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ARTICLE

Assessing Performance, Economic and Environmental Impact of EVs

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ABSTRACT

To date, the automotive industry remains the locomotive of the global economy, despite its diversity. Electric vehicle technology plays a vital role as its production and use increase in many cities around the world, which will undoubtedly impact human behavior in the future. Therefore, this work adopts an in-depth descriptive-comparative approach to evaluate and analyze a number of engineering, economic, and environmental factors to understand their advantages and disadvantages and predict their future impact on society. The research focused on environmental impact, specifically the differences in emissions, carbon footprint, and sustainability over the vehicle's lifecycle from production to disposal. Economic aspects were also examined, such as original purchase costs, maintenance, fuel and energy costs, and resale value. Performance and efficiency were evaluated in terms of range, battery life, efficiency, acceleration, and the overall driving experience. Furthermore, advances in battery management technology using artificial intelligence, charging infrastructure, and powertrain design were comprehensively explored. The findings emphasized the importance of sustainable reliance on clean energy compared to fossil fuels, given the potential and future prospects of renewable energy. This paper concludes

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by providing balanced recommendations to understand the current situation and anticipate new proposals for developing future automotive technology to improve the quality of life of passengers according to standardizations. Therefore, this paper will serve as a resource for stakeholders, including policymakers and researchers.
Keywords: Automotive; Electric Vehicle; Environmental Impact; Performance; Economic Aspects; Future Trained in Auto Industry

1. Introduction

The automotive industry is the locomotive of the global economy [1–3], whether it is traditional, as it progresses day after day, or hydrogen hybrid or electric vehicles (EVs). EVs are coming at an opportune time, particularly with regard to green innovation, the integration of artificial intelligence, smart infrastructure, and low-carbon transitions. This is to achieve strategies consistent with the Sustainable Development Goals (SDG). EVs represent a crucial transformation in the automotive industry, driven by the pressing need to solve environmental issues, improve energy security, and reduce reliance on fossil fuel. Over the last decade, technical breakthroughs and supporting regulations have expedited the adoption of electric vehicles, establishing them as a cornerstone of sustainable mobility. The beginnings of electric cars may be traced back to the early 19th century, when innovators began experimenting with electric propulsion technologies. In the 1820s, Robert Anderson created the first primitive electric carriage powered by non-rechargeable primary cells [4]. However, it wasn't until the late 20th and early 21st centuries that EVs became viable alternatives to internal combustion engine vehicles (ICEVs), mainly to advancements in battery technology and power electronics [5]. The development of lithium-ion batteries, in particular, has been critical, providing higher energy density, a longer lifespan, and faster charging capabilities than previous battery types [6]. In addition to technology advancements, government regulations and incentives have played an important role in encouraging EV adoption. Tax subsidies, rebates, and investments in charging infrastructure have reduced restrictions on entry for both consumers and producers [7]. For example, the California Air Resources Board's (CARB) Zero Emission Vehicle (ZEV) regulation, implemented in the 1990s, has played an important role in encouraging automakers to develop and sell EVs.

Advancements in battery technology have been the backbone of the modern EV movement. Lithium-ion batteries, which have become the industry standard, provide significant benefits over other battery technologies. They have a higher energy density, allowing for longer vehicle range, and can be recharged more quickly. Furthermore, the cost of lithium-ion batteries has been falling, making EVs more accessible to the typical user [8]. Solid-state batteries, which promise even better energy densities and more safety, are now being developed and might further revolutionize the EV industry in the future years [9]. Electric motors, a vital part of EVs, have also seen substantial advances. Permanent magnet synchronous motors (PMSMs) are popular because of their excellent efficiency and power density [10]. Tesla popularized induction motors, which are strong and cost-effective, but somewhat less efficient than PMSMs [11]. The development of improved power electronics has enabled greater control and efficiency of these motors, hence improving EV performance [12].

Many nations have enacted a variety of policies to stimulate the adoption of EVs, including tax credits, rebates, and subsidies for both users and manufacturers. For example, in the United States, the federal government provides tax credits for the purchase of EVs, and numerous states offer extra incentives [4]. In Europe, nations such as Norway have achieved high EV adoption rates using a mix of incentives such as tax breaks, free parking, and access to bus lanes [13].

The environmental benefits of electric vehicles are enormous. Unlike conventional cars, which generate greenhouse gases and pollutants while driving, EVs create no exhaust emissions. This transition not only contributes to limiting climate change, but it also improves urban air quality, lowering the health risks associated with pollution [14]. Furthermore, as the electrical grid is increasingly supplied by renewable energy sources, EVs' lifecycle carbon footprint is predicted to fall even further [15]. Countries with a high proportion of renewable energy in their electrical mix, such as Iceland and Norway, have the potential to achieve almost zero lifecycle emissions for EVs[15]. However, in areas where coal and other fossil fuels dominate the electrical mix, EVs' environmental advantages may be severely diminished. As a result, shifting to a cleaner energy infrastructure is critical for maximizing the potential of EVs as a sustainable transportation option[16].

Despite these benefits, wide adoption of electric cars faces several difficulties. The availability of charging infrastructure, battery recycling and disposal, and the initial purchase cost remain significant barriers. Furthermore, battery manufacture, namely the mining of raw materials such as lithium, cobalt, and nickel, creates environmental and ethical problems that must be addressed in order for EVs to be sustainable[17]. Charging infrastructure continues to be a major barrier to the widespread adoption of EVs. While fast-charging networks are increasing, they are still not ubiquitous, and potential EV purchasers continue to be concerned about range anxiety[18]. Furthermore, the initial purchase cost of EVs is often greater than that of similar ICEVs; however, this difference is diminishing as battery costs fall[8]. Battery recycling and disposal are both essential challenges. The growing number of EVs on the road will ultimately generate substantial amounts of battery trash, which must be managed responsibly. Developing effective recycling procedures and guaranteeing ethical raw material procurement are critical for reducing the environmental impact of electric vehicle batteries[19].

Therefore, it is clear that there is still a general trend and strong demand for further understanding and interpretation of the performance of electric vehicles and their economic and environmental impact, especially to clarify the vision for decision makers as well as to increase the understanding of researchers, target customers and society, especially as their production density increases and their widespread use begins. On the other hand, the phenomenon of global warming that affected us all this summer is a strange phenomenon that should indicate the need to reduce exhaust emissions.

This work provides an overview of performance, economic, and environmental impact of electric vehicles. Section 2 highlights the environmental impact of electric vehicles. Section 3 indicates the performance metrics of electric vehicles. Section 4 highlights the innovations in electric vehicles technology. Section 5 presents modern technology using AI in electric vehicles development. The study analysis is presented in section 6. Conclusions are presented at the end of the paper in Section 7.

2. Comprehensive Environmental Impact

In 2022, the European Commission considered reducing new car emissions by 65% by 2023, aiming to achieve carbon neutrality by 2050. Accordingly, the European Parliament approved a number of environmental rules and legislation, the most important of which are: 2035 is the time limit for the transition and imposing a comprehensive ban on the sale of cars and small trucks with internal combustion engines, meaning the end of the era of passenger cars with internal combustion engines!

The environmental benefits of electric vehicles (EVs) over conventional internal combustion engine (ICEs) vehicles have drawn a lot of attention. They pledge to lessen the negative consequences of climate change, enhance air quality, and cut greenhouse gas emissions. But because EVs have an environmental impact throughout their whole lifecycle from production to disposal a detailed analysis is required to determine their genuine sustainability.

The zero tailpipe emissions of EVs are among its most well-known environmental advantages in operation. During operation, EVs do not release pollutants, such as carbon dioxide (CO_2), nitrogen oxides (NOx), or particulate matter (PM), like ICEVs do. Air quality has improved, particularly in metropolitan areas, as a result of this notable decrease in local air pollutants[14]. In addition, EVs' regenerative braking systems increase energy efficiency by repurposing energy that would otherwise be wasted[11].

EVs have no tailpipe emissions, but how much of an environmental impact they have is determined by the carbon intensity in production and the power needed to charge them. The advantages of EVs may be lessened in areas where the electrical system is mostly dependent on fossil fuels. But the carbon footprint of EVs reduces significantly when renewable energy sources like hydropower, solar, and wind power become more and more integrated into the system[15]. Studies have revealed that EVs often have fewer lifespan emissions than ICE vehicles, even when charging from a grid that is dominated by coal. The benefit is amplified when using greener energy blends. For example, EVs lifecycle emissions are substantially lower than ICEs car lifespan emissions in Norway, where hydropower is the primary energy source[15].

The energy-intensive and heavily polluting aspect of the production process for EVs is the manufacturing of the batteries. The processing and extraction of raw minerals such as nickel, cobalt, and lithium add to the environmental impact. But over time, it's anticipated that improvements in battery science and production efficiency will lower these emissions[20]. The extraction of raw materials is where EVs' environmental effect starts. Mining operations for metals needed in batteries, like as cobalt and lithium, have the potential to seriously damage the environment and pollute it. Furthermore, producing batteries requires a significant amount of energy, which frequently results in greater emissions than when making ICE vehicles[21]. Improvements to recycling procedures and the development of more environmentally friendly battery technology are under progress. According to Janek and Zeier[9], solid-state batteries are a promising innovation that has the potential to lessen the environmental effect of battery manufacture. They have better energy densities and utilize fewer toxic elements. The environmental effect of ICEVs is measured by carbon footprint. The CO_2 emission from ICEVs per year is calculated by:

$$\begin{aligned}\text{Total Fuel Consumption } &= \\ (\text{Number of Cars})&(\text{Average Mileage}) \\ &\left(\frac{\text{Average Fuel Consumption}}{100}\right)\end{aligned} \tag{1}$$

$$\begin{aligned}\text{Total } CO_2 \text{ Emissions } &= \text{Total Fuel Consumption} \\ &\times \text{Carbon Intensity of Fuel}\end{aligned} \tag{2}$$

According to International Organization of Motor Vehicle Manufacturers (OICA) provides annual statistics on the global vehicle population, U.S. Department of Energy (DOE) and Environmental Protection Agency (EPA): provides data on the average fuel efficiency of vehicles in the U.S., which can be indicative of global trends and Intergovernmental Panel on Climate Change (IPCC) provides guidelines on greenhouse gas inventory and carbon intensity factors. **Table 1** indicates the total CO_2 emissions form IC cars at last decade.

Table 1. Total CO_2 Emissions form ICEVs at Last Decade.

Year	**Number of ICEVs (billion)**	**Average Fuel Efficiency (L/100 km)**	**Average Millage (km/year)**	**Total CO_2 Emissions (million metric Ton)**
2014	1.20	8	15,000	3,326.4
2015	1.25	8	15,000	3,4650
2016	1.30	8	15,000	3,603.6
2017	1.35	8	15,000	3,742.2
2018	1.40	8	15,000	3,880.8
2019	1.45	8	15,000	4,019.4
2020	1.5	8	15,000	4,1580
2021	1.55	8	15,000	4,296.6
2022	1.6	8	15,000	4,435.2
2023	1.65	8	15,000	4,573.8
Total				39,5000

The environmental effect of EV cars is measured by carbon footprint in electricity generation. The CO_2 emission from EV cars per year is calculated by:

$$\begin{aligned}\text{Total Energy Consumption } &= \text{ Number of EVs} \\ &\times \text{Average Mileage} \times \\ &\text{Average Energy Consumption}\end{aligned} \tag{3}$$

$$\begin{aligned}&\text{Total } CO_2 \text{ Emissions} = \\ &\text{Total Energy Consumption} \times \\ &\text{Carbon Intensity of Electricity}\end{aligned} \tag{4}$$

According to International Energy Agency (IEA): Global EV Outlook reports, U.S. Department of Energy (DOE): Fuel Economy data for electric vehicles and International Energy Agency (IEA): Global data on electricity generation and CO_2 emissions. **Table 2** indicates the total CO_2 emissions form EV cars electricity generation at last decade.

But, one of the world's leading automotive companies has announced that the carbon footprint of electric vehicles upon production is three times that of hybrid vehicles[22]. The extraction and processing of raw materials, particularly metals and rare earths (lithium, cobalt, nickel, and manganese for batteries), contributes up to 45% of the total global warming rate. All of this is undoubtedly a significant indicator that must be carefully considered and investigated with absolute integrity for the sake of humanity and future generations.

Table 2. Total CO_2 Emissions form EVs Electricity Generation at Last Decade.

Year	Number of EVs (million)	Average Energy Consumption (kWh/100 km)	Average Millage (km/year)	Total CO_2 Emissions (thousand metric tons CO_2)
2014	0.5	20	15,000	750
2015	1.0	20	15,000	1,500
2016	2.0	20	15,000	3,000
2017	3.5	20	15,000	5,250
2018	5.0	20	15,000	7,500
2019	7.5	20	15,000	11,250
2020	10.0	20	15,000	15,000
2021	15.0	20	15,000	22,500
2022	20.0	20	15,000	30,000
2023	25.0	20	15,000	37,500
Total				134,250

There are potential and problems at the end-of-life period of electric vehicles. No new raw material extraction is required because batteries include valuable components that may be recycled. But present rates of recycling lithium-ion batteries are rather low, and improper management of the processes can have negative environmental effects [19]. It's critical to create recycling techniques that are both effective and sustainable. The reduction of the environmental effect of EVs) at the end of their lifespan will be largely dependent on laws and policies that support battery recycling and the safe disposal of components. Standards roles pertaining to battery recycling are in place to guarantee efficiency, safety, and environmental preservation. The following are some essential guidelines and procedures:

1. **International Standards**
    - ISO 14001: Environmental management systems, applicable to organizations involved in battery recycling.
    - ISO 45001: Occupational health and safety management systems, relevant for recycling facilities to ensure safe handling and processing of batteries.
2. **European Standards:**
    - Directive 2006/66/EC (Battery Directive): Regulates the collection, recycling, and disposal of batteries in the EU, aiming to reduce the environmental impact of batteries.
    - EN 50625-2-1: Collection, logistics & treatment requirements for waste batteries and accumulators.
3. **North American Standards:**
    - R2 (Responsible Recycling) Standard: Provides a framework for responsible recycling of electronics, including batteries, with a focus on environmental and worker safety.
    - e-Stewards Standard: Certifies electronics recyclers, including battery recyclers, who adhere to strict environmental and social standards.
    - EPA Regulations: The U.S. Environmental Protection Agency (EPA) has various regulations under the Resource Conservation and Recovery Act (RCRA) for managing hazardous waste, including certain types of batteries.
4. **Safety Standards:**
    - UL 1974: Evaluates the process for sorting and grading battery packs, modules, and cells for reuse, repurposing, and recycling.
    - IEC 62133: Specifies safety requirements for portable sealed secondary cells and batteries.

According to the previous standards the best procedure to deal with waste batteries are Battery Identification and Sorting: To guarantee proper recycling procedures, batteries should be properly identified and sorted by type (e.g., lead-acid, lithium-ion, nickel-cadmium), Ensuring the safe transportation of batteries, particularly those categorized as hazardous goods, requires adherence to rules, Respecting local, national, and international environmental laws and norms is known as environmental compliance and Ensuring that personnel who handle batteries receive training on appropriate handling, processing, and storage techniques is known as worker safety training.

Even after taking into consideration the emissions from the production of electricity, EVs still emit fewer greenhouse gases than equivalent gasoline-powered cars, according to 2015 research by the Union of Concerned Scientists. There will be noticeable health advantages from this reduction in emissions, such as a decline in the prevalence of lung illness, asthma, and other respiratory disorders. There are immediate health advantages from the decrease in air pollution brought about by the use of EVs. Because ICEVs emissions are connected to respiratory and cardiovascular ailments, improved air quality lowers their prevalence. Widespread EV adoption might avert thousands of preventable lives each year in the United States alone, according to a study published in the journal Environmental Research Letters. EVs contribute to less noise pollution because they are typically quieter than ICE cars. In metropolitan areas, where traffic noise is a major issue, this reduction in noise might enhance the quality of life. Nonetheless, to preserve road safety, it's critical to make sure EVs are still audible to cyclists and pedestrians [23].

Reducing the environmental effect of EV when electric vehicles are combined with renewable energy sources, their environmental advantages are enhanced. EVs will be more sustainable if policies support the development of smart grid technology and renewable energy infrastructure. The efficiency and stability of renewable energy systems can be further enhanced by vehicle-to-grid (V2G) technology, which enable electric vehicles to return energy to the grid, ongoing research and development in battery technology. Solid-state batteries have the potential to drastically lower the environmental impact of battery manufacture and disposal due to their safer chemistries and greater energy densities and Effective recycling techniques may recover valuable resources and lessen the demand for extracting new raw material, to avoiding the ethical and environmental concerns associated with cobalt and lithium mining. It will be essential to implement policies that encourage recycling and to create more effective recycling technology. This is without neglecting the need for strict standards to be set by relevant international organizations to achieve strategies consistent with the SDG.

3. Technical Performance Metrics

The promise of electric vehicles to lower greenhouse gas emissions and rely less on fossil fuels has drawn a lot of interest as a sustainable alternative to internal combustion engine (ICE) cars. As technology develops, it is critical to evaluate EVs' technical performance indicators in comparison to ICE cars in order to provide customers, legislators, and industry stakeholders with relevant information. The performance characteristics of EVs and ICEVs are compared in this article with an emphasis on factors including efficiency, acceleration, range, and total cost of ownership. **Figures 1** and **2** depict the key parts of both EVs and ICEVs. Because the input power of the two vehicles is different, the performance criteria used are also different.

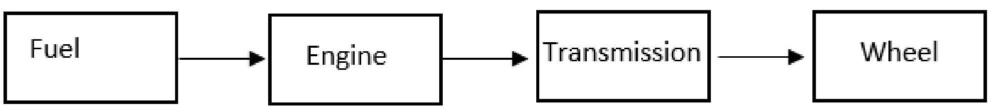

Figure 1. Main Technical Components of the ICEVs.

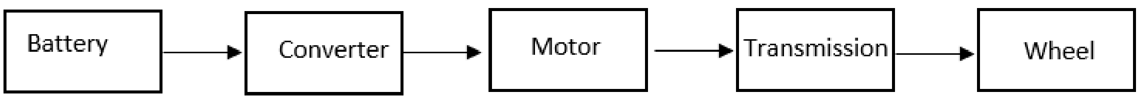

Figure 2. Main Technical Components of the EVs.

In ICE vehicles the necessary power is produced by fuel combustion and delivered to the drive system through coupling and transmission mechanisms. The majority of losses in an ICEV are caused via transmission and heat. An internal combustion engine vehicle can only have a fuel conversion efficiency of 25%[24]. In EV through the power converter, the battery provides the motor with the controlled power it needs. Electric vehicle power converters are more efficient. Quantity of mechanical and combustion components used in the process of power conversion from the electric vehicle's wheels are reduced, which intend reduces significant mechanical losses in comparison to ICE.

EVs provide maximum torque instantly at 0 RPM, enhancing initial performance, while ICEVs reach maximum torque at higher RPMs, which can reduce overall efficiency[25]. EVs exhibit lower maintenance requirements than ICEVs due to their simpler mechanical structure, which includes fewer moving parts and eliminates the need for oil changes. Additionally, EVs experience less mechanical wear on components such as brakes. Conversely, ICEVs necessitate regular maintenance for complex systems, including engines, transmissions, and exhausts, leading to increased long-term costs. Although the initial cost of EVs is higher, their reduced maintenance demands can result in cost advantages over time. In various driving conditions, electric vehicles (EVs) generally surpass ICEVs due to their ability to deliver instant torque at 0 RPM, resulting in faster acceleration and enhanced responsiveness, particularly in stop-and-go traffic. EVs perform exceptionally well in urban settings where frequent acceleration is necessary, whereas ICEVs may be less efficient and effective due to their dependence on higher RPMs for optimal torque. However, ICEVs often have an advantage in long-distance highway driving, where their extended fuel range and rapid refueling capabilities can outperform the current limitations of EVs charging infrastructure. When choosing between an electric vehicle (EV) and a traditional gasoline vehicle (ICEV), it's important to weigh several key factors. Consider the cost, including the initial purchase price, maintenance, and fuel savings, as EVs typically have higher upfront costs but lower long-term expenses. Assess the driving range and availability of charging infrastructure, particularly if you frequently take long trips. Finally, think about your performance needs; EVs offer instant torque and excel in urban driving, while ICEVs may be more advantageous for long-distance highway travel due to their extended range and quick refueling. For the most part, the ranges of gasoline-powered vehicles and electric vehicles are similar. For example, high-end EVs can go up to 300 miles between charges, whereas gasoline-powered vehicles can go up to 400 miles between tanks. Both vehicle types' ranges are impacted by variables like weather, driving style, and auxiliary system usage. The ability to refill quickly and easily is a benefit of gasoline cars, which facilitates long distance travel. Although improvements in battery technology are expected to increase EVs' range and charging efficiency, EVs still face obstacles in the form of infrastructure and charging periods. Nevertheless, these factors might eventually close the gap with gasoline-powered cars[26]. **Table 3** shows the main different between the EV and ICEV in performance metrics[7, 8].

Table 3. The Performance Metrics of EVs Verses ICEVs[7, 8].

Vehicle Type / Metric	EVs[7]	ICEVs[8]
Range	150–400 miles per charge depending on model	300–400 miles per tank depending on model
Charging/Refueling Time	Typically 30 minutes for fast charging to 80%	About 5 minutes for a full tank
Energy Efficiency	3.0–4.0 miles per kWh	20–30 miles per gallon
Performance	Instant torque, smooth acceleration	Torque build-up, generally less smooth acceleration
Operational Cost	Lower cost per mile, but higher initial purchase price	Higher cost per mile, lower initial purchase price
Maintenance	Fewer moving parts, generally lower maintenance costs	More moving parts, higher maintenance requirements
Battery/Engine Life	Battery degradation over time, typically 8–10 years	Engine lifespan is variable, often 10–15 years

4. Innovations in Electric Vehicles Technology

The latest developments in electric passenger car technology are examined in this section, with particular attention paid to battery technology, electric drivetrains, charging infrastructure, and vehicle-to-grid (V2G) integration. These developments help achieve the more general objectives of sustainability and less environmental effect in addition to enhancing the efficiency, performance, and range of electric cars.

The performance of electric vehicles is mostly driven by battery technology. Energy density, cost reduction, and battery chemistry have all advanced significantly in recent years. While lithium-ion batteries continue to be the industry standard, recent advancements in solid-state battery technology provide increased safety, quicker charging times, and better energy density. The time needed to fully charge an electric vehicle's battery is called its charging time. The level 1, level 2, or DC fast charging of the charger and the battery capacity of the car affect how long a charge takes. According to U.S. Department of Energy, charging systems can be classified into three categories:

- Level 1 (120V): Adds about 4–5 miles of range per hour.
- Level 2 (240V): Adds about 25–30 miles of range per hour.
- DC Fast Charging: Adds about 60–100 miles of range in 20–30 minutes.

Several innovative technologies and techniques are needed to fast-charge EVs. By supplying a direct current (DC) to the EV battery instead of using the onboard charger of the car, high-power DC fast charging systems enable significantly quicker charging rates. Electromagnetic fields are used in wireless inductive charging to transmit energy between a receiver on the car and a charging pad on the ground. This approach may accelerate the charging procedure and does away with the requirement for physical connections. EVs battery technologies have advanced dramatically over the years. Lead-acid batteries ($Pb\text{-}PbO_2$) are the first rechargeable batteries, but their low specific energy and energy density are their main drawbacks. Because of worries about the memory effect and environmental impact, nickel-metal hydride (Ni-MH) batteries have mostly replaced nickel-cadmium (Ni-Cd) batteries, which were popular in the 1990s due to their higher energy density. The market for EVs is now dominated by lithium-ion batteries, which function well even at low temperatures but are prone to self-discharge in really cold weather. The high energy density and efficiency of advanced technologies such as sodium-sulfur (Na-S) and sodium-nickel chloride (Na-NiCl) batteries in high-temperature applications are being investigated. In the meanwhile, cutting-edge battery technologies including magnesium-ion batteries, lithium-air, lithium-metal, and lithium iron phosphate are under research to enhance energy density, durability, and charging times, promising further improvements in EV performance [27]. **Table 4** shows the comparison between the types of batteries used in electric vehicles (EVs) based on energy density and range, charging speed and infrastructure, sustainability and resource availability, battery lifespan and degradation, and cost reduction.

Table 4. The Comparison between the Batteries Used in EVs.

Battery Type	Energy Density & Range	Charging Speed & Infrastructure	Sustainability & Resource Availability	Battery Lifespan & Degradation	Cost Reduction
Lead-Acid ($Pb\text{-}PbO_2$)	Low energy density (30–50 Wh/kg); Limited range; Primarily used for auxiliary power.	Slow charging; Limited infrastructure due to declining use in EVs.	Relatively abundant materials, but recycling is critical due to environmental concerns.	Short lifespan with significant degradation over time; Typically 3–5 years.	Low cost, but heavy and bulky, making them impractical for modern EVs.
Nickel-Cadmium (Ni-Cd)	Moderate energy density (45–80 Wh/kg); Once used in early EVs, but limited range.	Moderate charging speed; Limited use in current EV infrastructure.	Environmental concerns due to cadmium toxicity; Recycling is important, but usage is declining.	Moderate lifespan; Suffers from memory effect, leading to reduced capacity over time.	Higher cost than lead-acid; Being phased out due to environmental and performance concerns.
Nickel-Metal Hydride (Ni-MH)	Moderate energy density (60–120 Wh/kg); Better range than Ni-Cd; Used in hybrid vehicles.	Moderate charging speed; Common in hybrid vehicles, but less so in full EVs.	More sustainable than Ni-Cd, but less energy dense than lithium-based batteries; Recyclable.	Better lifespan than Ni-Cd, but still suffers from degradation, especially under high loads.	Moderate cost; More expensive than lead-acid, but cheaper than lithium-ion.
Lithium-Ion (Li-Ion)	High energy density (150–250 Wh/kg); Dominant in modern EVs; Enables ranges of 150–400 miles.	Fast charging supported by widespread infrastructure; Charging speed decreases with battery aging.	Concerns over the sustainability of lithium and cobalt; Recycling is challenging but improving.	Good lifespan (8–10 years), but affected by fast charging and extreme temperatures; Gradual degradation.	Costs have dropped significantly, but still relatively high; Economies of scale and research are driving further reductions.

Table 4. *Cont.*

Battery Type	Energy Density & Range	Charging Speed & Infrastructure	Sustainability & Resource Availability	Battery Lifespan & Degradation	Cost Reduction
Sodium-Sulfur (Na-S) & Sodium-Nickel Chloride (Na-NiCl)	Very high energy density (150–240 Wh/kg); Suitable for high-temperature applications.	Requires high-temperature operation, which limits infrastructure compatibility; Slow initial adoption.	Better sustainability due to the use of more abundant materials; Still niche in market.	Long lifespan due to stable chemistry; Degradation mainly due to thermal cycling.	Costs are relatively high due to complex manufacturing; Potential for reduction with technological advancements.
Solid-State (Emerging)	Potentially very high energy density (300+ Wh/kg); Promises extended range.	Promises faster charging, but infrastructure adaptation is required; Still in early development.	Potentially more sustainable with safer materials; Avoids some issues of lithium-ion batteries.	Expected to have a longer lifespan with reduced degradation; Yet to be fully commercialized.	Currently very high cost due to limited production; Significant cost reduction expected with future commercialization and mass production.
Lithium-Iron Phosphate (LiFePO4)	Moderate energy density (90–160 Wh/kg); Lower range compared to other Li-ion batteries.	Similar charging speed to Li-ion; Compatible with existing infrastructure.	More sustainable and safer due to iron and phosphate materials; Less resource-intensive.	Longer lifespan and better thermal stability; Lower degradation compared to other Li-ion chemistries.	Lower cost than traditional Li-ion batteries; Becoming more popular for budget-conscious EVs and large-scale applications (e.g., buses, trucks).

Every battery type has advantages and disadvantages according to various criteria. Solid-state batteries, an emerging technology, promise major increases in energy density, longevity, and safety. Currently, lithium-ion batteries dominate the market due to their high energy density and relatively excellent balance of other aspects. For these more recent technologies, cost containment and infrastructure adaption continue to be major obstacles. This fascinating and quickly developing topic of sustainability is being driven by worries about resource availability and environmental effect, as well as research into improved recycling technologies and alternative materials [28].

Continuous advancements in electric drivetrain technology have a major impact on the shift to EVs. The electric drivetrain, which consists of the electric motor, power electronics, transmission, and control systems that work together to transform electrical energy into mechanical motion, is a crucial part of this revolution. Electric drivetrains have distinct benefits including rapid torque and regenerative braking, and they are easier to use and more economical than ICEVs drivetrains, which depend on intricate mechanical components. The EV drivetrain's electric motors are its core component, and recent developments have greatly increased both its output and efficiency. This is because of their great performance at different speeds, high efficiency, and power density.

The DC brushed, DC brushless, Induction (Asynchronous), Synchronous, and Switched Reluctance motors are among the motors that are commonly utilized by electric car makers.

The selection of an appropriate motor depends on key parameters such as the power-to-weight ratio, torque-speed characteristics, and overall efficiency.

A DC brush motor is a type of electric motor that runs by passing current through brushes to the motor windings in order to create rotational motion. A DC brush motor's main parts are the rotor (armature), stator, brushes, and commutator. These parts work together to produce a magnetic field that propels the rotor. This particular motor type is well-known for its easy speed regulation, high starting torque, and straightforward control, which makes it perfect for a variety of uses including power tools, toys, and small domestic appliances.

Due to brush wear and tear, DC brush motors require routine maintenance to avoid higher operating costs and periodic replacement of the brushes. These motors are often less efficient than their brushless counterparts in terms of efficiency because friction and heat produced by the brushes cause energy losses. DC brush motors can also spark and create electrical noise at the brushes, which lowers dependability and may cause interference with neighboring delicate electronic equipment. These elements are crucial to take into account when assessing the overall effectiveness and appropriateness of DC brush motors for certain applications.

An electric motor that runs on direct current (DC) without the use of brushes is known as a DC brushless motor since it uses electronic controllers to manage its operation. The motor is made up of a stator with windings and a rotor with permanent magnets. To produce rotational motion, the electronic controller precisely sequences the supply of current to the windings in the stator. Higher efficiency, less maintenance because there are no brushes, quieter operation, and a longer lifespan are just a few benefits of this design. DC brushless motors are especially well-suited for applications like computer cooling fans, drones, and electric cars because of these advantages. Despite the many benefits that DC brushless motors provide, their cost is often higher than that of brushed motors because of the intricacy of their electronic controllers and the extra parts needed to make them function. Sophisticated electronics and control systems are also required because to the increasing complexity, which can make design and integration into different applications more difficult. Furthermore, the performance and dependability of DC brushless motors can be affected by environmental factors like humidity and temperature, which they are more susceptible to. When choosing DC brushless motors for particular applications, these variables especially need to be carefully taken into account, especially in severe settings.

An electric motor that runs on alternating current (AC) and produces torque via the electromagnetic induction principle is called an induction motor, often referred to as an asynchronous motor. The motor is made up of a rotor that rotates because it is induced by a revolving magnetic field created by the windings in the stator. Because of their reputation for durability, ease of maintenance, and straightforward design, induction motors are widely used in industrial settings as well as in fans, pumps, and other machinery. When working with large loads, induction motors may require the usage of extra starting mechanisms due to their generally lower starting torque. They can use more energy since they are often less efficient than synchronous motors in terms of efficiency, especially at lower speeds. Furthermore, induction motors are less appropriate for applications requiring precise speed regulation due to their limited ability to adjust speed without the need for extra equipment. When choosing an induction motor for a particular application, several aspects should be taken into account.

Synchronous motors are AC motors that run at a steady pace in sync with the supply current's frequency. This means that the rotor and stator revolve in perfect unison, producing a revolving magnetic field. The motor consists of an electromagnet (which needs an external power source for excitation) or a permanent magnet (which has windings in its stator). Synchronous motors are perfect for applications like power factor correction, big industrial drives, and synchronous condensers because of their excellent efficiency, accurate speed control, and capacity to work at leading power factors. The additional parts required for rotor excitation in synchronous motors can complicate the design and raise the total cost of the system, making them more complicated. They also cannot start when under load, thus an additional motor or independent starting mechanism is needed to get the rotor up to synchronous speed. In addition, the need for excitation systems and more complex control mechanisms makes synchronous motors often more costly than induction motors. When determining whether synchronous motors are appropriate for a certain application, several variables should be taken into account.

A switched reluctance motor (SRM) is an electric motor that runs on the reluctance torque concept, in which the rotor turns to lower the reluctance of the magnetic circuit. The motor is mechanically strong since it has a basic stator and rotor with prominent poles and doesn't need any permanent magnets or rotor windings. SRMs are especially well-suited for use in electric cars, industrial motors, and robots because of their great efficiency, simple design, and exceptional performance at high speeds. Significant torque ripple is a common occurrence for switched reluctance motors (SRMs), which can cause noise and vibrations while operating and could affect performance in precision applications. Furthermore, the management of phase switching by SRMs requires complicated control algorithms and electrical drive systems, adding to the entire system's complexity. SRMs work better at high speeds than other motor types, although they could be less effective at low speeds and beginning torque. When determining if SRMs are appropriate for a certain application, these variables need to be taken into account[29]. **Table 5** shows the summarizing of power-to-weight ratio, torque-speed characteristics, and overall efficiency of various motor types.

Table 5. Comparative Analysis of Motor Types: Power-to-Weight Ratio, Torque-Speed Characteristics, and Overall Efficiency.

Motor Type	Power-to-Weight Ratio	Torque-Speed Characteristics	Overall Efficiency
Brushed DC Motor	Moderate	Good starting torque, variable speed control	Generally lower (due to friction and heat)
Brushless DC Motor	High	Excellent torque control, high speed performance	High (due to reduced friction and heat loss)
Induction Motor	Moderate	Good controllability, variable torque at different speeds	Moderate (less efficient at low speeds)
Synchronous Motor	High	Constant speed, precise control	High (operates at leading power factor)
Switched Reluctance Motor	Moderate	High performance at high speeds, torque ripple at low speeds	High (efficient at high speeds, but variable)

In EVs, BLDC motors and PMSMs are favored because of their increased efficiency, improved torque control, and smoother operation. Additionally, induction motors are employed, especially where affordability and durability are important factors. The vehicle's budgetary limits and unique performance needs are taken into consideration while choosing a motor type.

5. Modern Technology in EVs Using AI

The automotive industry is undergoing a change thanks to artificial intelligence (AI), especially in the realm of electric passenger cars (EPCs). The application of AI technology to improve the efficiency, security, and user experience of EPCs is examined in this article. The influence of recent developments in AI on EVs is the main topic of discussion. These developments include machine learning, computer vision, and autonomous driving systems. The automobile industry has seen a substantial transformation with the incorporation of AI technology in electric passenger vehicles, mostly due to the need for safer, more intelligent, and more efficient transportation options. AI improves the capabilities of EPCs in a number of areas, including advanced driver assistance systems (ADAS) and autonomous driving, as well as battery management optimization.

5.1. AI Battery Management System

In order to guarantee battery performance and safety in electric cars, the Battery Management System (BMS) is essential. It keeps an eye on important variables including temperature, voltage, current, and state of charge (SoC) to guard against problems like deep discharge, overcharging, and overheating. These variables can be tracked in real time by current BMS systems thanks to sophisticated sensors and algorithms. In addition, the BMS defends the battery by putting safety measures in place to prevent overvoltage, under voltage, overcurrent, and thermal runaway. In the event that dangerous conditions are detected, the BMS has the ability to separate the battery from the load or charger. Additionally, the BMS evaluates the battery's State of Health (SoH), directing decisions about maintenance and replacement by forecasting deterioration and remaining usable life through analysis of past data and present performance. It controls the battery pack's cell balancing to maintain consistent voltage across all of the cells and avoid any of them from being overcharged or over drained, which might otherwise compromise performance and safety [30].

Constant current charging (CCC) and constant voltage charging (CVC) are the two main approaches used in traditional battery charging procedures. While it may seem simple, CCC entails charging the battery continuously, which increases the danger of overcharging and can reduce battery life if the current is not appropriately controlled. On the other hand, CVC lowers the danger of overcharging by applying a set voltage to the battery and allowing the current to progressively drop when the battery approaches full charge. While sophisticated algorithms have been created to improve charging efficiency and overcome some of these techniques' drawbacks, they can also add complexity, increase the danger of battery deterioration, and cause other long-term problems. These advancements are meant to strike a balance between longer-term battery health maintenance and enhanced performance. Through the analysis of variables such vehicle state of charge, journey distance, future pricing signals, and charging station availability, artificial intelligence (AI) smart charging systems use sophisticated algorithms to optimize charging times. Batteries are kept longer by using models of reinforcement learning and deep learning to improve charging efficiency, cut cycle times, and save driving expenses. Real-time monitoring and control are also made possible by these AI-driven methods, which facilitate better energy management and improve the integration of electric cars into smart energy networks [31].

Algorithms for machine learning are used to evaluate large-scale information and find patterns that inform decision-making, especially when it comes to electric car charging plans. These algorithms improve efficiency and convenience for drivers by predicting the best times to recharge based on factors like energy pricing, grid load, and user behavior. Furthermore, they have the ability to adjust to shifting circumstances, continually improving their efficacy and accuracy to offer suggestions that are more accurate over time. Electric vehicle (EV) charging behavior is predicted using machine learning models, which use a variety of techniques to improve efficiency and decision-making. Regression approaches (e.g., XGBoost, Linear Regression) and supervised learning models are used to predict departure times and energy usage. Decision trees (DT), Random Forest (RF), and Support Vector Regression (SVR) can help to make a variety of forecasts about charging needs. Gaussian Mixture Models (GMM) as an example of an unsupervised learning model that clusters charging activities to find unique patterns and improve charging infrastructure. Recurrent neural networks (RNN), long short-term memory (LSTM) networks, and convolutional neural networks (CNN) are examples of deep learning models that are used for advanced charging load forecasting and charging profile classification. These models handle complex and sequential data to improve operational efficiency and predictive accuracy [32]. **Table 6** indicates AI techniques using in Battery Management Systems (BMS) for EVs, along with recent references [33–36].

Table 6. Comparison of AI Tech in Battery Management Systems for EVs [33–36].

AI Technique	Key Features	Advantages	Challenges
Machine Learning (ML)	Utilizes algorithms to analyze historical data and predict battery health.	Improves predictive maintenance and efficiency; adapts to changing conditions.	Requires large datasets and may face issues with data quality and integration [33].
Deep Learning (DL)	Employs neural networks to extract features and predict battery performance.	Provides high accuracy in pattern recognition and prediction; handles complex data.	Computationally intensive; may require extensive training data [34, 35].
Reinforcement Learning (RL)	Uses algorithms that learn optimal charging strategies through trial and error.	Optimizes battery usage and charging efficiency over time.	Requires extensive training; may not perform well in all scenarios [36].

5.2. Advanced Driver Assistance Systems (ADAS)

Smart EVs are not complete without Advanced Driving Assistance Systems (ADAS). These devices use a variety of sensors, cameras, radar, and artificial intelligence (AI) algorithms to keep an eye on the environment around the car, identify any threats, and help the driver make judgments. The goal of advanced driver assistance systems (ADAS) such automated emergency braking, adaptive cruise control, and lane-keeping assistance is to increase road safety by lowering the risk of collisions.

Sensor fusion's is significance for smart electric vehicles. The process of creating a thorough picture of the vehicle's environment through sensor fusion entails integrating data from many sensors. The system may overcome the limits of individual sensors and give more precise and dependable information by merging inputs from cameras, radar, lidar, and other sensors. In smart EVs, this improved perception is essential for efficient control and decision-making. The function of vehicular ad hoc networks (VANETs) for vehicle-to-vehicle (V2V) communication is also used by EV. Vehicle-to-vehicle (V2V) communication makes it possible for cars to communicate with other cars in the area about their position, speed, and direction. This promotes coordinated driving and increases road safety. In order to minimize fuel consumption and maximize road capacity, many cars ride closely together in a coordinated way, a phenomenon known as platooning, which is made possible by this technology [37].

State of charge (SOC), dynamic vehicle, battery, and electric motor models are integrated into an ADAS-based system to study the effect on energy usage. Because of the impacts of regenerative braking, as evidenced by the negative values seen in the power curve graphs, the results showed that, when the ADAS model is active, a reduction in the distance between cars favorably improves the battery's charge state. A notable reduction in battery charge status is noted as vehicle speed approaches the conclusion of the driving cycle, which is succeeded by a rise brought on by the forceful braking action and regenerative power [38].

6. Analyses

It has become clear that studies and research are closely being conducted for develop the technical systems to improve the performance of electric vehicles, while the economic and environmental dimensions are among the most important dimensions that should also be analyzed and interpreted as follows:

– Although the initial cost of ownership of electric cars is reasonable, it is considered the most expensive when we consider the expected life of the battery, which is about 10 years. This expected life may also be negatively affected by harsh climatic conditions such as the summer heat in Egypt. Given concerns about the short lifespan of electric car batteries and the potential loss of value due to potential fires in hot climate conditions, the overall cost of owning an electric car in Egypt may be higher than that of a conventional internal combustion engine vehicle, despite lower operating costs. This is important to consider customer preferences and trends in other regions, especially since these concepts change with climate conditions and, consequently, people's perceptions change, as is the case in European countries [39–42].
– In addition to what we have discussed extensively in the current pressing issues that are limited to the overall environmental impact, technical performance metrics, innovations in electric vehicle technology, and modern technology in electric vehicles using artificial intelligence above. However, by studying and analyzing the case carefully, it becomes clear that there are many inquiries that need more time and research efforts, among them:

7. Conclusions

It is clear that the issue of evaluating the economic and environmental; performance and impact of electric vehicles according to standard criteria has become very important and urgent at the present time, especially with the increase in production intensity and the beginning of widespread use. Although the electric car industry has become a reality and inevitable, through a clear comparison between fossil fuel-powered vehicles (ICEVs) and electric vehicles (EVs), it is clear that each has unique advantages and disadvantages that need more and more studies. Hence, the objectives of this paper were achieved in helping stakeholders from policy makers, researchers and consumers to see the current scene clearly and provide proposed solutions for the development of automotive technology. More important conclusions were reached as follows:

– EVs are especially well-suited for driving in cities, especially in underground modern cities, since they have zero exhaust emissions at operation and less maintenance expenses. EVs also have the advantage of greater torque and max speeds on intercity highways. However, due to their longer range and faster recharging times, ICEVs often perform better for long-distance travel.
– Hopes are still pinned on scientific research to improve battery health and charge management system, whether for constant current charging (CCC) or constant voltage charging (CVC) method, as well as the importance of enhancing charging efficiency and reducing charging frequency time using AI.
– There is also another very important dimension, which requires a huge amount of serious research and honest disclosure of its results, to determine the types of other environmental pollutants emitted by electric vehicles in both during manufacturing and during use, and how they affect the health of the driver, passengers and pedestrians in the community. This is especially true after a leading company announced that the carbon footprint of EVs upon production is three times that of hybrid cars [22]. And, is this achieved according to current global standardizations? So, EVs need further research and development to predict become more com-

petitive in a wider range of driving circumstances as the gap between them and ICEVs closes due to advancements in battery technology and charging infrastructure. This is particularly evident with the use of AI in battery management system and advanced driver assistance system.

Eventually, currently, given the concerns of electric vehicle users in global communities about critical issues related to safety, improved charging systems, and pollution from battery production, although the authors does not expect electric vehicles to be sustainable given the risks of their production and use that have yet to be uncovered, experts and interested users are waiting to learn how and by whom the G7 will fund research in the automotive industry. Will most of it focus on developing fuel injection systems for various vehicle types, or on developing electric vehicle systems, especially over the next two decades? Therefore, implementing strict safety protocols (focusing primarily on safety which may require the development of strict standards from the International Organization for Standardization (ISO) or the International Electrotechnical Commission (IEC) to achieve the SDG-aligned strategies, not just economic aspects) must be a top priority to maximize the benefits of this technology and ensure a sustainable and safe future for societies. If the author's opinion holds, he expects that attention will enthusiastically turn to hybrid and conventional vehicle systems, rather than electric ones, in the development of these systems. We also expect that financing hydrogen car projects will play a significant role in driving progress in the automotive industry in the future, given its numerous positive impacts on all levels [43].

It's only natural for some outstanding scientific research to conclude with a set of solutions and/or questions that the authors can formulate for future work. This opens the door for other researchers to facilitate and conduct their own scientific research, hoping to find useful answers to this question in the future. These questions include:

The urgent inquiry now is: Can we expect that the electric car industry will face environmental difficulties or health and safety problems in light of reports of toxic chemical leaks or business or technical injuries by increasing accident rates? In other words: Can we expect that there will be a slowdown or growth in the development of electric car manufacturing technology or its sales in the future? and where? The most important inquiry is: Is there a conflict between compliance with environmental rules and regulations at the expense of the economy or imports? In other words, what is the position of environmental legislation in light of the difference in competitiveness (China is ahead of European countries in the electric car industry, because it has the lead in its advanced manufacturing proficiency and cheaper)? In other words, will increasing customs duties on imports of Chinese electric cars be the solution? While long-term projections and potential market shifts driven by policy changes, such as moving toward more green hydrogen production to lower its prices, will lead to a greater advantage? In other words, is moving toward hybrid or hydrogen vehicles the best solution? However, these matters must be studied and considered, based on the principle of commitment to science and its ethics. Finally, what will the coming days hold for us? In addition to what we have concluded at the end of this work, the truth is that future informed and honest studies and research will soon provide us with clearer answers to all these questions.

Author Contributions

The authors developed the research plan, investigation and wrote the paper. The second author wrote the abstract, methodology and conclusion, defined future work, reviewed and edited the manuscript, and served as the corresponding author for communication with the journal.

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