Análisis Económico, 41(106), 209–230, enero - abril de 2026, ISSN: 0185-3937, e-ISSN: 2448-6655

https://doi.org/10.24275/uam/azc/dcsh/ae/2026v41n106/Martinez

Key technologies, challenges, and trends in electric vehicles: a systematic review

Tecnologías clave, desafíos y tendencias de los vehículos eléctricos: una revisión sistemática

Adriana Martínez Martínez[*], Alejandro García Garnica[**] y Samuel Estrada Jasso[***]

*Profesora-Titular C de Tiempo Completo, Universidad Nacional Autónoma de México.
Correo electrónico: adriana.martinez@enes.unam.mx. ORCID: https://orcid.org/0000-0003-0639-4007

**Profesor-Investigador de Tiempo Completo, Universidad Autónoma del Estado de Morelos.
Correo electrónico: alejandro.garciag@docentes.uaem.edu.mx. ORCID: https://orcid.org/0000-0003-4755-4644

***Egresado de la licenciatura de Economía Industrial, Universidad Nacional Autónoma de México.
Correo electrónico: samuele129615@comunidad.unam.mx. ORCID: https://orcid.org/0009-0007-3986-8113

ABSTRACT

This study analyzes key technologies, challenges, and trends in the development of electric vehicles (EVs) through a systematic literature review (2010–2024) following the PRISMA methodology. It examines advancements in batteries, charging infrastructure, energy management, and sustainable manufacturing. The results highlight the importance of battery energy efficiency, the development of fast-charging networks, and vehicle-to-grid (V2G) integration for EV adoption, although challenges such as critical material shortages, limited infrastructure, and battery lifecycle sustainability remain. The study concludes that mass EV adoption requires technological advancements, effective public policies, infrastructure investments, and sustainable regulations. It recommends exploring battery recycling strategies, assessing economic impact, and developing grid integration models to drive the transition to electromobility.

RESUMEN

Este estudio analiza tecnologías clave, desafíos y tendencias en el desarrollo de vehículos eléctricos (VEs) mediante una revisión sistemática de la literatura (2010-2025) siguiendo la metodología PRISMA. Se examinan avances en baterías, infraestructura de carga, gestión de energía y manufactura sostenible. Los resultados destacan la importancia de la eficiencia energética de las baterías, el desarrollo de redes de carga rápida y la integración vehículo-red (V2G) en la adopción de VE, aunque persisten desafíos como la escasez de materiales críticos, la infraestructura limitada y la sostenibilidad del ciclo de vida de las baterías. Se concluye que la adopción masiva de VE requiere avances tecnológicos, políticas públicas efectivas, inversiones en infraestructura y regulaciones sostenibles. Se recomienda explorar estrategias de reciclaje de baterías, evaluar el impacto económico y desarrollar modelos de integración con la red eléctrica para impulsar la transición hacia la electromovilidad.

Received: February/17/2025
Accepted: May/23/2025
Posted: January/12/2026

Keywords:
| Electric vehicles |
| Battery technology |
| Charging infrastructure |
| Energy management |
| Sustainable mobility |

Palabras clave:
| Vehículos eléctricos |
| Tecnología de baterías |
| Infraestructura de carga |
| Gestión de energía |
| Movilidad sostenible |

JEL Classification |
Clasificación JEL |
O33, Q55, L62, Q42, R41

INTRODUCTION

The automotive industry (AI) is a fundamental pillar of the global economy due to its significant impact on economic growth, job creation, and environmental sustainability (Mohammad & Shavarebi, 2019). In recent years, electric vehicles (EVs), have gained prominence due to battery advancements, cost reductions, and the push for sustainable manufacturing.

Sustainable manufacturing encompasses the adoption of environmentally friendly practices in vehicle and auto parts production, as well as in their operation and maintenance. This includes reducing CO_2 emissions and implementing circular economy strategies in material usage. Sustainability has become a major challenge for the automotive industry, prompting companies not only to adopt greener manufacturing methods but also to invest in technologies that enhance energy efficiency and reduce environmental impact (Chinoracky *et al*., 2022).

In 2009, the 15th Conference of the Parties (COP15) under the United Nations Framework Convention on Climate Change (UNFCCC) convened in Copenhagen, where an international agreement to mitigate climate change was reached. Orendain (2023) highlights that this agreement recognized the urgent need to limit global emissions, with participating countries accounting for 80% of total greenhouse gas emissions. Subsequently, in 2015, 196 nations signed the Paris Agreement, which came into force in 2016, setting ambitious targets to restrict global warming.

More recently, in February 2023, the European Parliament formally approved legislation that prohibits the sale of new gasoline and diesel vehicles in the European Union by 2035, aiming for a 100% reduction in CO_2 emissions. This regulatory shift is accelerating the transition to electric mobility, reinforcing EVs as the future of the automotive industry (El Economista, 2023).

The production of electric vehicles (EVs) has become a global strategy to combat climate change, with expectations of a significant positive impact on sustainability (Ahuja *et al*., 2020; Anastasiadou & Gavanas, 2022; Husain *et al*., 2021; Moyo *et al*., 2023). The drive toward carbon neutrality has been a key catalyst in the development of EVs, which are increasingly recognized as a viable solution to reducing greenhouse gas emissions from the traditional automotive sector.

This push for electrification has led to rapid growth in the EV market. According to the International Energy Agency (IEA, 2024), over 14 million electric cars were sold in 2023, and sales are projected to increase by 35% in 2024. The market share of EVs within the global automotive industry has expanded significantly, rising from 4% in 2020 to 14% in 2022, with expectations of reaching 18% by 2024. Sales are heavily concentrated in three key regions —China, Europe, and the United States— highlighting the pivotal role of EVs in reshaping the automotive industry.

Within this context, this study conducts a systematic review of scientific and technical literature to analyze key technologies driving EV development, along with emerging challenges and trends. The research is guided by two key questions: *1*) What are the essential technologies advancing EVs? and *2*) What major trends arise from this technological shift?

The article is structured as follows: the first section outlines the methodological approach used in this study. The second and most extensive section examines the key technologies underpinning electric vehicle development. The third section discusses emerging trends that will shape the future of the industry. Then, the Analysis and Results section is presented. Finally, the conclusions summarize the main findings and propose directions for future research.

I. METHODOLOGICAL DESIGN

A review of electric vehicles in the automotive industry from 2010 to the present was carried out for the following reasons:

- Technological development: Since 2010, significant advances have been made in battery technology, particularly with the development of more efficient and cost-effective lithium-ion batteries, which are crucial for electric vehicles.
- Policies and regulations: During this decade, many countries implemented policies and regulations to promote the adoption of EVs as part of global initiatives to reduce carbon emissions and mitigate climate change. For example, the European Union and China began introducing stricter emission regulations and offering incentives for the purchase of EVs.
- Market growth: The demand for EVs began to grow significantly after 2010, with companies like Tesla contributing to this trend. This market growth fueled further investment in research and development.
- Charging infrastructure: Since 2010, investments in EV charging infrastructure have been crucial for adoption, driving exponential growth in public and private charging stations. Anastasiadou and Gavanas (2022) highlight infrastructure availability and fast charging as key adoption factors.
- Research and publications: In recent years, academic research on electromobility has surged, addressing key technologies, adoption challenges, environmental impact, business models, policies, and consumer preferences.

Scope and research topic

This review focused on three key thematic areas:

- Key technologies: Analysis of batteries, electric motors, charging infrastructure, software, and connectivity, as well as leading companies in EV implementation.
- Challenges: Examination of technical, social, and environmental obstacles identified in recent literature.
- Future trends: Review of studies exploring the future of electromobility and emerging innovations.

Search strategy and data sources

The literature search was conducted in English and Spanish, using the following keywords:

- Electric vehicles AND key technologies / vehículos eléctricos AND tecnologías clave.
- Electric vehicles AND challenges / vehículos eléctricos AND desafíos.
- Electric vehicles AND trends / vehículos eléctricos AND tendencias.

The databases consulted are listed in Table 1.

Inclusion and exclusion criteria

To ensure the rigor and relevance of the selected studies, the following inclusion and exclusion criteria were applied (Table 1). This Table outlines the parameters that guided the selection process, specifying six criteria that guided the selection process, ensuring a structured and transparent approach in identifying high-quality research aligned with the objectives of this study.

Table 1
Inclusion and exclusion criteria

Criterion	Inclusion	Exclusion
Timeframe	Studies published between 2010 and 2025.	Studies published before 2010.
Language	English and Spanish publications from peer-reviewed journals and reputable industry reports.	Articles in languages other than English and Spanish.
Relevance	Studies focusing on key EV technologies, adoption challenges, and future trends.	Studies unrelated to EV technology, policies, or future trends.
Study Type	Empirical studies, systematic reviews, meta-analyses, and policy-related news articles from reputable sources.	Opinion pieces, non-verified blogs, or speculative articles lacking technical backing.
Data Sources	Indexed databases (ScienceDirect, MDPI, SciELO, Redalyc, Springer, IEEE, BMJ, Emerald Insight) and industry reports (McKinsey, IEA, WEF, Deloitte).	Sources lacking methodological rigor or data transparency.
Methodological Rigor	Studies with clear methodologies, quantitative/qualitative analysis, or case studies.	Studies with unclear methodology, anecdotal evidence, or unsupported claims.

Source: own elaboration.

Methodological approach

This study followed the PRISMA methodology (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) to ensure rigor and transparency in the literature review process. The PRISMA framework consists of sequential stages, beginning with identification, where relevant studies are retrieved from databases, followed by screening, in which titles and abstracts are evaluated for relevance. Next, the inclusion phase selects studies that align with the research objectives within the 2010–2025 timeframe (Page *et al*., 2021). In the review and synthesis stage, full-text studies are analyzed to extract key insights, which are then categorized into technologies, challenges, and future trends during the analysis and results phase. Finally, in discussion and conclusions, the findings are integrated to highlight implications and propose future research directions. Although PRISMA is widely used in health sciences, its adaptability has led to increasing applications in systematic reviews within the social sciences and education (Barrios *et al*., 2021).

II. ELECTRIC VEHICLES: KEY TECHNOLOGIES

Electromobility is a sustainable mode of transportation promoted to achieve zero-carbon objectives (Chinoracky *et al*., 2022). Montayo (2021) defines electromobility as the use of various forms of transportation powered by electricity. However, Kett (2018) takes a broader approach, associating the term with the development of electric drivetrains aimed at reducing dependence on fossil fuels in traditional internal combustion engine vehicles.

Building upon these perspectives, Anastasiadou and Gavanas (2022), referencing the European Union Science Hub, define electromobility as clean and efficient transportation using electric vehicles (EVs) powered by batteries or hydrogen fuel cells. This category encompasses electric cars, motorcycles, e-bikes, public transport systems such as trolleybuses, subways, and electric buses, as well as hybrid vehicles.

Given these definitions, electromobility is fundamentally linked to advances in renewable energy, battery storage, and environmental sustainability, which drive the ongoing evolution of electric vehicle technology. Therefore, this study focuses on electric vehicles (EVs), excluding other modes of electromobility such as electric bikes or public transport.

Table 2 provides an overview of the different types of electric vehicles, along with a brief description and the main industry players driving their development.

Table 2
Types of electric vehicles

Type of vehicle	Description	Key players
Battery Electric Vehicles (BEV)	Operate entirely on electricity stored in rechargeable batteries, with no internal combustion engine.	Tesla, Nissan, Chevrolet, BMW, Hyundai, Volkswagen
Plug-in Hybrid Electric Vehicles (PHEV)	Combine an electric motor with an internal combustion engine. Batteries can be externally recharged.	Toyota, Ford, Mitsubishi, Volvo
Extended-Range Electric Vehicles (EREV)	Feature a small combustion engine that generates electricity when battery levels are low, extending the vehicle's range.	BMW, Chevrolet, Ford
Hybrid Electric Vehicles (HEV)	Use both an internal combustion engine and an electric motor. Batteries are primarily recharged through regenerative braking.	Toyota, Honda, Hyundai, Ford, Lexus
Fuel Cell Electric Vehicles (FCEV)	Utilize hydrogen as fuel to generate electricity through a fuel cell, producing zero emissions.	Toyota, Honda, Hyundai, Mercedes-Benz

Source: own elaboration.

The global electric vehicle (EV) stock reached 26.8 million units in 2022, and by 2030, EVs are projected to represent nearly 50% of total vehicle sales (EY, 2023). This rapid growth highlights the critical role of technology and infrastructure in ensuring widespread adoption. The shift to electric mobility is one of the most significant transformations in the automotive sector since the internal combustion engine, driven by the need to reduce greenhouse gas emissions and enhance vehicle sustainability. Key technological innovations include advancements in battery technology, charging infrastructure, and energy management systems (Moyo *et al*., 2023). Table 3 summarizes these technologies describing their impact and the major industry players involved.

Table 3
Key technologies in electric vehicles

Technology	Description	Key players
Charging Infrastructure	Development of facilities for recharging electric vehicles, including both public and private charging stations.	ChargePoint, EVBox, Tesla, Blink Charging, Electrify America
Battery Management Systems (BMS)	Technologies that optimize battery efficiency, longevity, and performance in electric vehicles.	Panasonic, LG Chem, Samsung SDI, BYD
Battery Recycling Technology	Innovative recycling and reuse processes that recover valuable components from EV batteries, promoting sustainability and circular economy models.	Umicore, Redwood Materials, Li-Cycle
Electrified Transmission and Driveline Systems	Advanced electric drivetrains, including electric axles and electric traction modules, enhancing EV performance and efficiency.	GKN, Bosch, ZF Friedrichshafen, Magna
Fuel Cell Electric Vehicles (FCEV)	Utilize hydrogen as fuel to generate electricity through a fuel cell, producing zero emissions.	Toyota, Honda, Hyundai, Mercedes-Benz

Source: own elaboration.

The role of charging infrastructure in electric mobility

A robust and accessible charging infrastructure is essential for the mass adoption of electric vehicles (EVs). Without a well-developed network of public and private charging stations, the transition to electric mobility would face significant hurdles. Leading companies such as ChargePoint, EVBox, Tesla, Blink Charging, and Electrify America are driving the development and expansion of this infrastructure. According to the International Energy Agency (IEA, 2024), the scalability and strategic deployment of charging infrastructure must accelerate rapidly to ensure EV viability across all regions, including urban and rural areas.

Charging stations are primarily classified into two types. Alternating Current (AC) Charging is generally slower and suitable for overnight charging or locations where vehicles remain parked for extended periods, with Level 2 chargers being the most common in residential and commercial settings. Direct Current (DC) Charging, on the other hand, provides significantly faster charging, making it ideal for roadside stations where drivers require quick recharge, though its installation is more expensive and requires higher voltage power infrastructure (Saraswathi and Ramachandran, 2024).

Interoperability is another critical factor in charging infrastructure development. Just as mobile phone roaming allows users to connect to various service providers, EV charging networks must ensure seamless access across different charging stations. Companies such as EV Connect are developing software solutions that enable cross-platform interoperability, improving the efficiency and accessibility of charging networks (Arrow, 2022). Additionally, cloud-based charging management systems facilitate real-time monitoring and maintenance, optimizing station performance (Locke, 2021).

Despite technological advancements, several challenges remain. The lack of public charging stations is a major barrier, with 34% of potential EV buyers citing this issue as a deterrent to adoption (Morales, 2023). Additionally, the electric grid must be upgraded to handle increased demand efficiently, requiring the implementation of smart grid technologies. Lastly, installation costs, particularly for DC fast-charging stations, remain high, limiting the scalability of charging infrastructure (Fernandez *et al*., 2023; Gamage *et al*., 2023).

According to projections by Woodward *et al*. (2020), the number of electric vehicles (EVs) is expected to grow at an annual rate of 29% worldwide by 2030. At this pace, EVs, including hybrids, are projected to account for 80% (25.5 million) of total vehicle sales that year. The adoption of dynamic load management technologies will allow for better energy distribution, prioritizing users in need of rapid charging and optimizing the overall grid load (Arrow, 2022). While significant challenges remain, EV charging infrastructure presents an opportunity to improve sustainable mobility and enhance the user experience. Soon, wireless and ultra-fast charging technologies will play a crucial role in increasing accessibility. Additionally, charging standardization and smart grid integration will be key to overcoming current barriers (IEA, 2024).

Battery Management Systems (BMS)

Battery Management Systems (BMS) are critical for the safe and efficient operation of EV batteries and other energy storage systems. Companies such as Panasonic, LG Chem, Samsung SDI, and BYD are leading the development of advanced BMS technologies. These systems not only optimize battery performance but also ensure safety by monitoring essential parameters such as temperature and charge levels (Rodríguez *et al*., 2015).

A BMS performs several key functions, including:

- Cell monitoring: Tracks voltage, temperature, and state of charge for each battery cell (Jiang *et al*., 2017; Milde & Lux, 2025).
- Charge and discharge control: Regulates charging and discharging limits to prevent overcharging and excessive depletion, which could damage battery cells (Xu *et al*., 2021; Yang *et al*., 2024).
- Cell balancing: Ensures that all battery cells maintain similar charge levels, thereby extending overall battery lifespan.
- Safety measures: Implements protective mechanisms, including automatic disconnection in case of faults or hazardous conditions, enhancing operational security (Khan *et al*., 2025).

Over time, BMS technology has evolved from simple circuits in the 1970s to intelligent and connected systems. There are currently three main types of BMS:

- Centralized Battery Management System (CBMS): In this system, a single controller manages all the cells in the battery pack. This centralized approach simplifies the design and can be more cost-effective for smaller battery systems (Aganti *et al*., 2022; Shabana *et al*., 2025).
- Distributed Battery Management System (DBMS): This type involves multiple controllers managing groups of cells, which communicate with a central controller. It is useful for large battery packs where decentralized control can enhance performance and reliability (Aganti, *et al*., 2022).
- Modular: This system is composed of modules, each with its own BMS. These modules can operate independently or in coordination with other modules, providing flexibility and scalability (Aganti *et al*., 2022).

Beyond electric vehicles, BMS plays a crucial role in Battery Energy Storage Systems (BESS), ensuring optimal battery conditions for backup power applications. This is particularly relevant for renewable energy installations, such as solar power systems, where efficient energy management is essential (Rodríguez *et al*., 2015). However, BMS faces challenges, including design complexity and the need for adaptation to emerging battery technologies, such as solid-state batteries. Research continues in areas like artificial intelligence (AI) to enhance fault detection and energy management capabilities. The ongoing evolution of BMS technology is expected to further improve safety, efficiency, and lifespan, not only for EV batteries but also for renewable energy storage systems.

Advancements in lithium-Ion batteries and recycling technologies

Batteries are the core energy storage component of electric vehicles, supplying power to all electrical systems within the vehicle. In recent years, battery technologies have become increasingly sophisticated, significantly improving EV performance.

Lithium-ion batteries were first commercialized in 1991 by Sony, revolutionizing consumer electronics and later becoming the preferred power source for electric vehicles. These batteries offer higher energy density, fewer memory effects, and reduced weight compared to earlier battery technologies (Tarascon & Armand, 2001). By the 2010s, models such as the Tesla Model S demonstrated that lithium-ion batteries could provide over 300 miles of range, making EVs a viable large-scale transportation alternative (Burke & Miller, 2009).

Some of the most significant advancements in lithium-ion battery technology include:

- Increased energy density and range: Over the past decades, battery energy density has significantly increased, allowing for longer driving ranges, thus addressing one of the major limitations of electric propulsion (Mercado & Córdova, 2014).
- Reduced charging time: Fast-charging technology has advanced significantly, with new charging algorithms such as CC-CVησT (VEST) optimizing charging speed while mitigating battery degradation, improving efficiency, and extending battery lifespan (Mohtat *et al*., 2021, Mateen *et al*., 2023).
- New materials development: Research into graphene and other advanced materials has expanded the potential for higher energy storage and more efficient power delivery (Mercado & Córdova, 2014).
- Exploration of next-generation battery technologies: Current research is focused on solid-state, zinc-air, and sand-based batteries, which offer improved safety, efficiency, and sustainability compared to existing lithium-ion technologies.
- While lithium-ion batteries are becoming the dominant power source for EVs, proper end-of-life management is essential to prevent environmental contamination and optimize resource utilization (Ahuja *et al*., 2020).

Battery recycling and the circular economy

Safe battery disposal and recycling processes are critical to ensuring that lithium-ion batteries do not become an environmental liability. Poor handling at the end of their lifecycle can lead to significant pollution and safety risks (World Economic Forum, WEF, 2018). Developing efficient battery recycling systems is necessary to prevent increased waste accumulation while maintaining a sustainable supply of critical materials.

One innovative solution to battery costs and sustainability is the leasing model proposed by Ahuja *et al*. (2020). This approach suggests selling EVs without including the battery cost, allowing consumers to lease batteries separately. Renault, for example, applies this model to its ZOE vehicles, where customers purchase the car but lease the battery.

Meanwhile, the cost of lithium-ion batteries has declined significantly, making EVs more affordable and facilitating mass adoption (Helmers & Marx, 2012). As the circular economy model continues to expand, recycling initiatives and sustainable battery production will become crucial in ensuring the long-term viability of electromobility.

Lithium-Ion battery recycling and sustainability

The rapid rise in demand for lithium-ion batteries, fueled by global decarbonization efforts and ambitious climate goals, has created an urgent need for efficient recycling technologies. Currently, only half of the lithium-ion batteries reaching end-of-life are recycled globally, while a significant portion is discarded (Ferreira & Sucre, 2024). Companies such as Umicore, Redwood Materials, and Li-Cycle are developing advanced recycling processes to recover valuable materials like lithium and cobalt.

Large-scale lithium-ion battery recycling remains an emerging field with various methods, technologies, and processes still under development (Ferreira & Sucre, 2024). The complexity of materials and high energy densities of residual charges pose technological challenges. However, battery recycling not only reduces dependence on virgin mineral extraction but also creates regional economic value. By 2040, as the costs of producing unprocessed minerals continue to rise, the economic and environmental benefits of recycling are expected to grow significantly (Ferreira & Sucre, 2024).

While proper recycling of lithium batteries can mitigate environmental pollution and prevent resource depletion, it is not without challenges. The presence of heavy metals and toxic electrolytes complicates recovery efforts, requiring intensive energy consumption and producing additional waste (Yang, 2023). For this reason, recycling processes must be carefully optimized to balance environmental benefits with energy efficiency. Proper end-of-life management not only reduces contamination risks but also minimizes fire hazards and potential safety concerns (Ferreira & Sucre, 2024).

The development of best practices in lithium-ion battery reuse and recycling could significantly reduce waste, allowing for the processing of up to 2.8 million tons of batteries between 2024 and 2050 (Ferreira & Sucre, 2024). Achieving this goal requires specific regulations, extended producer responsibility frameworks, and appropriate infrastructure for efficient material separation and processing.

Electrified transmission and driveline systems

Electrified transmission and driveline systems in modern EVs integrate electric motors, optimized transmission mechanisms, and final drive components to enhance efficiency and performance. Innovations such as dual-motor configurations and planetary gear systems contribute to improved power distribution and vehicle stability. Continuous advancements focus on refining gear transmission systems and reducing production costs through advanced modeling techniques (Farfan-Cabrera *et al*., 2024; Fang *et al*., 2016; Pakniyat & Caines, 2017; Liu *et al*., 2022).

Electrified transmission systems integrate electric components into energy transfer mechanisms, improving overall efficiency and flexibility compared to conventional systems. The key advantages of these systems include:

- Higher energy efficiency – The use of electric motors instead of internal combustion engines reduces energy losses, resulting in lower consumption and reduced greenhouse gas emissions (Calderón-Guizar, 2010).
- Lower maintenance costs – With fewer mechanical components, electrified drivetrains require less maintenance and are less prone to failures, making them ideal for industrial and public transport applications.

- Energy recovery – Many electrified transmission systems incorporate regenerative braking, which enhances battery range and overall vehicle efficiency (Velasco-Ramírez *et al*., 2013).

Despite their advantages, electrified transmission systems face challenges such as the need for adequate charging infrastructure and EV range optimization. Additionally, the environmental impact of battery production and recycling must be addressed to ensure sustainability.

The electrified driveline consists of components that transmit power from the motor to the wheels, including drive shafts and differentials. These components are optimized for electric motors, simplifying design and improving vehicle efficiency. Notable innovations include:

- Electronic controllers – These manage power delivery to the electric motor, ensuring optimal performance and rapid responses to driving conditions, improving the overall user experience.
- Smart transmission systems – Advanced sensors and real-time data analytics are increasingly being integrated into transmission technology, enhancing reliability, efficiency, and adaptability (Romero-Carrión & Carrión-Galarza, 2022).

Electrified transmission and driveline systems are already widely applied in passenger EVs, public transportation fleets, and industrial machinery. Their ability to operate with greater efficiency and sustainability makes them an attractive solution in the shift toward clean energy transportation. However, to maximize their long-term impact, challenges related to implementation, performance, and infrastructure development must be addressed through continued research and innovation (Romero-Carrión & Carrión-Galarza, 2022).

Advancements in EV battery technologies

Batteries serve as the core energy storage component of electric vehicles (EVs), supplying power to all onboard electrical systems. Over recent years, battery technology has significantly evolved, improving energy efficiency, performance, and longevity.

During the mid-20th century, nickel-cadmium (NiCd) batteries were introduced as an alternative, offering higher energy density and improved rechargeability. However, these batteries suffered from the memory effect and environmental contamination risks due to cadmium toxicity (Xu & Cao, 2015). By the 1990s, nickel-metal hydride (NiMH) batteries emerged as a better alternative, increasing energy density and reducing memory effect issues. This technology was widely used in hybrid vehicles, such as the Toyota Prius, which combined an electric motor and an internal combustion engine, improving fuel efficiency and lowering emissions (Chan, 2007).

The breakthrough moment for EV batteries came with the commercial introduction of lithium-ion (Li-ion) batteries by Sony in 1991. These batteries revolutionized the consumer electronics industry and later became the dominant energy source for EVs. Compared to previous technologies, Li-ion batteries offer higher energy density, reduced weight, and better overall performance (Tarascon & Armand, 2001). By the 2010s, vehicles like the Tesla Model S demonstrated that lithium-ion batteries could provide over 300 miles of range, making EVs a practical alternative to traditional vehicles (Burke & Miller, 2009).

Key advancements in EV battery technology include:

- Increased charge density and range: Battery energy density has significantly improved, allowing longer driving ranges, overcoming a major limitation of early EVs (Mercado & Córdova, 2014).
- Reduced charging time: Fast-charging capabilities now enable full charges in under 10 minutes, enhancing practicality for daily use (Iberdrola, s/f-a).

- New material development: Research into graphene and advanced composite materials has led to higher energy storage capacity and power efficiency (Mercado & Córdova, 2014).
- Exploration of next-generation battery technologies: Solid-state, zinc-air, and sand-based batteries are under investigation as safer and more efficient alternatives to conventional lithium-ion technology.

While lithium-ion batteries remain the industry standard, proper disposal and recycling processes are crucial for minimizing environmental impact. Additionally, the continued optimization of battery chemistry and performance is necessary to meet the growing demands of EV adoption.

III. CHALLENGES AND TRENDS IN ELECTRIC VEHICLES

As discussed earlier, electric vehicles (EVs) are considered one of the most sustainable alternatives to internal combustion engines (ICE) vehicles, primarily due to their low direct greenhouse gas emissions. However, several studies and analyses (Koroma *et al*., 2022; Walters & Brusselaers, 2024; Agusdinata *et al*., 2018) highlight a range of challenges and concerns related to EV production and operation.

Key challenges in EV adoption

The widespread adoption of electric vehicles (EVs) faces multiple challenges beyond technological advancements, including environmental, ethical, geopolitical, and infrastructural concerns. Environmentally, the production of EV batteries requires large-scale extraction of critical minerals such as lithium, cobalt, nickel, and manganese, often resulting in severe environmental degradation, including water contamination and soil erosion.

Additionally, the energy-intensive battery manufacturing process generates substantial carbon dioxide emissions, with studies estimating that this phase can produce 40% to 50% more emissions than those of internal combustion engine vehicles (Ran & Duan, 2025; Carvalho *et al*., 2023; Shahzad & Iqbal Cheema, 2024).

From an ethical perspective, concerns arise regarding labor exploitation in global supply chains. Subcontracting practices allow lead firms to deflect responsibility for unethical labor conditions, while the extraction of cobalt—an essential component in lithium-ion batteries—has been linked to exploitative practices in artisanal mining sectors, particularly in the Democratic Republic of Congo (DRC), where miners often work under precarious conditions with no social protections (Cuervo-Cazurra *et al*., 2021; Horst *et al*., 2023; Rachidi *et al*., 2021).

Geopolitically, the concentration of battery mineral reserves in politically unstable regions creates significant supply chain vulnerabilities, leading to market monopolization, fluctuating prices, and protectionist trade policies that threaten the affordability of EVs (Prakhar *et al*., 2024). Additionally, the globalization of trade and the shift toward renewable-based electrification may externalize decarbonization costs, creating negative externalities in other regions (Basu, Jamasb & Sen, 2024).

Finally, the large-scale electrification of transportation will impose unprecedented pressure on existing power grids. Increased energy demand, if met using fossil fuel-based sources, could undermine the expected reductions in greenhouse gas emissions, while infrastructure limitations necessitate substantial investments in grid modernization and expansion to support the rising adoption of EVs. Without addressing these interconnected challenges, the transition to electric mobility may face significant economic, social, and environmental obstacles.

Balancing sustainability and scalability

While EVs offer substantial benefits in terms of reducing direct CO_2 emissions, achieving a truly sustainable transition requires addressing their entire life cycle impact. Sustainability must be improved at every stage, from material extraction and battery production to recycling and clean energy generation for vehicle operation.

Future trends in electric vehicles

The success of EVs adoption will depend on technological advancements, policy support, and infrastructure improvements to overcome current challenges. Continued investment in battery innovation, smart grids, and ethical supply chain management will be critical to ensuring the long-term viability of electric mobility.

This section explores the key trends shaping the future of electric vehicles, including their environmental and economic impact, technological advancements, and the transformation of the workforce.

Environmental and economic impact

Electric vehicles (EVs) produce zero direct emissions during operation, making them a cleaner and more sustainable alternative to internal combustion engine (ICE) vehicles. Their widespread adoption is expected to significantly reshape global transportation infrastructure, driving a fundamental shift in mobility patterns. However, one of the most pressing challenges remains the proper management of batteries at the end of their life cycle, ensuring that sustainability extends beyond vehicle operation.

From an economic perspective, the production and adoption of EVs are stimulating economic growth, creating new market opportunities, and driving demand in related industries. For instance, the EVs sector has had a notable impact on economic output in countries such as Indonesia, where it contributed to a 1.87% increase in total economic output and a 1.5% increase in value-added growth. This expansion is primarily driven by the manufacturing and battery production sectors, highlighting the industry's potential to transform national economies (Pirmana *et al*., 2023; World Bank, 2022).

Technological advancements in electric vehicles

A key driver of EVs adoption has been the continuous improvement in battery technology. According to Nykvist and Nilsson (2015), lithium-ion battery costs have fallen by 85% since 2010, making EVs more affordable and accessible to the mass market. This cost reduction has been facilitated by large-scale investments in research and development (R&D) and economies of scale, which have driven significant production efficiencies.

Furthermore, ongoing research into alternative battery materials, such as solid-state lithium and graphene, aims to enhance energy density and reduce charging times (Pellow *et al*., 2020). These breakthroughs could address key challenges limiting EV adoption, particularly range anxiety and lengthy charging times.

Despite substantial progress in extending battery range, electric vehicles still face limitations compared to ICE vehicles. According to the International Energy Agency (IEA, 2024), range improvements and energy recovery systems have significantly enhanced EV performance. However, extreme weather conditions, intensive use, and long-distance travel continue to present challenges, making further advancements in battery technology and charging infrastructure critical.

Job creation and workforce transformation

The transition to electromobility is expected to have significant implications for both job creation and work transformation. The expansion of the electric vehicle (EV) industry, along with the growth of renewable energy, is generating employment opportunities in areas such as EV maintenance, battery manufacturing, and the development of charging infrastructure (Gokasar *et al*., 2023). Additionally, broader economic benefits can be observed in countries that invest in energy efficiency and electromobility, as evidenced by Luxembourg, where these sectors have contributed to job creation and economic growth (Karimabadi & Leal-Arcas, 2023).

However, the shift towards electromobility is also reshaping existing job roles in the automotive sector. As traditional manufacturing processes evolve, workers must adapt to new technologies, requiring retraining and upskilling programs (Gokasar *et al*., 2023). The broader impact of digital transformation, including automation in electromobility, follows complex patterns. Some mechanisms, such as the substitution effect, may lead to job displacement, while others, like productivity gains and new task creation, can generate new employment opportunities (Gao *et al*., 2025; Sun *et al*., 2023).

Public policies play a crucial role in maximizing employment benefits while mitigating potential job losses. Government incentives and regulatory frameworks can facilitate workforce adaptation, ensuring a smooth transition toward a more electrified transport sector. For example, strategic investment policies and non-fiscal measures have been identified as key drivers for electromobility adoption in countries like Colombia (Negrete *et al*., 2024; Lopez-Arboleda *et al*., 2023). Ultimately, the extent to which electromobility fosters job growth or labor market disruptions will depend on policy support and the ability of the workforce to adapt to evolving technological demands.

IV. DISCUSSION AND RESULTS

The literature review reveals key patterns in the evolution of electromobility, highlighting technological milestones, persistent challenges, and emerging trends. The discussion on electric vehicles (EVs) is structured around three fundamental dimensions:

1) Key Technological Innovations Driving EV Adoption.
2) Challenges in Charging Infrastructure and EV Regulations.
3) Adoption patterns in international markets.

1) Key technological innovations driving EV adoption

A crucial factor influencing EV adoption is the evolution of battery technology and energy management systems. Over the past decades, major milestones (Table 4) have been observed in cost reduction, increased range, and the development of new battery technologies.

Table 4
Milestones in Battery Development for EV

Year	Event / Innovation	Impact on EV adoption
1991	Commercialization of lithium-ion batteries (Sony).	Revolutionized consumer electronics, later adopted in EVs.
2010	Accelerated cost reduction in batteries (-85%) (Nykvist & Nilsson, 2015).	Made EVs more affordable and competitive.
2015	Introduction of the Model S with +300-mile range.	Demonstrated the feasibility of EVs as a real alternative.
2023	Advances in solid-state batteries.	Reduced charging times and improved safety.

Source: own elaboration.

A clear pattern of technological evolution can be observed, where innovation in battery materials and thermal management systems has been the primary drivers of improvements in range and cost. However, significant challenges remain, particularly regarding battery recyclability and dependence on critical minerals such as lithium and cobalt.

Regarding vehicle infrastructure, the electrification of transmission and propulsion systems has significantly improved EVs energy efficiency. Three key patterns in this evolution include:

1) Simplification of mechanical components, reducing maintenance costs.
2) Optimization of energy efficiency, incorporating regenerative braking and advanced power management.
3) Integration with artificial intelligence (AI) and machine learning to improve range and vehicle response.

2) Challenges in charging infrastructure and EV regulations

The deployment of charging infrastructure remains one of the most significant obstacles to mass EVs adoption. Table 5 shows a clear distinction between regions with high EVs adoption rates and those where the transition has been slower.

Table 5
Comparison of EVs adoption strategies

Criterion	High adoption countries (Norway, China, Germany)	Developing countries (Mexico, Brazil, South Africa)
Charging infrastructure	Extensive public and private charging networks.	Limited availability, mostly in urban areas.
Fiscal incentives	Tax exemptions and direct subsidies.	Partial or inconsistent incentives.
Electricity costs	Preferential rates for EV users.	Standard electricity tariffs, no special incentives.
Regulation and policies	National interoperability standards for charging stations.	Lack of uniform regulations, bureaucratic barriers.

Source: own elaboration.

A significant milestone in charging infrastructure has been the development of ultra-fast charging networks and smart grid integration, enabling more efficient energy distribution while preventing grid overloads.

However, major challenges remain, particularly in charging system standardization and the electrical grid's capacity to handle increased EV demand. It is projected that the growth in EV sales will require a 25% increase in charging infrastructure investment over the next decade (IEA, 2024).

3) Adoption patterns in international markets

A comparative analysis of global EVs adoption reveals clear patterns (Table 6) of success and persistent challenges, shaped by disparities in infrastructure availability, regulatory support, and production costs.

Table 6
EVs adoption strategies by country

Adoption model	Examples of countries	Characteristics
Early adoption leaders	Norway, China, Germany	Strong government support, subsidies, extensive charging network.
Accelerated transition	United States of America, France, United Kingdom.	Growing adoption with infrastructure incentives.
Moderate adoption with barriers	Mexico, Brazil, South Africa.	Limited infrastructure, intermittent incentives, high initial costs.

Source: own elaboration based on Torralba & Medina, 2025; Bencivelli, *et al*. 2024; Quiñónez, *et al*. 2024, IEA, 2023.

A consistent trend emerges across global EV adoption: countries with clear regulations, sustained incentives, and significant infrastructure investments have successfully integrated EVs, whereas those with fragmented policies or insufficient charging networks continue to lag. These findings align with previous research (Torralba & Medina, 2025; IEA, 2024), highlighting the pivotal role of policy stability and financial support in fostering electromobility.

The future of electromobility depends on the intersection of technological progress, infrastructure expansion, and regulatory efficiency. EVs have shifted from an experimental alternative to a central pillar of transportation and energy transition. However, widespread adoption remains constrained by structural barriers, including supply chain vulnerabilities, charging infrastructure gaps, and inconsistent policy incentives. To overcome these challenges and accelerate global EV adoption, key strategies must include:

- Enhancing fiscal and regulatory incentives to lower entry costs for consumers.
- Expanding charging networks and smart grid integration to prevent energy system overloads.
- Boosting investment in battery manufacturing and recycling to reduce dependency on critical materials and improve supply chain resilience.

The next decade will be decisive in shaping a sustainable and inclusive EV ecosystem, where battery innovations improve efficiency, electrical grids become more resilient, and regulatory frameworks ensure equitable access to electromobility. The insights from this study provide a foundation for policymakers, industry leaders, and researchers, guiding them in designing strategies that connect technological advancements with large-scale implementation.

By addressing these barriers and seizing emerging opportunities, electromobility can transition from a promising alternative to a fully integrated, sustainable transportation model, fostering long-term economic, social, and environmental benefits.

CONCLUSIONS

This study provides an updated and structured review of key technologies, challenges, and trends in electric vehicle (EV) development from 2010 to 2025, applying the PRISMA methodology. Unlike previous research that relies on bibliometric analysis, this study systematically integrates technological advancements, persistent barriers, and emerging trends, offering a holistic perspective on the transition to sustainable mobility.

Several bibliometric studies have focused on EV research trends rather than technological and industry challenges. Ibrokhimjon *et al*. (2024) conducted a bibliometric analysis using Scopus covering 1985-2023, primarily identifying frequent authors, publishing countries, and research specializations. Similarly, Barbosa *et al*. (2022) used Web of Science to examine publication growth and citation impact between 2020-2021, while Guevara *et al*. (2021) concentrated on Latin American contributions to electromobility research. Other studies, such as Campoverde-Pillco *et al*. (2024) and Morejón-Monteros *et al*. (2024), have focused on specific aspects of electromobility, including battery reuse and grid impact.

In contrast, this study takes a broader approach, analyzing key EV technologies, market challenges, and regulatory frameworks through a systematic literature review, covering multiple databases and sources. This perspective offers a more comprehensive understanding of electromobility's evolution, highlighting technological advancements, infrastructure investments, and policy developments as key determinants of EV adoption (IEA, 2024).

The findings indicate that countries with clear regulations, fiscal incentives, and charging infrastructure investments have accelerated EV adoption (Torralba & Medina, 2025), while nations with fragmented policies and insufficient infrastructure experience slower growth (Morejón-Monteros *et al*., 2024). Technological progress —such as battery cost reductions, energy efficiency improvements, and ultra-fast charging systems— has driven market expansion (Nykvist & Nilsson, 2015; Mohtat *et al*., 2021), yet challenges persist in material dependency, battery recycling, and grid stability (Campoverde-Pillco *et al*., 2024).

Study Contributions

This study provides a comprehensive analysis of electromobility, integrating technological, economic and regulatory perspectives. Unlike previous studies that examine these aspects separately, this research underscores the need for a holistic approach to facilitate an efficient transition toward EVs.

From a technological perspective, advancements in battery technologies, electrified transmissions, and energy management systems are highlighted, with a focus on efficiency and recyclability challenges. Economically and politically, key factors influencing EV adoption across regions are identified, establishing patterns of success and barriers to implementation. From a sustainability standpoint, the study underscores the urgency of circular economy models, particularly in battery lifecycle management.

A key contribution of this study is the identification of gaps in literature, including:

- The lack of consensus on battery standardization, affecting supply chains, second-life applications, and recycling strategies.
- Limited economic viability assessments of emerging fast-charging technologies and their long-term implications.
- Insufficient discussion on regulatory frameworks for vehicle-to-grid (V2G) integration, despite its potential to optimize energy demand and support EV adoption.

Study Limitations and Future Research

- Despite offering a structured and updated perspective on electromobility, this study has certain limitations:
- Lack of quantitative modeling: While patterns and trends were identified, no economic modeling or adoption forecasts were conducted.

- Global focus without regional specificity: The review considers international trends but does not provide in-depth analysis of developing countries, where challenges may differ significantly.
- Ongoing technological evolution: Given the rapid transformation of the EV sector, advancements in energy storage, smart grids, and materials science could reshape current conclusions.

To address these limitations, future research should focus on:

- Investment models for charging infrastructure: Examining how public and private sector investments influence EV adoption rates (IEA, 2024).
- Battery life cycle impact and sustainability: Assessing the environmental footprint of EVs, from raw material extraction to recycling (Campoverde-Pillco *et al*., 2024).
- Integration of artificial intelligence (AI) in electromobility: Investigating how AI can enhance energy efficiency, optimize charging networks, and improve EV autonomy (Pellow *et al*., 2020).
- Comparative analysis of regulatory frameworks: Identifying which policy incentives have been most effective in accelerating EV adoption and their replicability across different regions (Quiñónez Guagua *et al*., 2024).

Acknowledgments

This work was supported by UNAM PASPA – DGAPA.

- DGAPA PAPIIT IN304122 Methodological Proposal for Measuring Innovation and Absorptive Capabilities 4.0.
- DGAPA PAPIIT IN305525 Impact of Electromobility on the Auto Parts Sector: Opportunities and Challenges.

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