

# Electric vehicles and sustainable transportation: A comprehensive review of environmental benefits, adoption trends, challenges, and future perspectives

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## ABSTRACT:

This paper examines the transition from internal combustion engine vehicles (ICEVs) to electric vehicles (EVs) as a pathway toward sustainable transportation, reduced fossil-fuel dependence, and lower environmental impacts. Rather than viewing vehicle electrification as an inherently sustainable solution, the review evaluates how environmental performance, technological development, infrastructure, consumer behaviour, policy support, and broader system-level conditions influence the sustainability of EV deployment. Evidence from peer-reviewed studies and authoritative institutional reports, primarily published between 2015 and 2025, is critically synthesized to assess the opportunities and limitations of electric mobility. The results show that battery electric vehicles (BEVs) have zero direct tailpipe emissions, higher drive train efficiency and generally lower life-cycle greenhouse gas emissions than conventional vehicles. However, these benefits are highly dependent on the electricity-generation mix, the battery chemistry and capacity, the manufacturing conditions, the vehicle utilization and the end-of-life management. The uptake of EVs has been driven by falling battery prices, technology improvements, growing charging infrastructure and supporting policies, but there are large regional differences. The big hurdles are the upfront cost, lack of charging stations, range anxiety, battery degradation, critical-mineral dependency, grid capacity and recycling. The paper argues that sustainable electric mobility is more than a shift away from combustion engines toward electric drivetrains. It is based on clean electricity, efficient vehicles, accessible charging infrastructure, responsible supply chains for batteries, circular material flows and enabling policies. The paper concludes with the need for a coordinated development of these dimensions to ensure the effective contribution of EVs to sustainable transport and long-term transport decarbonization.

**Keywords:** Electric vehicles; Battery electric vehicles; Sustainable transportation; EV adoption; Green House Gas Emission

## Introduction

Transportation is central to economic and social activity, but its continued dependence on petroleum fuels contributes substantially to greenhouse-gas emissions and urban air

pollution. Road transport is therefore a critical target for decarbonization because rising mobility demand can offset efficiency gains achieved by conventional internal-combustion-engine vehicles (ICEVs). A transition toward electric

mobility, low-carbon electricity, efficient transport systems, and supportive policy is increasingly viewed as necessary for long-term transport decarbonization (Creutzig et al., 2015; Knobloch et al., 2020). Electric vehicles (EVs), particularly Battery electric vehicles (BEVs), offer two immediate advantages over conventional vehicles: elimination of direct tailpipe emissions during operation and substantially higher drivetrain efficiency. Electrification can also reduce petroleum dependence and provides a pathway for lowering transport emissions as electricity systems become cleaner. However, the sustainability of EVs cannot be judged only at the vehicle tailpipe. Their environmental performance depends on the complete life cycle, including raw-material extraction, battery and vehicle manufacturing, electricity generation, vehicle use, and end-of-life management (Aichberger & Jungmeier, 2020; Chordia et al., 2021; Peters et al., 2017).

Using the LCA method, it becomes evident that BEVs are capable of reducing GHG emissions in comparison with ICEVs, although the level of positive impacts is dependent on such variables as type of electricity used for recharging of batteries, batteries' type and capacity, place of production, car's efficiency and mileage, and many others (Ellingsen et al., 2016; Marmioli et al., 2018; Knobloch et al., 2020; Märtz et al., 2021; Verma et al., 2022). Thus, EVs could be regarded as zero emission vehicles as far as exhaust emissions are concerned, but not as zero emission technologies.

On the contrary, the latest improvements in batteries, battery durability, recharging speed, number of existing models and different kinds of incentives, emission reduction and necessary infrastructure help people to use electric cars more often (Chandra, 2022; Patil et al., 2024; Sathiyar et al., 2022). Particularly, this transition is especially vital for emerging economies such as India since the issue of electrification of mobility is connected not only with environment-related problems but also with energy security and economic development of highly polluted by vehicle emissions urban areas. In addition,

approaches to adoption of electric cars might vary depending on income levels, car parks, electric power and recharging infrastructure in every country. The introduction of electric mobility leads to interconnected sustainable challenges. Increased battery demand causes additional pressure on lithium, nickel, cobalt, graphite and other critical materials supply chain; the wide availability of the charging points can cause additional peak loads and grid distribution requirements; increased number of the end-of-life batteries will need recycling and reuse systems to be developed. However, renewable energy integration, smart charging, vehicle-to-grid operation, reuse of the batteries and circular material flow can help to avoid these issues (Inci et al., 2024; Taghizad-Tavana et al., 2023).

Existing research has often examined environmental performance, technology, consumer adoption, policy, charging infrastructure, or battery sustainability as separate topics. This fragmentation is important because the sustainability of EVs is a system property: improving one dimension can create trade-offs in another. For example, increasing battery capacity can improve range and consumer acceptance while increasing material demand and production-stage impacts; similarly, rapid EV diffusion can reduce petroleum consumption while increasing electricity-grid and mineral-supply pressures. Accordingly, this review integrates evidence across environmental, technological, market, behavioural, infrastructural, and policy dimensions to evaluate EVs within a broader transport-energy transition. It examines (i) environmental benefits and lifecycle emissions, (ii) global adoption and market development, (iii) determinants of EV adoption, (iv) system-level sustainability challenges, and (v) emerging technologies and policy pathways (vi) Role of EVs in promoting sustainable transportation. Particular attention is given to the conditions under which EVs deliver the greatest sustainability benefits rather than treating electrification as an intrinsically sustainable outcome.

The review therefore contributes an integrated perspective linking lifecycle performance with adoption dynamics, electricity-system conditions, critical-material dependence, circular battery management, and long-term policy. By bringing these dimensions together, the study identifies major trade-offs, research gaps, and priorities for aligning large-scale EV deployment with sustainable-development objectives.

## **Background And Evolution Of Electric Mobility**

### **Evolution of Electric Vehicles and Sustainable Transportation**

There is a growing trend of sustainable transportation because of the need for reducing greenhouse gas emissions, cleaning the polluted air in urban areas, ensuring energy security and reducing dependence on oil in the transport sector (Avesh, M., et.al. 2024; Kashem, M., et.al.(2024). In the course of this transition, EVs, especially BEVs, have become one of the important technologies to help decarbonize road transportation. The development of these types of vehicles has been facilitated by the progress in lithium-ion batteries, decreasing prices for batteries, extended driving distances, new standards concerning vehicle emissions, availability of charging stations, and incentives offered by governments. All of these trends have increasingly helped increase the competitiveness of EVs compared to ICEVs (Coffman et al., 2017; Kumar & Alok, 2020; Patil et al., 2024). Nevertheless, electric mobility is to be understood not only as a shift from internal combustion engines to electricity-based drivetrains but also as a change in the entire transport and energy systems paradigm. Sustainable mobility involves the interaction between electric vehicles, renewable energy sources, smart grids, recharging infrastructure, energy storage, public transport, and behavioural change in travel activities. Consequently, transport decarbonization requires concerted effort in technological, infrastructural, behavioural, and policy dimensions (Creutzig et al., 2015; Gallo & Marinelli, 2020).

The research on electric mobility has evolved from the purely technological focus into an understanding of the connection between technological issues, consumer behavior, infrastructure, economic factors, and policy considerations. Literature review reveals that affordability, driving range, access to charging facilities, consumer characteristics, and policy have been identified as factors affecting EV uptake over and over again (Coffman et al., 2017; Kumar & Alok, 2020; Anastasiadou & Gavanias, 2022; Rahman & Thill, 2024).

The intervention of the Government has played very significant role in the evolution of the EV market. Financial and technological obstacles have been lowered through purchase rebates, tax reductions, zero emission vehicle regulations, fuel economy requirements, investments in charging infrastructure, and supporting research. Evidence from all around the world has proven that the combined approach works better than individual approaches (Chandra, 2022; Hardman, 2019; Yao et al., 2020). The evolution of EVs thus requires recognizing a socio-technical transition that comprises technological, market, energy, institutional, and behavioural dimensions.

### **Methodology**

This literature review is an attempt to summarize the state of knowledge regarding electric vehicles (EVs) and their role in developing greener and sustainable transport systems. The relevant literature sources were collected mainly using Web of Science, Scopus, and Google Scholar databases and were complemented with data from internationally known organizations like IEA, IPCC, IRENA, ICCT. Studies released between 2015 and 2025 were considered as the major part of the literature base, but some works of the older period were also used for basic information. The reviewed literature dealt with the issues related to the topic of electric mobility, such as life cycle greenhouse gases emissions, energy efficiency, EV uptake, battery technology, charging infrastructure, renewable energy use, consumer behaviour, economy aspects, transport policy, critical raw materials, and batteries recycling. The scientific sources of the literature

were the peer-reviewed research articles, review articles, life cycle assessment studies, and reports of reputable organizations. A consistent analysis of the literature was performed considering six interrelated topics, namely, environmental impacts, global EV adoption, batteries and charging technologies, consumer behavior and economics, policy and infrastructure and other sustainability issues. Special emphasis was placed on the linkages between electricity production, battery manufacturing, vehicle operation, charging technologies, material needs, recycling, user opinions and enabling policies. The data were analyzed from the life cycle and system level perspectives, offering an in-depth assessment of the environmental, technological, economic, and social aspects of electric mobility. In this way, it was possible to follow the latest developments, challenges, knowledge gaps and future research priorities around the potential role of electric vehicles in sustainable urban mobility.

### Global Oil Consumption by Sector

Source: International Energy Agency (IEA), *Oil 2023 – Analysis and Forecast to 2028*, IEA, Paris, 2023

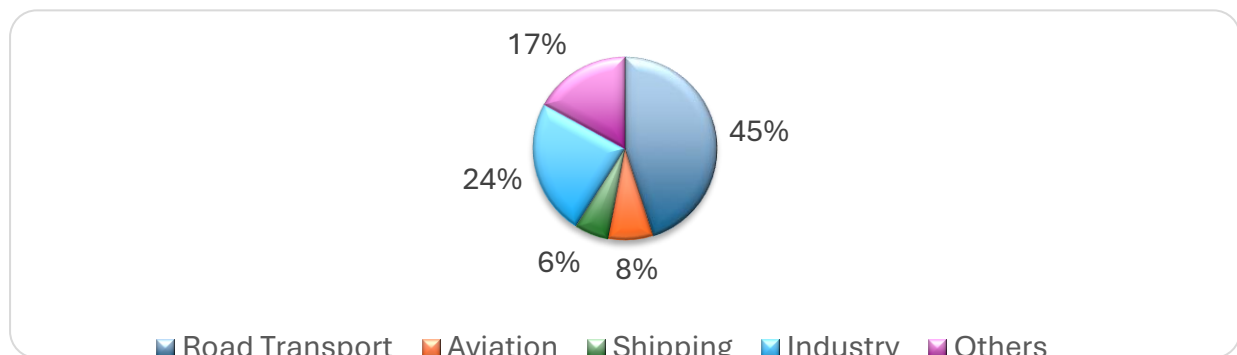


**Figure 1. Global oil consumption by sector. Road transport is shown as the largest share, supporting the importance of road-vehicle electrification for reducing petroleum dependence.**

Source: International Energy Agency (IEA), *Oil 2023*.

### Reduction in Greenhouse Gas and Air Pollutant Emissions

The most obvious environmental factor that distinguishes BEVs from ICEVs is the one at the tailpipe. This is because the combustion of gas and diesel results in the production of carbon dioxide and some forms of pollution to the atmosphere. On the other hand, there is no combustion engine for the BEVs.

**Table 1. Direct Tailpipe Emissions by Vehicle Technology**

| Pollutant       | Gasoline ICEV | Diesel ICEV | BEV |
|-----------------|---------------|-------------|-----|
| CO <sub>2</sub> | High          | High        | 0   |

### Results And Discussion

It can be seen from the evidence reviewed that EVs are capable of providing notable environmental benefits compared to ICEVs due to the potential for reduced use of petroleum, lack of emissions from tailpipes, better drivetrain efficiency, and lower greenhouse gas emissions during their entire life cycle.

### Reduction in Fossil Fuel Consumption

However, the transport sector still relies heavily on petroleum products, thus making the transition to the use of electric motors one of the ways to reduce oil consumption. According to IEA, road transport has been the leading portion of transport oil demand because the passenger cars, trucks, buses, and motorcycles used gasoline and diesel as fuels (IEA, 2024). The growing number of EVs leads to lower demands for those resources. In contrast to the ICEV, the BEV does not use gasoline and diesel at all.

| Pollutant         | Gasoline ICEV  | Diesel ICEV    | BEV |
|-------------------|----------------|----------------|-----|
| CO                | Present        | Present        | 0   |
| NO <sub>x</sub>   | Present        | Present/high   | 0   |
| Exhaust PM        | Present        | Present        | 0   |
| VOCs/hydrocarbons | Present        | Present        | 0   |
| SO <sub>2</sub>   | Fuel dependent | Fuel dependent | 0   |

The zeroes for BEVs in Table. 1 are with respect to exhaust emissions, not the life cycle emissions. The use of BEVs over ICEVs means that there will be no direct combustion-induced emissions, thereby reducing the risk of traffic pollution due to the emissions. Despite that, EVs emit some particulate matter emissions in the form of non-exhaust emissions that arise through tyre wear, road wear, and dust resuspension, but this is alleviated through the use of regenerative brakes. Their impact on the environment depends on their source of electricity.

Nealer and Hendrickson (2015) analysed more than twenty lifecycle assessment studies and found out that electric cars always emit less greenhouse gases than traditional ones irrespective of the electricity production scenario. Likewise, Das et al. (2024) proved that extensive electrification of transportation substantially

decreases emissions of air pollutants causing cardiovascular and respiratory illnesses.

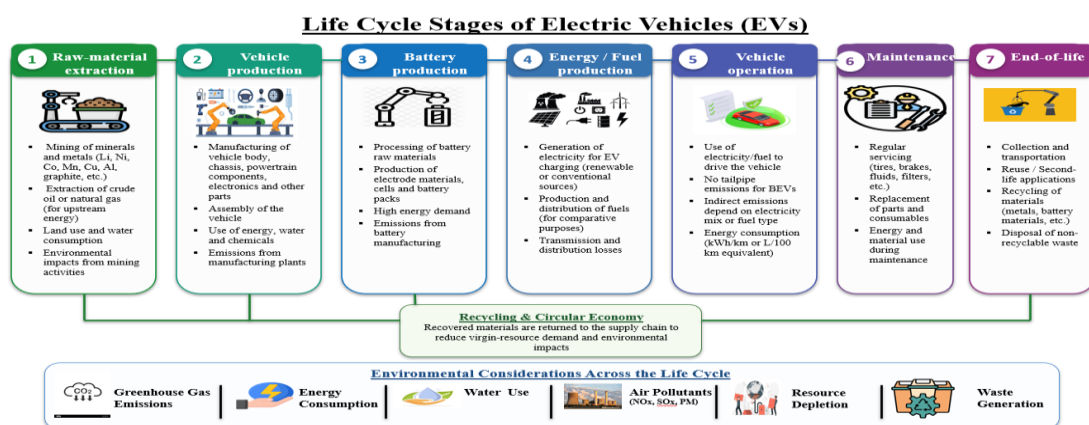
### Tailpipe and Lifecycle Carbon Emissions

#### Tailpipe CO<sub>2</sub> Emissions

There exists a definite mathematical difference between car technologies when comparing by tailpipe. The direct tailpipe emissions of CO<sub>2</sub> for BEV are 0 g CO<sub>2</sub>/km, whereas traditional vehicles release CO<sub>2</sub> in exhaust gases due to constant combustion of gas and diesel. Below there can be made an indicative comparison through tailpipe figures.

#### Lifecycle GHG Emissions

Emissions at tailpipes are only a partial environmental comparison since BEVs tend to use more resources and energy in their production process, especially in lithium-ion batteries. Hence, a more accurate comparison is:



Recent studies performed by Simaitis et al. (2025) present additional confirmation of the environmentally-friendly lifecycle profile of

BEVs. Specifically, the authors conducted a time-dependent prospective life cycle assessment of passenger cars over a lifecycle of 200,000 km and

found out that in all different energy systems' decarbonization scenarios, BEVs had lower carbon footprints when compared with hybrid,

plug-in hybrid, and fuel cell vehicles, which was proven for about 5,000 different comparative cases (Šimaitis et al., 2025).

**Table 2. Reported Lifecycle GHG Advantage of EVs**

| Scenario                                                            | Reported EV GHG advantage                                                                                          |
|---------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------|
| <b>BEV; 200,000 km lifetime</b>                                     | Lowest lifecycle carbon footprint among the passenger-car powertrains assessed under most decarbonization pathways |
| <b>BEV in regions with cleaner/decarbonizing electricity</b>        | Substantial lifecycle GHG advantage over ICEVs                                                                     |
| <b>BEV in carbon-intensive electricity regions</b>                  | GHG advantage reduced; some powertrains may have relatively similar footprints                                     |
| <b>BEV as electricity supply decarbonizes over vehicle lifetime</b> | Lifecycle GHG advantage increases                                                                                  |
| <b>BEV tailpipe CO<sub>2</sub></b>                                  | 0 g CO <sub>2</sub> /km                                                                                            |

Source: Šimaitis et al. (2025).

It is evident from Table. 4 that the lifecycle GHG benefits associated with BEVs vary depending on the mix of the electricity used. The use of greener electricity improves the benefits whereas the use of carbon-intensive energy sources limits the environmental benefits. Though batteries have relatively high initial emission values, low operational emission values can balance out those.

#### ***Effect of Electricity Mix on Lifecycle Emissions***

Electricity carbon intensity became one of the critical variables for understanding the differences between LCA studies.

The relationship can be summarized as:

**Table. 3 Effect of Electricity on Lifecycle Performance of BEVs**

| Charging electricity            | Expected lifecycle performance of BEV         |
|---------------------------------|-----------------------------------------------|
| Solar/wind/hydropower dominated | Very low GHG emissions                        |
| Low-carbon grid                 | Low                                           |
| Mixed electricity grid          | Low–moderate                                  |
| Fossil-intensive grid           | Moderate–high                                 |
| Coal-dominated electricity      | Environmental advantage substantially reduced |

Marmioli et al. (2018) demonstrated that the electricity-generation assumptions used in LCA substantially influence estimated EV environmental impacts. Similarly, Knobloch et al. (2020) showed that regional differences in power-generation systems explain considerable variation in EV lifecycle performance.

- BEV—renewable/low-carbon electricity

- BEV—average grid electricity

### Energy Efficiency of Electric Vehicles

Data on energy efficiency give yet another reason why EVs are environmentally friendly. Much of the energy stored in the form of fuel such as gasoline and diesel is lost as heat energy by ICEVs, while EVs convert much more of the energy to mechanical energy. An example of this is provided below.

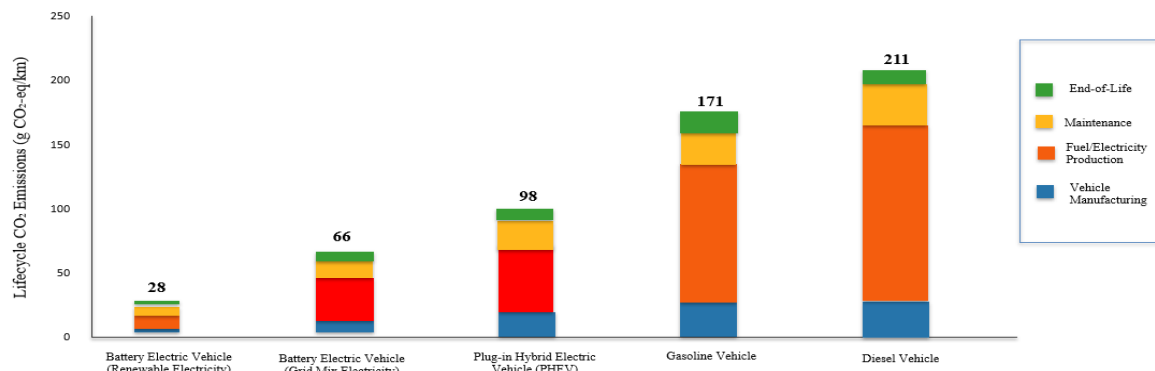
**Table 4. Comparative Drivetrain Efficiency**

| Vehicle technology       | Approximate efficiency | Energy loss |
|--------------------------|------------------------|-------------|
| Gasoline ICEV            | 20–30%                 | 70–80%      |
| Diesel ICEV              | 25–35%                 | 65–75%      |
| Hybrid vehicle           | 30–45%                 | 55–70%      |
| Battery electric vehicle | 75–90%                 | 10–25%      |

Note: Values represent approximate drivetrain/energy-conversion ranges and vary according to the system boundary and operating conditions. Regenerative braking can increase the efficiency of EVs through kinetic energy recovery. Nevertheless, all these advantages can be affected negatively by heavy weights, aggressive driving, high speed, environmental conditions, climate control needs, and charging inefficiencies. Thus, making EVs efficient is more than just having an electric drivetrain.

### Lifecycle CO<sub>2</sub> Emissions by Vehicle Type

(g CO<sub>2</sub>-equivalent per kilometer)



Source: Adapted from International Energy Agency (IEA), 2023; Transport & Environment, 2022; Various LCA Studies.

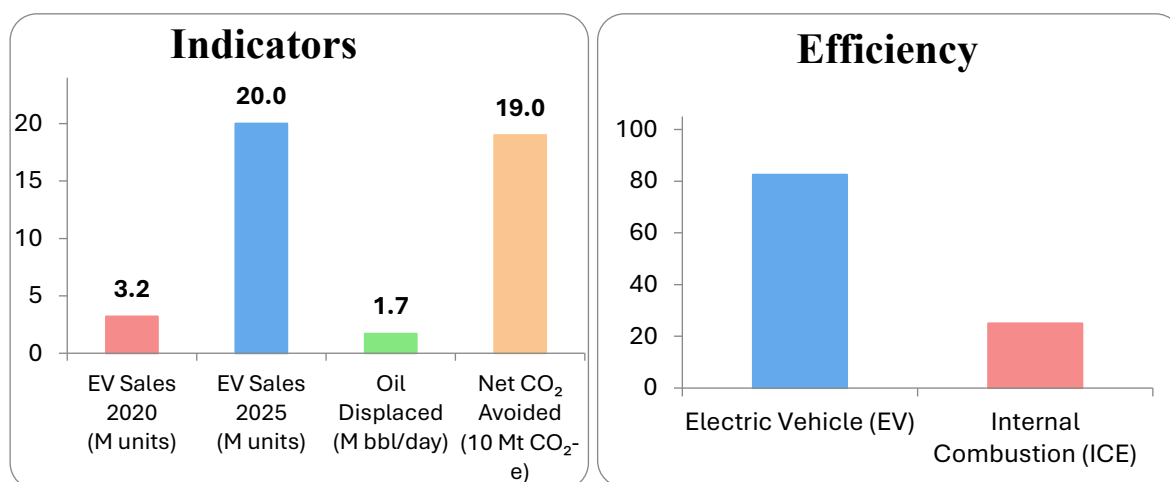
**Figure 3.** Example of CO<sub>2</sub>-equivalent emissions lifecycle for different types of vehicles. The lifecycle of BEVs performs significantly better when low-carbon electricity is used, despite the emissions resulting from battery production. Source: based on IEA, Transport & Environment, and lifecycle assessment literature, as specified in the figure.

Drivetrain efficiency decreases energy use, operating expenses, and emissions. Moreover, the regenerative braking system collects kinetic energy during braking and stores it in the battery.

### Global EV Adoption & Efficiency Dashboard (2020–2026)

#### Drivetrain Efficiency Range (%)

#### EV Growth & Environmental Impact Indicators

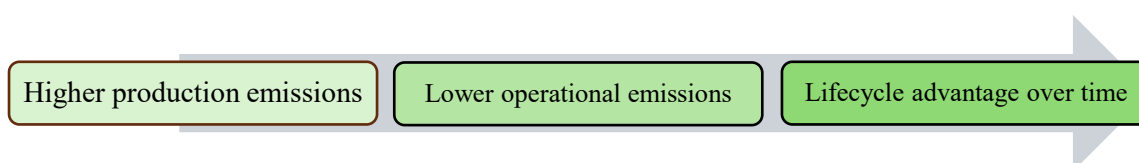


Source: International Energy Agency (IEA), *Global EV Outlook / Industry Data (2020–2026)*,

### Integrated Environmental Performance

The combined data reveal an important trade-off. EVs generally have a higher environmental burden during manufacturing but a substantially lower burden during operation.

This relationship can be represented as:



BEV:

ICEV:

This explains why lifetime mileage is an important parameter in EV lifecycle assessments.

### Contribution to Sustainable Development Goals

The quantitative environmental results also establish links between electric mobility and the United Nations Sustainable Development Goals.

**Table 5. Relationship between EV Benefits and SDGs**

| SDG                                                    | EV contribution                   | Supporting result                         |
|--------------------------------------------------------|-----------------------------------|-------------------------------------------|
| <b>SDG 7</b> – Affordable and Clean Energy             | Renewable-electricity integration | BEVs can operate entirely on electricity  |
| <b>SDG 9</b> – Industry, Innovation and Infrastructure | Battery and charging innovation   | Expansion of EV and charging technologies |
| <b>SDG 11</b> – Sustainable Cities                     | Reduced urban exhaust pollution   | 0% direct BEV exhaust emissions           |
| <b>SDG 12</b> – Responsible Consumption and Production | Battery reuse and recycling       | Potential recovery of critical materials  |

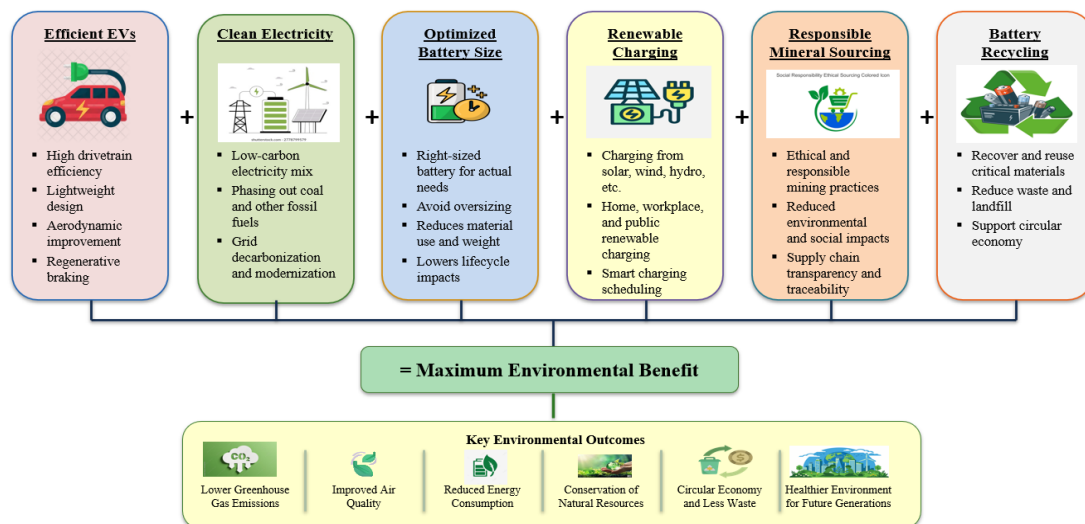
| SDG                     | EV contribution                      | Supporting result                         |
|-------------------------|--------------------------------------|-------------------------------------------|
| SDG 13 – Climate Action | Reduction in transport GHG emissions | Lower lifecycle emissions in most regions |

The most convincing case is made for SDG 13 since the shift to EVs offers an immediate route to reduced burning of fossil fuels. However, meeting SDG 12 involves better battery recycling, mining of minerals in an environmentally responsible way, and circular material management.

Therefore, even though it is true that the quantitative information presented above shows the great environmental advantages of EVs, it is also clear that labeling EVs as "zero-emission vehicles" is extremely misleading. The BEVs do not emit any direct CO<sub>2</sub> emissions when operating, but there are emissions produced during battery manufacturing and electricity generation. Thus, the importance of the lifecycle assessment can hardly be overstated. Hawkins et al. (2013) show that the use of EVs powered by

the European electricity mix results in a 1757-1774% decrease in GHG emissions in the 150,000 km lifecycle. In turn, Knobloch et al. (2020) demonstrate that electric vehicles have lower emissions on the lifecycle stage in 53 out of 59 regions around the world analyzed. The emissions benefit of EVs is boosted by decarbonizing electricity, because as the grid moves to renewable and low-carbon energy, the emissions of EVs go down. ICEVs, however, remain tied to fossil fuels. But this has increased needs for materials and energy for batteries and larger vehicles which limits some of the benefits. Thus, sustainable transport should focus on efficient EVs, cleaner electricity and sustainable battery manufacturing, rather than only EV adoption. Overall, the results suggest the following pathway:

#### Pathways to Enhance the Environmental Sustainability of Electric Vehicles



Consequently, EVs need to be seen as an important element in sustainable transport, yet their sustainability potential will be fully realized only when there is electrification of the car alongside decarbonization of the electricity sector, efficient battery production, and effective battery management.

#### Global Electric Vehicle Adoption Trends And Market Growth

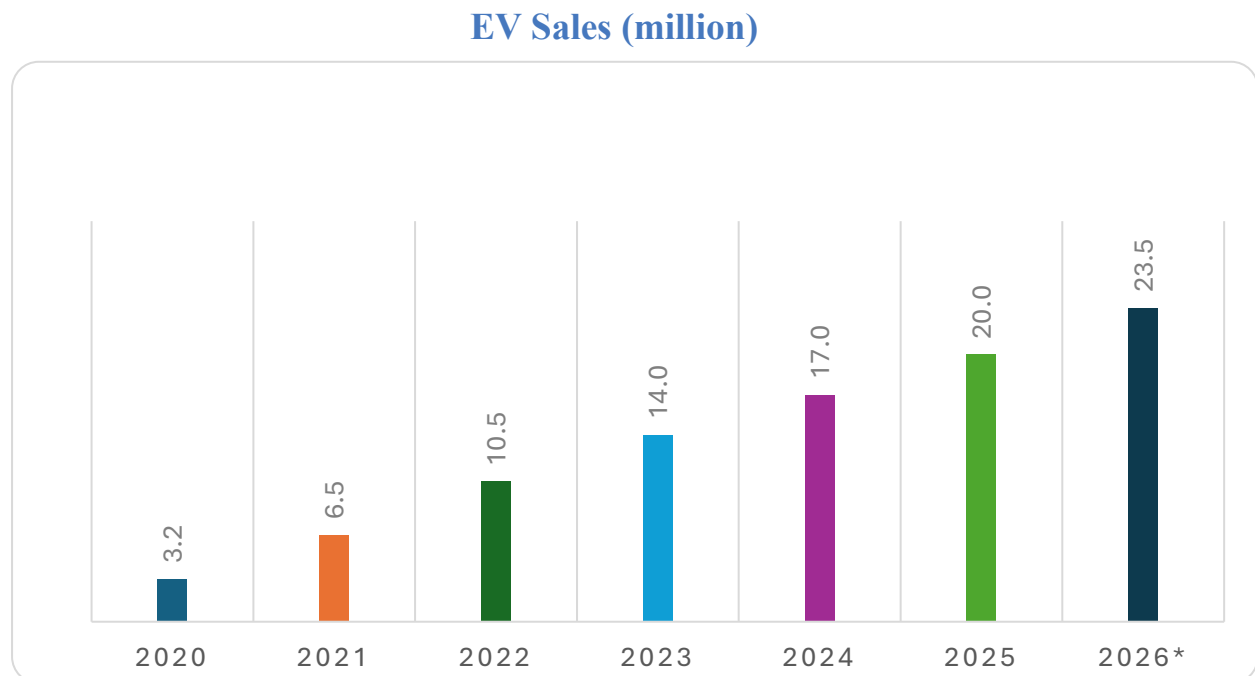
##### Global Growth of Electric Vehicles

The electric car market has seen rapid growth worldwide in the last decade, driven by technological improvements, policy support, falling battery prices, and increased awareness of

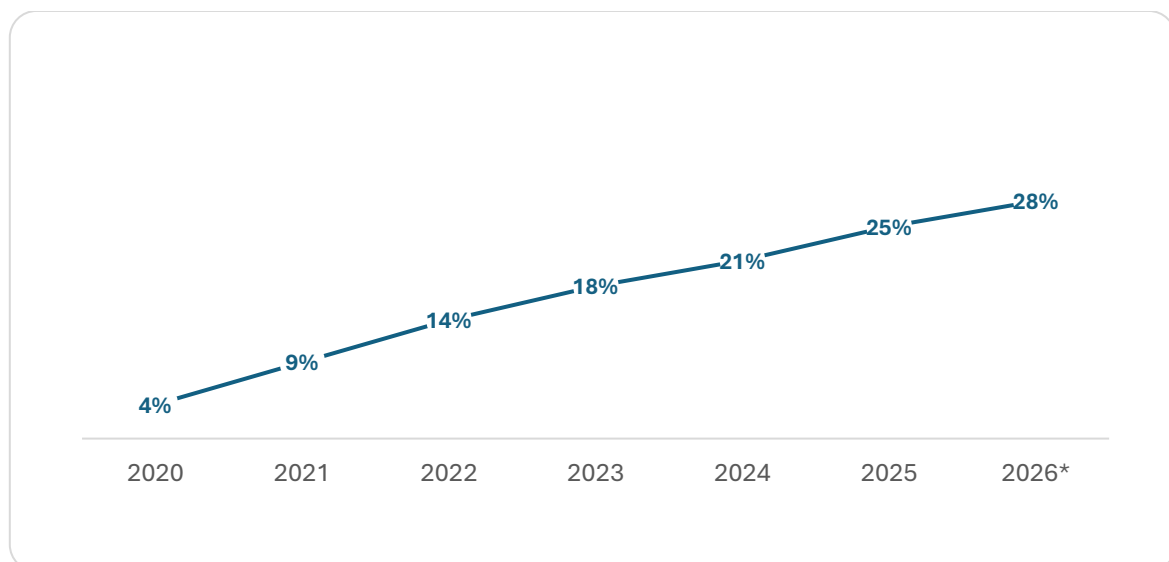
environmental concerns. Sales of electric vehicles hit nearly 14 million globally in 2023, representing 18 percent of all new passenger cars sold. The largest markets were China, Europe and the USA

(IEA, 2024). The key drivers are high battery efficiency, reducing costs, increasing charging facilities, stringent emission standards and consumers' preference for low emission vehicles.

#### Global Growth of Electric Vehicles (2020–2026)



#### Share of new vehicle sales (%)



Source: International Energy Agency (IEA), *Global EV Outlook* / Industry Estimates.

**Figure 4. Global Electric Vehicle Growth (2020–2026)** The figure illustrates the continuous increase in global EV sales and market share, highlighting strong growth between 2020 and the projected values for 2026. International Energy Agency (2024) projects that EV sales will continue to rise throughout this decade, supported by policy measures and sustained technological progress.

### Regional Trends In Electric Vehicle Adoption

Regional Patterns Of Electric Vehicle Uptake However, Even With The Growth In Electric Vehicles Worldwide, There Is Evidence Of Serious Geographical Inequalities Arising From Differences In Economic Development, Policy Frameworks, Infrastructure And Consumer Behavior.

#### China

China Is Leading The EV Market Because Over Half Of The Global Market Share Belongs To China. Subsidies, Infrastructure, Battery Manufacturing Within The Country, And Policy Support Have Contributed To The Leadership Of China In The Global Drive Toward Evs (IEA, 2024).

#### Europe

The European Region Has Turned Out To Be The Second Biggest Market For Evs Because Of Strict CO<sub>2</sub> Emissions Regulations, High Purchase Subsidies, And Development Of Charging Infrastructure. The Country Of Norway Still Leads The World In Terms Of Penetration Of Evs, Where Electric Cars Comprise The Major Part Of Passenger Car Sales.

#### United States

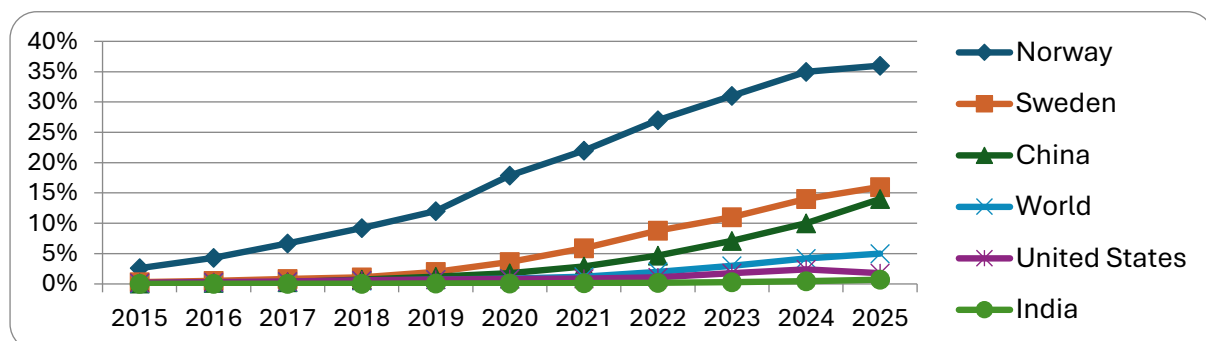
There Have Been Significant Advancements Made Towards The Adoption Of Evs In The U.S. Due To Technological Innovation, Tax Rebates, Legislation, And The Development Of Fast Charging Infrastructure. The Inflation Reduction Act Has Further Increased Investments In Battery And EV Manufacturing In The Country (U.S. Department Of Energy, 2023).

#### India

India Is Among The Rapidly Growing Markets For Evs. Several Government Policies Such As FAME, Which Stands For Faster Adoption And Manufacturing Of Electric Vehicles, PM E-DRIVE, And PLI For Advanced Chemistry Cell Batteries Are Among Those That Have Contributed Greatly To The Promotion Of Electric Mobility In India.

### Share Of Electric Cars In Use, 2015–2025

Battery-electric and plug-in hybrid cars as a share of cars currently in use



Source: International Energy Agency, Global EV Outlook 2026

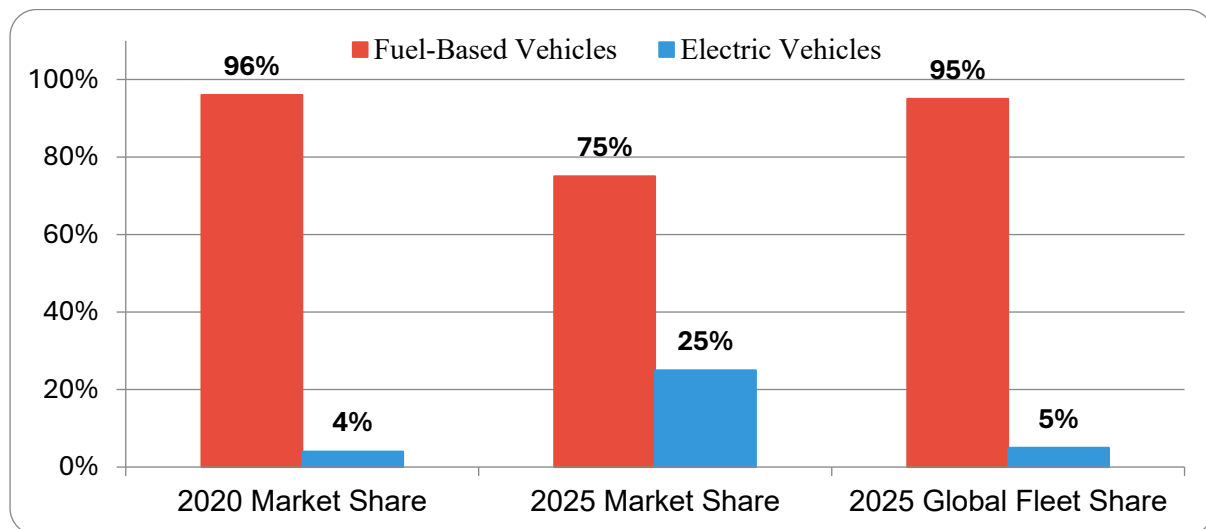
**Figure 5. Share of Electric Cars in Use (2015–2025)** The figure compares EV penetration across different countries and demonstrates the leadership of Norway and the rapid growth observed in China, Sweden, and other regions.

### Market Share of Electric Vehicles

There have been steady gains in the market share of electric vehicles in the last ten years, with the drivers being consumer confidence and advancements in technology. These advances include improvements in driving range, battery life, charge time, and overall vehicle performance. At the same time, the decline in battery costs has reduced the cost gap between electric and regular

cars. As stated by IEA (2024), in 2023, electric vehicles accounted for around 18% of all vehicle sales, and there is further projected growth in the next ten years. It is predicted by BloombergNEF (2024) that electric vehicles will prevail in many developed nations prior to 2040 driven by declining battery costs, technological advances, expanding charging infrastructure, and supportive government policies.

### Comparison of Vehicle Growth & Market Share (2020–2025)



Source: International Energy Agency (IEA), *Global EV Outlook / Market Data (2020–2025)*,

**Figure 6. Comparison of Vehicle Growth and Market Share (2020–2025).** The figure demonstrates the increasing market share of electric vehicles and the corresponding decline in conventional fuel-powered vehicles.

### Factors Influencing Electric Vehicle Adoption

EV adoption is driven by technology, economics, infrastructure, environment, policies, and behavior, with large country differences. Analyzing theoretical models like TPB, TAM, DOI, and UTAUT revealed such factors (Rezvani et al., 2015; Kumar & Alok, 2020).

### Affordability and Purchase Cost

However, higher initial costs still constitute a key obstacle in EV adoption regardless of low cost of operations and maintenance (Kumar & Alok, 2020). High cost of batteries that makes up a considerable portion of total vehicle cost is one reason behind the high cost difference (IEA, 2024). Financial incentives and availability of charging stations can serve as significant catalysts

for the adoption of electric vehicles (Sierzchula et al., 2014). Falling cost of lithium-ion batteries by about 90% since 2010 is gradually making EVs more affordable (BloombergNEF, 2024).

### Charging Infrastructure

The limited availability of charging facilities leads to range anxiety which is important for the development of EVs (Coffman et al., 2017). The broad development of charging facilities has been essential for the development of EVs in countries such as Norway, China, and the Netherlands, whereas in many developing countries it is the problem of insufficient infrastructure (IEA, 2024). Development of advanced facilities like fast, smart, and wireless charging could be beneficial in addition to their integration into renewable energy (Lutsey, 2015).

### Government Policies and Incentives

Government policy has been a key contributor to the adoption of EVs in many countries. Various policies that range from emission standards, zero emissions, incentives to buy EVs, tax breaks, and exemption from registration fee have made consumers and car makers consider electric vehicles (IEA, 2024; Sierzechula et al., 2014). Some of the government schemes that promote EVs in India include FAME and PLI. Affordable EVs, charging facilities and increased consumer readiness are generally the outcome of supportive policies (Kumar & Alok, 2020).

### Environmental Awareness

Global warming, air pollution and sustainability issues are all driving the increased awareness of EVs. Environmentally conscious consumers are generally more likely to use eco-friendly modes of transportation even when they are more expensive (Rezvani et al., 2015). This aspect is mostly seen in the young population and urban areas who are aware of the problem of carbon emission and dependence on fossil fuels (Jabeen et al., 2021). This factor is more prominent in the young and urban population who are aware of the issue of carbon emission and dependence on fossil fuels (Jabeen et al., 2021).

### Technological Advancements

Technological progress has been the reason behind significant improvements in electric vehicle performance, efficiency, and design. The introduction of lithium-ion batteries has led to higher energy density levels and shorter charging times with lower production costs. New generation EVs come with increased driving range, enhanced safety and battery management, regeneration capability, and intelligent energy management technologies (IEA, 2024). Solid-state batteries, lithium-sulfur batteries, and sodium-ion batteries are some examples of promising batteries that will make electric cars perform even better and reduce their reliance on critical elements (Tarascon & Armand, 2001).

### Consumer Perception and Behavioural Factors

The adoption of EVs depends on consumer behavior, which has been proven in various studies. Consumer adoption has been found to depend on perceived usefulness, perceived ease of use, social influence, technological trust, and perceived behavioral control.

The theory of planned behavior (TPB) proposes that consumers will be willing to use electric cars if they have positive attitudes towards EVs, have perceived high social pressure, and have sufficient resources to purchase and adopt them (Ajzen, 1991).

Technology acceptance model (TAM) is similar to TPB and indicates that consumers' perceived usefulness and ease of use are critical determinants of adoption of technologies, including EVs (Davis, 1989).

### System-Level Sustainability Challenges

The challenges of EV adoption difficulties range from system-level issues, such as supply of crucial materials, battery recycling, electricity-grid capacity, renewable energy integration, and regulatory policy continuity. The increased demand for lithium, cobalt, nickel, manganese and graphite may lead to concerns with the secure supply of the commodities and their environmental effects (IEA, 2024). Battery recycling and reuse is vital to the circular usage of materials (Gaines, 2014). At the same time, mass charging of the cars may impose a load on the power grid, whereas the electricity production from coal may reduce the positive impact of the cars' climatic impact during their life cycle (IPCC, 2023). These challenges could be addressed by solutions such as smart charging, vehicle-to-grid, renewable energy, grid modernization, and regulatory framework continuity (IEA, 2024). Thus, sustainable development of the field requires a mix of advancements in the automotive technology, material management, electricity production, infrastructure and legislation.

Table. 6 System-Level Sustainability Challenges of EV Adoption

| Challenge                       | Impact on EV Adoption                                                           | Key References                                |
|---------------------------------|---------------------------------------------------------------------------------|-----------------------------------------------|
| High purchase cost              | Reduces affordability and consumer willingness to purchase                      | Kumar & Alok (2020); Sierzchula et al. (2014) |
| Limited charging infrastructure | Increases range anxiety and limits long-distance travel                         | Rezvani et al. (2015); IEA (2024)             |
| Battery performance             | Concerns regarding driving range and battery degradation                        | Tarascon & Armand (2001); ICCT (2023)         |
| Critical raw material supply    | Affects battery cost and long-term production capacity                          | IEA (2024)                                    |
| Battery recycling               | Environmental and resource management challenges                                | Gaines (2014); Harper et al. (2019)           |
| Electricity grid capacity       | There is the need of investment in grid modernization and renewable integration | IPCC (2023); IEA (2024)                       |
| Awareness of Consumer           | This Influences the purchase intention and technology acceptance                | Rezvani et al. (2015)                         |
| Policy uncertainty              | Slows investment and market expansion                                           | IEA (2024)                                    |

Future Prospects And Emerging Technologies For Sustainable Electric Mobility

The development of electric mobility in the future will depend more on a combination of factors rather than one breakthrough. In other words, the future of electric mobility will be influenced by a number of technological advances in such areas as batteries, charging, power grids, digital control, recycling and policies. Therefore, the technologies described below are analyzed in the context of the problems they can solve and the new system conditions they create.

Advances in Battery Technology

Battery technology is a crucial aspect of the development of EVs, and most of them have lithium-ion batteries because they are known for their energy density, durability, and safety. Some new battery technologies that could prove better than lithium-ion batteries in terms of energy density and safety are solid-state batteries, although they still require more research to solve their manufacturing, cost, and safety issues (Janek & Zeier, 2023). Among other technologies are the lithium-sulfur, lithium-air, and sodium-ion batteries, the latter being very interesting because of its raw material.

### **Expansion of Charging Infrastructure**

To enable widespread use of EVs, sufficient charging station facilities are required. To expand access and reduce range anxiety, more public, private, home and fast charging stations are needed. Ultra-fast DC charging technology would significantly reduce charging time. With the wireless charging technology, the process would be much easier by the inductive power transmission (Bi et al., 2016). Artificial intelligence and IoT could further improve the efficiency of charging station management.

### **Integration with Renewable Energy**

The environmental impacts associated with the use of EVs depend largely on the type of electricity being used for charging them. Using EVs along with solar, wind and other renewable forms of energy can help in lowering the GHG emissions. V2G system makes it possible for the energy stored in the batteries of EVs to be transferred back to the grid (Xu et al., 2020; Falkoni et al., 2020; Taqvi et al., 2022; Mojumder et al., 2022).

### **Artificial Intelligence and Smart Mobility**

There are various ways through which AI can boost EV performance in the area of intelligent energy management, maintenance, monitoring of batteries, and route optimization (Cavus, M., et.al (2025)). AI techniques have been proven to be effective in predicting the state of charge (SOC), state of health (SOH), and the remaining life of batteries. Furthermore, AI can be used for selecting charging stations, managing traffic, and optimizing fleets.

### **Circular Economy and Battery Recycling**

Fast adoption of EVs will lead to the creation of significant amounts of used batteries, hence the need for proper recycling mechanisms in order to ensure sustainable development in the future. There are modern recycling technologies which can allow the recovery of such materials as lithium, cobalt, nickel, copper, and graphite that can be used in the manufacture of batteries (Harper et al., 2019).

### **Policy Priorities for Accelerating EV Adoption**

Electric cars need a well-coordinated policy framework, not one-off incentives. Some of the major areas that should be addressed are building the right infrastructure to charge the electric cars, affordability, supply chain for batteries, recycling, renewable energy production, standardization of technologies, and development and research. Consistent policy framework will eliminate uncertainty on the part of consumers, manufacturers, power companies, recyclers, and investors (IEA, 2024).

### **Future Research Directions**

Future EV research should be targeted at conditions that maximize environmental and economic benefits. Key priorities are to compare battery chemistries on cost, safety, durability, mineral use and recyclability; assess smart, fast and renewable charging and V2G impacts on electricity grids; and improve lifecycle analysis with realistic battery, electricity, recycling and usage data. Further research is also needed for developing countries, non-passenger vehicles, charging accessibility, policy, affordability and AI in improving battery life and system efficiency. Addressing these research priorities will accelerate the transition toward environmentally sustainable transportation while improving energy security and reducing greenhouse gas emissions.

### **Conclusions**

The review draws on environmental, technological, market, behavioral, infrastructural, and policy perspectives to assess electric vehicles in the context of sustainable transport-energy transitions. In the reviewed literature, BEVs invariably produce no direct tailpipe emissions, are less reliant on petroleum, and have significantly more efficient drivetrains than conventional ICEVs. The lifecycle results are typically positive, albeit the extent of improvement will depend on carbon intensity of the electricity used, battery size and chemistry, production conditions, vehicle longevity and utilization, and battery end-of-life handling.

However, fast uptake of EVs is not necessarily synonymous with maximal sustainability benefit. The cost, infrastructure of charging, policy, characteristics of the car, and perception of the consumers have an influence on market penetration rate. The problems of supply of minerals, environmental costs due to the process of producing batteries, the lack of infrastructure of the grid, and lack of capacity for battery recycling can add to environmental costs or new infrastructure problem. Such dynamics are especially crucial for developing countries, where car segments, infrastructure of electricity, purchasing capacity, and institutional capacity are different from developed EV markets.

The key finding of the review is that EV sustainability is a feature of the wider system in which vehicles operate, not an attribute of the vehicle itself. Efficient vehicles, low carbon electricity, accessible and well-managed charging infrastructure, responsible and diversified material sourcing, durable batteries, second life applications and effective recycling are linked to strongest sustainability outcomes. Smart charging and vehicle-to-grid integration can further support renewable-energy integration when coupled with electricity-grid planning.

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