical processes, on the other hand, use high temperatures to smelt battery materials, separating metals from other components. While effective, pyrometallurgy is energy-intensive and can result in significant emissions [115]. Advances in this field aim to reduce the environmental footprint of the process [132]. Direct Recycling is an emerging method that involves the direct recovery and reconditioning of battery materials without breaking them down into their elemental forms. This process can be more cost-effective and environmentally friendly, preserving the integrity of battery components for reuse [133].

Recycling batteries and recovering cobalt and lithium offer substantial economic and environmental benefits. Recycling reduces the need for mining raw materials, which can be costly and environmentally damaging [134]. By recovering valuable metals, recycling can lower the cost of battery production and create new business opportunities in the recycling sector [135]. Environmentally, effective recycling minimizes the impact of mining activities, reducing habitat destruction, water pollution, and carbon emissions [136]. It also decreases the volume of waste sent to landfills, promoting a circular economy where materials are reused and repurposed [137].

Government policies and regulations play a pivotal role in promoting battery recycling. For example, the European Union's Battery Directive mandates the recycling of batteries and sets targets for the recovery of specific materials [138]. Similarly, countries like China and the United States have introduced policies to meet climate change targets [139].

Despite advancements, current recycling practices still have gaps that need addressing. Research is required to develop more efficient and cost-effective recycling technologies for the growing volume of spent batteries [140]. Innovations in material recovery can enhance the yield and purity of recovered metals, making recycling more economically viable [141]. Focus should be on creating a circular economy for EV batteries, where materials are reused, reducing the demand for new raw materials and minimizing environmental impact.

Developing effective recycling strategies and recovering cobalt and lithium are crucial for the sustainable growth of the EV industry. By tackling economic, environmental, and technological challenges in battery recycling, we can ensure a steady supply of critical materials and reduce EVs' environmental footprint. Future research and policy support will be vital in promoting a circular economy for battery materials [142].

4.4.3. EV Charging Strategies and Technologies

Building on advancements in battery technologies, the next step in EV integration is to implement efficient charging strategies. Essential for infrastructure availability, energy optimization, and cost reduction, Table 17 highlights innovative strategies and technologies aligned with sustainability goals, from renewable energy integration to leveraging V2G systems and AI for enhanced grid stability.

Table 17. Overview on EV charging strategies and technologies.

Ref.	Focus	Key Findings	Implications
[143]	Integration of renewable energy sources into EV charging stations; strategic placement.	Highlights role in bolstering sustainability of EV ecosystems.	Aligns with global renewable energy goals.
[144]	Optimization framework for EV charge scheduling.	Enhances energy efficiency and cost-effectiveness.	Emphasizes smart charging strategies for scalability and grid stability.
[145]	Smart charging coordination framework using AI.	Improves efficiency and grid stability.	Demonstrates AI's transformative potential in EV charging.
[146]	V2G integration in EV sharing systems with stochastic optimization.	Enhances profitability and socio-environmental outcomes.	Highlights V2G's potential to improve economic and environmental efficiency.
[147]	Comprehensive review of EV fast-charging technologies and infrastructure under various conditions.	Strategic insights into charging infrastructure efficiency.	Critical need for adaptable charging technologies for cost and performance optimization.
[148]	Tool for assessing the load shifting capabilities of EVs.	Facilitates the exploration of flexible charging opportunities.	EV fleets contribute to grid stability and energy efficiency.

These studies underscore the transformative potential of smart charging technologies and the pivotal role they play in the EV ecosystem. For instance, Sun et al. [143] highlight how the strategic placement of charging stations powered by renewable energy can achieve optimal financial and environmental outcomes, thus reinforcing the alignment with global sustainability targets.

Mahyari's [144] optimization framework for EV charge scheduling further illustrates the importance of efficient energy management, suggesting that such approaches can significantly enhance the cost-effectiveness and energy efficiency for fleet operators, thereby supporting the scalability of EV adoption and maintaining grid stability.

In a similar vein, Tuchnitz [145] showcases how AI can revolutionize EV charging strategies, making them more adaptable to the needs of the power grid and enhancing overall system efficiency. This integration of AI into charging coordination could set a new standard for how energy resources are managed within the EV charging network.

Zhang's exploration [146] of V2G technology within EV sharing systems reveals how these systems can enhance the profitability and environmental benefits of EV operations, presenting a compelling case for the dual benefits of economic efficiency and socio-environmental sustainability.

Additionally, Zentani et al. [147] provide a comprehensive overview of the technical challenges associated with fast charging under various operational conditions, including extreme weather, emphasizing the critical need for adaptable charging technologies to optimize performance and costs.

Lastly, Wulff's [148] development of a tool to assess the load shifting capabilities of EVs underscores the importance of flexible charging strategies that can adapt to the fluctuating dynamics of energy demand, thus contributing positively to grid stability and energy efficiency.

Further expanding on the infrastructure needed for EV integration, Şahin [149] presents a novel approach to PV-powered EV charging systems that enhances efficiency and stability. The study introduces a Hybrid Modulated Filter Compensation (HMFC) scheme, which ensures maximum energy utilization from photovoltaic (PV) arrays while minimizing inrush current transients and voltage fluctuations. The HMFC scheme stabilizes the DC-bus voltage and integrates a multi-loop error-driven PID control strategy, which allows for fast charging and minimizes the impact of varying PV conditions such as shading or cloud cover. The system's robustness was validated through digital simulations under various fault conditions, confirming its effectiveness in maintaining stable operation.

Moreover, Şahin [149] explores the integration of dual PV arrays with V2G systems, highlighting the scheme's capability to optimize power delivery even under fluctuating environmental conditions. This approach not only enhances the efficiency of the battery charging process but also supports the broader integration of renewable energy into EV charging infrastructure. The study suggests that such PV-powered systems could be particularly beneficial in regions with high solar potential, maximizing the utilization of solar energy for EV charging.

In addition to the advancements in PV-powered systems, Sahin [150] examines the hydrogen refueling process for fuel cell electric vehicles (FCEVs). This study highlights the design of a vehicle with an 80 kW fuel cell and a 2.64 kWh lithium-ion battery, simulated to refuel 4.34 kg of hydrogen in 280 s, enabling a travel distance of 650 km. The findings demonstrate that FCEVs are competitive with conventional vehicles regarding range and refueling time, while offering significant environmental benefits, especially when utilizing green hydrogen. This research underscores the importance of developing robust hydrogen refueling infrastructure to support the widespread adoption of FCEVs, complementing the advancements in battery electric vehicle (BEV) charging strategies.

These collective insights not only highlight the crucial role of charging strategies in facilitating the widespread adoption of EVs but also underscore the need for continuous innovation in this field to meet the growing demands of an electrified transportation future.

4.4.4. Managing and Optimizing EV Charging Infrastructure

Building on innovative charging strategies, the focus now shifts to the intricate processes of managing and optimizing EV charging infrastructure. The transition to a fully integrated electric mobility system requires not only robust technological solutions but also strategic management to ensure operational efficiency and grid reliability. Table 18 showcases diverse approaches ranging from strategic electrification planning and optimized charge scheduling to the data-driven management of electric buses. These studies highlight the critical role of thoughtful management in maximizing the potential of EV infrastructure, thereby enhancing the overall efficiency of transport systems and reducing the environmental footprint. Collectively, these studies underscore the complexity and necessity of effective management strategies in the operation of EV charging infrastructures.

Among the various strategies outlined in Table 18, Alp et al. [151] discuss how strategic fleet electrification planning can integrate vehicle adoption with the development of charging infrastructure, offering both economic and environmental benefits. This strategic approach is vital for organizations aiming to transition their fleets to electric while ensuring that infrastructural developments keep pace with vehicle deployments.

Klein's work [152] on optimizing scheduling to balance operational efficiency with infrastructure demand introduces a model that minimizes peak charging times, thus easing the load on the electrical grid and reducing operational costs. This balance of technological advancement and operational pragmatism is essential for the sustainable integration of EVs into existing systems.

Table 18. Management and optimization in EV charging infrastructure.

Ref.	Focus	Key Findings	Implications
[151]	Strategic fleet electrification planning integrating vehicle adoption and infrastructure.	Highlights economic and environmental benefits of coordinated efforts.	Crucial for organizations transitioning fleets to electric.
[152]	Optimal scheduling balancing efficiency and infrastructure strain.	Model minimizes peak charging demand.	Balances technological advances with practical EV integration.
[153]	Tailored charging for electric buses optimizing efficiency under constraints.	Personalized strategies enhance public transport efficiency.	Custom solutions boost public transport efficiency.
[154]	Data-driven insights for tuning corporate EV fleet charging strategies.	Guides planning via analytics.	Emphasizes data in sustainable electrification strategies.
[155]	Solutions for routing and charging in mixed fleets.	Optimizes logistics and charging tactics.	Addresses the complexities of integrating EVs in logistics.
[156]	Operational implications of electric buses with different charging infrastructures.	Assists public transit authorities in decision-making.	Critical for advancing sustainable urban mobility.
[157]	Integrated energy management strategy for EVs and power grid interaction.	Optimizes costs and energy use.	Highlights EVs' positive contributions to energy systems.
[158]	Scheduling strategy for electric buses considering travel times and energy needs.	Enhances efficiency and reduces transit delays.	Improves public transport fleet management.
[159]	Environmental impacts of various EV charging behaviors.	Emission reduction through strategic scheduling.	Advocates charging alignment with cleaner power periods.
[160]	Unsupervised learning for optimal placement of smart charging stations.	Enhances strategic infrastructure planning.	Supports urban planning integration of charging solutions.
[161]	Multi-agent deep deterministic policy gradient (MADDPG) for EV charging station recommendations.	Streamlines charging process and optimizes travel time in smart environments.	Supports efficient urban mobility and smart city infrastructure development.
[162]	Dynamic EV routing focused on mid-journey recharging needs.	Enhances routing efficiency.	Emphasizes need for adaptive urban electric mobility planning.
[163]	Economic benefits of V2G technologies considering advanced battery models and price volatility.	Illustrates cost savings and operational benefits.	Highlights V2G's role in economic and energy resilience.

Moreover, Zhao's [153] proposal of a tailored charging approach for electric buses illustrates the customization required to optimize efficiency despite operational constraints, which boosts the overall efficiency of public transportation systems. Similarly, Goncalves's study [154] uses data-driven insights to fine-tune corporate EV fleet charging strategies, reinforcing the crucial role of analytics in sustainable electrification efforts.

These examples highlight how thoughtful management and innovative optimization strategies are crucial for overcoming the challenges posed by the integration of EVs into complex transportation and energy systems. As these systems evolve, continuous innovation in management strategies will be paramount in ensuring that the transition to electric mobility is both efficient and sustainable. Moving forward, the integration of advanced management technologies, such as AI and machine learning, will further enhance the operational efficiencies and environmental benefits of EVs, paving the way for a more sustainable future in urban mobility and beyond.

4.4.5. Software Solutions for EV Fleet Management

The seamless integration of EVs into urban environments and logistical operations hinges not only on physical infrastructure but also on sophisticated software solutions capable of managing the complex dynamics of EV fleets. As we delve deeper into digital innovations, it becomes clear that software solutions are indispensable for effectively managing EV fleets, ensuring they are efficient, scalable, and adaptable to various operational demands. Table 19 highlights several cutting-edge software solutions that facilitate the management of electric fleets, including optimizing routing and charging strategies and enhancing overall operational efficiency.

Table 19. Summary on software solutions for EV fleet management.

Ref.	Focus	Key Findings	Implications
[8]	Framework for managing electric drayage truck operations and charging at ports through dynamic programming.	Optimizes logistics and charging, reducing costs and boosting cargo efficiency.	Highlights smart software solutions' potential in sustainable fleet management.
[9]	Innovative routing approach for a heterogeneous electric taxi fleet to maximize profitability and consider charging needs.	Uses simulated annealing for scalability, enhancing operational efficiency and profitability.	Demonstrates the role of algorithmic strategies in sustainable urban mobility.
[164]	Evolutionary algorithm for optimizing EV routing, addressing specific EV recharging needs.	Shows the efficiency of tailored software solutions for electric fleet management.	Points to more resilient and efficient urban transport systems.

Wu's [8] dynamic programming approach for electric drayage trucks at ports exemplifies how intricate programming can drastically enhance the logistics and charging strategies, thereby reducing costs and increasing efficiency. This framework is pivotal in streamlining operations at critical transport hubs, demonstrating the significant benefits that can be realized through targeted software interventions.

Nafarieh's work [9] on routing for electric taxis integrates complex algorithms to address the varied needs of a heterogeneous fleet, enhancing profitability while maintaining sustainability. This approach underlines the capability of advanced software to adapt to the operational requirements of diverse fleet configurations, ensuring optimal performance and profitability.

Additionally, Iwankowicz's development [164] of an evolutionary algorithm for EV routing addresses the specific challenges of recharging and operational efficiency, paving the way for smarter, more responsive urban transport systems. By tailoring software solutions to the unique dynamics of EVs, these innovations offer a glimpse into a future where fleet management is not only automated but also inherently adaptive and more efficient.

As EVs continue to spread urban landscapes and commercial fleets, the role of sophisticated software solutions in managing these assets becomes increasingly crucial. These technological advancements ensure that electric fleets are not just feasible but operate at peak efficiency, marking a significant step forward in the quest for sustainable urban mobility.

4.5. Policy Recommendations and Future Directions

As EVs capture the attention of consumers and industries worldwide, robust policy frameworks are becoming increasingly crucial for accelerating their adoption and ensuring their sustainable integration into transportation networks. Effective policy and regulatory strategies are essential for navigating the complexities of transitioning to electric mobility while addressing environmental and economic considerations.

4.5.1. Comprehensive Policy Frameworks

Research by Neagoe et al. [165], highlighted in Table 20, underscores the critical role of comprehensive policy frameworks in guiding the adoption and efficient use of EVs across various sectors. Their robust framework encompasses socio-technical, economic, and environmental aspects, addressing the multifaceted challenges of electrifying and decarbonizing road logistics. This approach facilitates the transition to alternative fuel vehicles and aligns with broader sustainable transport objectives. The table provides an overview of various policy approaches and their implications, emphasizing the need for informed, strategic policymaking to create a conducive environment for EV adoption and achieve broader sustainability targets.

Table 20. Policy and regulatory frameworks for EV adoption.

Ref.	Focus	Key Findings	Implications
[165]	Framework for decarbonizing road logistics, focusing on alternative fuel vehicles including EVs.	Explores socio-technical, economic, and environmental facets, offering a multidimensional approach.	Guides policymakers and organizations in crafting strategies for sustainable transport goals.
[166]	Efficacy of carbon emissions regulations and pricing on fleet management.	Highlights the tangible impact of regulatory strategies on emissions reductions.	Offers perspective for organizations aligning with carbon regulations while optimizing operations.
[167]	Sustainable Transport Index to assess EV adoption policies in Tunisia.	Offers insights into sustainability impacts of policy decisions.	Underscores informed policy-making in fostering electric mobility.
[168]	Electrification of on-demand fleets in Chinese megacities, focusing on policy targets and charging coordination.	Highlights the role of targeted policy interventions and strategic infrastructure planning.	Provides insights for enhancing urban mobility solutions.
[169]	Role of transition intermediaries in steering the shift to low-carbon mobility.	Emphasizes the importance of intermediaries in bridging policy intentions and implementation.	Highlights their critical contribution to sustainable transport transitions.
[170]	Modeling impacts of transitioning higher education institution fleets to EVs, focusing on carbon footprint and economics.	Provides a comprehensive view of institutional fleet electrification's potential.	Relevant policy and organizational strategy implications.
[171]	Sustainable framework for urban freight delivery with cargo cycles and electric vans.	Aims to reduce delivery costs and environmental footprints.	Explores innovative urban logistics strategies leveraging green transportation modes.

4.5.2. Specific Policy Studies

Khammassi's introduction of a Sustainable Transport Index [167] in Tunisia provides a practical tool for evaluating the effectiveness of EV adoption policies, highlighting the importance of policy decisions informed by comprehensive sustainability assessments. This approach ensures that policies are not only effective but also aligned with long-term environmental and social goals.

Bauer's study [168] on the electrification of on-demand fleets in Chinese megacities highlights the need for precise policy targets and coordinated infrastructure development. This research emphasizes the pivotal role of government intervention in facilitating the transition to electric mobility, particularly in urban settings where demand and impact are significant.

Furthermore, Nordt's exploration of the role of transition intermediaries [169] shows how these agents effectively translate policy into practice, acting as crucial catalysts in the shift toward sustainable transportation. Their role is especially vital in ensuring that the theoretical benefits of policies are realized in practical, operational improvements across the transportation sector.

The multi-scale analysis by Juang [170] of institutional fleet transitions to EVs within the context of higher education showcases the broader implications of such moves for sustainability. This study provides a template for other institutions and organizations looking to transition their fleets, highlighting the dual benefits of reduced carbon footprints and economic viability.

Lastly, Shojaei's framework [171] for sustainable urban freight delivery using a mix of cargo cycles and electric vans offers innovative solutions to urban logistics challenges. By integrating electric mobility into existing urban infrastructures, this approach not only reduces environmental impacts but also enhances the efficiency of urban freight operations, paving the way for a more sustainable urban future.

4.5.3. Systemic and Regulatory Impacts

Building on the policy frameworks discussed above, it is crucial to examine the broader systemic and regulatory impacts on EV integration into transportation systems. Table 21 highlights how comprehensive regulatory strategies and systemic changes can enhance EV adoption across various sectors, from ride-hailing to commercial transport. This shift emphasizes the need for a fully integrated electric mobility ecosystem rather than just individual policy measures.

Table 21. Systemic and regulatory impacts on EV adoption.

Ref.	Focus	Key Findings	Implications
[172]	Framework for efficient operation of electric ride-hailing fleets, including fleet rebalancing and optimized charging strategies.	Highlights systemic benefits of integrated fleet and charging management.	Provides actionable insights for urban mobility service providers.
[173]	Synergies between EV fleet integration and renewable energy sources in commercial transport.	Emphasizes the need for harmonized energy and transport policies.	Crucial role of renewable energy in supporting fleet electrification, enhancing EV sustainability.
[174]	Potential pathways for significant CO_2 emission reductions in European road transport by 2050.	Focuses on electrification and efficiency improvements, presenting a comprehensive overview of systemic changes required.	Highlights the pivotal role of policy and regulatory frameworks in transitioning to a low-carbon transport sector.
[175]	Optimized vehicle routing strategy for cold chain distribution using mixed fleets, including EVs.	Aims to minimize environmental impacts and operational costs.	Forward-looking insights into green urban logistics, presenting a model for integrating EVs into specialized distribution networks for sustainable and efficient operations.

Yu's study [172] on electric ride-hailing fleets presents a framework that optimizes fleet operations and enhances urban mobility efficiency, serving as a blueprint for other providers to follow. Pietracho's study [173] underscores the need for integrated energy and transport policies to support EV adoption powered by renewable energy, maximizing environmental benefits. Similarly, Krause's analysis [174] emphasizes systemic changes required for substantial emission reductions in European road transport by 2050, focusing on electrification, efficiency improvements, and regulatory transformations.

Moreover, Chen's study [175] on optimizing vehicle routing for cold chain distribution with mixed fleets demonstrates strategies to reduce environmental impacts and costs, highlighting the adaptability of EV technologies in various contexts. These examples collectively emphasize the need for holistic policy and systemic changes to facilitate EV adoption and integration into a sustainable transportation ecosystem.

4.5.4. Summary of Research

In conclusion, Figure 13 provides a detailed visual summary of the multifaceted impacts of EV adoption, using a multi-tiered bubble diagram to illustrate key themes derived from a wide array of studies. The sizes of the primary bubbles are scaled proportionally to illustrate the relative volume of research dedicated to each main theme, indicating the concentration of scholarly attention and the number of papers published within each area. Nested within these bubbles are smaller ones representing specific topics and keywords. The diagram covers technological advancements, operational hurdles, policy developments, and future projections. It provides a comprehensive view of the interconnected aspects of EV adoption. This visualization summarizes the research and helps identify trends, gaps, and potential areas for future study.

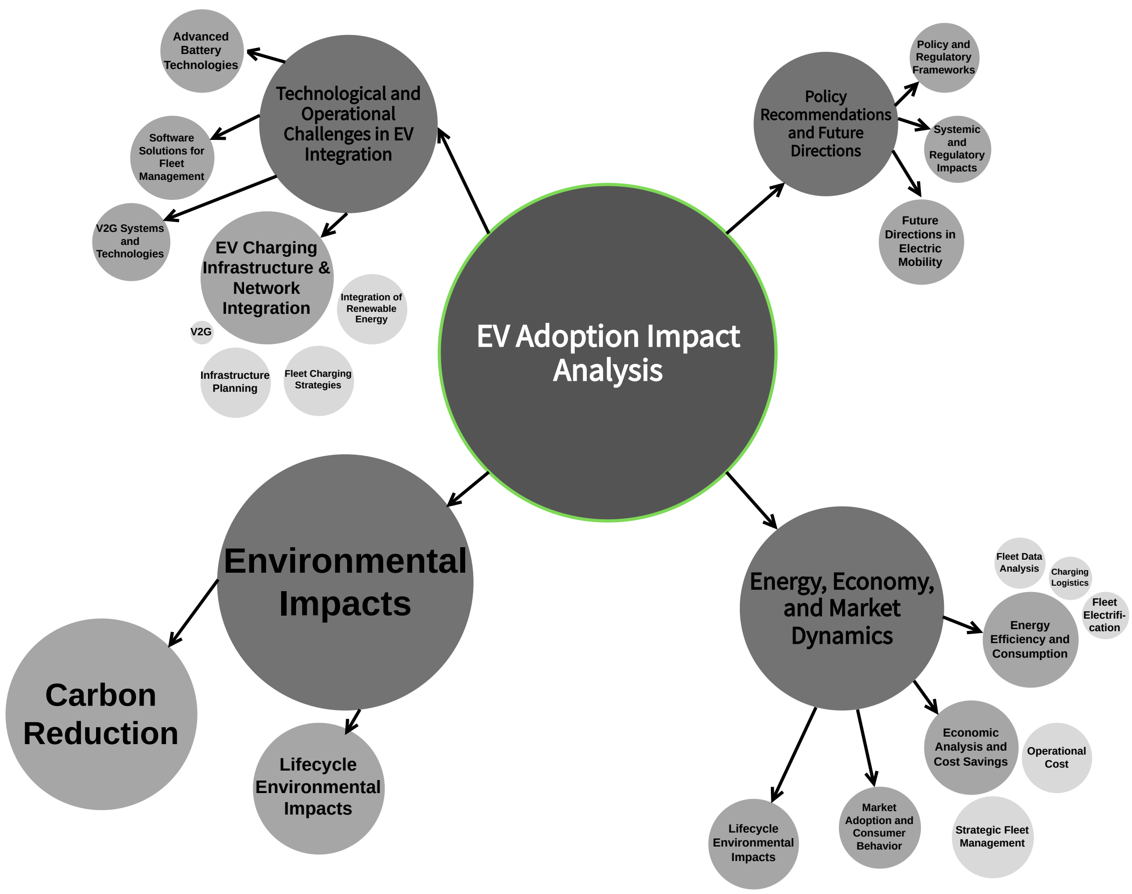

Figure 13. Summary of research on the impact of EV adoption.

5. Conclusions and Future Research

This systematic review, analyzing 88 pivotal papers, offers a comprehensive exploration of current research on the impact of EV adoption from technological, environmental, organizational, and policy perspectives. The findings underscore the significant role EVs play in fostering sustainable mobility and aligning with global climate goals by reducing carbon emissions.

5.1. Key Findings

- Technological Advancements : EV technology is advancing steadily. Improvements in battery life, charging infrastructure, and energy efficiency are driving adoption rates. However, ongoing innovation and investment are crucial to address challenges like limited battery range and the need for more robust charging networks.
- Policy and Regulatory Frameworks : Strong policy support is crucial for accelerating EV adoption. Effective strategies include incentives, subsidies, and clear regulatory frameworks. While these approaches have successfully stimulated market expansion in various regions, their varying effectiveness underscores the need for tailored policies that consider local market conditions and technological maturity.
- Economic and Organizational Impacts : Despite higher upfront costs compared to traditional vehicles, EVs offer potential lifecycle cost savings. Organizations, especially those with large fleets, can benefit from these cost efficiencies, improved fleet management capabilities, and a more sustainable corporate image.
- Environmental Benefits: The shift to EVs, especially when coupled with a transition to renewable energy sources, significantly reduces GHG emissions. Additionally, EVs contribute to improved urban air quality and noise reduction, creating a healthier urban environment.

- Challenges and Barriers: Despite clear advantages, challenges remain that impede broader EV adoption. These include the high initial cost of EVs, limitations in battery technology and charging infrastructure, and the cultural and behavioral changes needed to adapt to electric mobility.

5.2. Future Research Directions

This review also highlights several areas where further research is necessary to optimize the integration of EVs into modern transportation systems and energy grids:

- Long-term Sustainability Assessments : Comprehensive LCAs considering the environmental impact of battery production and disposal are crucial for understanding EVs' long-term sustainability.
- Technological Integration : Research is needed to explore how EV technology can seamlessly integrate with smart grids and renewable energy systems. Focusing on technological integration can enhance overall sustainability and energy efficiency.
- Economic Analyses : Detailed cost-benefit analyses comparing EVs with traditional vehicles across various operational scenarios and market conditions are necessary. These studies can inform economic forecasts and support the development of robust business models for EV adoption.
- Behavioral Studies: Insights into consumer behavior and organizational change management can assist in designing effective policies and business strategies. Understanding these factors can help stakeholders create incentives and approaches that encourage broader EV adoption.
- Policy Evolution: As the market for EVs evolves, so must the policies that support their adoption. Continuous monitoring and evaluation of existing policies, along with the development of new strategies to address emerging challenges, are crucial for maintaining momentum and overcoming future hurdles.
- Global Comparative Studies: Expanding research to include more comparative studies across different countries and regions can provide deeper insights into the global landscape of EV adoption. Examining variables that influence adoption rates in diverse contexts can inform the development of universally applicable strategies.

5.3. Limitations

A formal risk of bias assessment tool was not employed due to the observational nature of the included studies. However, the selection prioritized studies with robust methodologies to mitigate potential bias.

5.4. Conclusions

The transition to electric mobility presents numerous benefits and opportunities. However, realizing this potential fully requires coordinated efforts across the technology, policy, and market domains. This systematic review serves as a foundational resource for stakeholders engaged in the ongoing dialogue and decision-making processes related to EV adoption. It highlights critical areas where further research and policy development are needed to support this transformative shift in transportation and shape a more sustainable future.

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