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A Systematic Review of Hybrid Electric Vehicle Technologies and Their Impacts on Environmental Sustainability

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Abstract

The increasing concerns over climate change and air pollution have resulted in a burgeoning interest in alternative transportation technologies that mitigate Greenhouse Gas (GHG) emissions and enhance air quality. Hybrid Electric Vehicle (HEV) technologies have emerged as a viable option to these challenges, providing a more efficient and eco-friendly alternative to conventional Internal Combustion Engine (ICE) automobiles. There are still uncertainties regarding the environmental sustainability of HEV technologies, as well as constraints associated with their acceptance and incorporation into the transportation system. This study addresses these concerns by systematically reviewing current literature on HEV technologies and their environmental impact. The research methodology encompassed thoroughly examining scholarly articles, studies, and other pertinent materials on HEV technologies, their ecological consequences, and their ability to mitigate GHG emissions. The search was performed via online academic databases and relevant industry reports. The literature evaluation concentrated on research assessing HEV technologies' environmental efficacy, encompassing their capacity to decrease emissions, enhance fuel efficiency, and promote overall sustainability. An analysis was conducted on the outcomes of this research to uncover significant patterns, trends, challenges, and prospects for enhancing the sustainability of HEV technology. The findings suggest that HEV technologies can substantially decrease emissions and improve fuel economy compared to conventional ICE vehicles. It was observed that HEV can reduce GHG emissions by as much as 50% and improve fuel efficiency by an average of 20-30%. Nevertheless, challenges must be resolved, including battery technology, infrastructural development, and customer acceptability. The findings suggest that more research and development should be conducted to improve the sustainability of HEV technologies and accelerate their acceptance in the market.

Keywords: GHG emissions, Hybrid electric vehicle, Environmental sustainability, Fuel efficiency, Transportation technology.

1 | Introduction

An Hybrid Electric Vehicle (HEV), as described by Sidharthan Panaparambil et al. [1], is a vehicle that utilizes several energy sources to propel itself, with electrical power being one of those sources. Hybrid electric automobiles are often propelled by a hybrid powertrain consisting of an electric motor and a gasoline engine. Hybrid cars possess the capacity to make a valuable contribution to sustainable transportation by diminishing reliance on fossil fuels and decreasing emissions. Nonetheless, hybrid cars' long-term viability and

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sustainability are contingent upon variables such as the vehicle's durability, the capacity to recycle its components, and the presence of charging infrastructure for Electric Vehicles (EVs) [2]. Furthermore, it is important to consider the ecological consequences of hybrid cars during their lifespan, encompassing production, usage, and disposal [3]. HEVs have garnered considerable interest in recent times as a viable approach to mitigate Greenhouse Gas (GHG) emissions and decrease reliance on fossil fuels in the transportation industry. HEVs combine an Internal Combustion Engine (ICE) with an electric motor and a battery pack [4]. This combination enables enhanced fuel economy and decreased pollution in comparison to conventional gasoline-powered automobiles. Modern HEVs use electric motors powered by batteries and ICEs to generate electricity. A mutually advantageous scenario is created by merging the capabilities and scope of conventional automobiles with the benefits of HEVs, such as minimal emissions and exceptional fuel economy [5].

Although a conventional wall socket cannot directly recharge the batteries of a hybrid electric automobile, the battery is charged by a combination of ICE and regenerative braking. The electric motor's supplementary power enables a smaller engine in HEVs. The battery serves other purposes, such as minimizing engine idling when stationary and supplying power to secondary devices. The combined effect of these factors results in enhanced fuel efficiency while maintaining optimal performance. Several studies have been conducted on HEV technologies in the context of environmental sustainability. Zaino et al. [6] comprehensively analyzed the effects of technology, environment, organization, and policy on adopting EVs. The findings indicate that technical breakthroughs in battery technology and energy storage systems have greatly improved the performance of EVs and reduced concerns about limited driving range. The environmental study demonstrated a considerable decrease in GHG emissions, as evidenced by lifecycle evaluations that indicated significant reductions for EVs compared to ICE vehicles, especially when powered by renewable energy sources.

The organizational effects became apparent when organizations embraced new fleet management and logistics frameworks, utilizing EVs to enhance operational efficiency and promote sustainability. The policy analysis highlighted the pivotal importance of government incentives, regulatory measures, and infrastructure expenditures in expediting the adoption of EVs. Hawkins et al. [7] conducted a comprehensive assessment of the environmental effects of hybrid and electric automobiles. While EVs seem to show a reduction in Global Warming Potential (GWP) compared to traditional Internal Combustion Engine Vehicles (ICEVs), high-efficiency ICEVs and HEVs that are not dependent on the grid were observed to outperform EVs powered by coal-fired electricity. The findings indicated that the GWP of EVs running on coal-generated electricity is between small and big conventional cars. However, EVs fuelled by natural gas or low-carbon energy sources outperform even the most efficient ICEVs. The findings of EVs in regions that rely on coal energy showed a clear tendency towards higher SO_x emissions than ICEVs. Mustafa [8] reported that it is crucial to implement a real-time control approach for a HEV that can effectively coordinate the power sources on board, resulting in improved fuel efficiency and decreased CO_2 emissions.

Nevertheless, there are challenges in developing a highly effective management strategy that meets conflicting control limitations related to fuel usage, pollution, and drivability while avoiding excessive battery depletion at the last stage of a certain driving cycle. Pipitone et al. [9] conducted a comparative study on the environmental impact of traditional, hybrid, and EVs in the European context. The results demonstrated that the Global Warming (GW) impacts of a Battery Electric Vehicle (BEV) throughout its entire lifespan is approximately 60% of that of an equivalent ICEV. Additionally, acidifying emissions and particulate matter were twice as high in BEVs compared to ICEVs. The HEV was validated as an outstanding alternative to ICEV, demonstrating a favorable balance between its GHG impact (85% compared to ICEV), terrestrial acidification, and particle generation (Comparable to ICEV). A significant challenge arose from deploying mineral sources, namely manufacturing Lithium-ion (Li-ion) batteries for BEVs. Limon et al. [10] utilized the Bayesian best-worst approach framework to investigate the factors that impact the increase in the adoption of HEVs in developing nations. The findings revealed that the absence of a need for a charging station, the use of regulatory measures to encourage customers, and improved fuel efficiency are the three main factors that drive the increase in the adoption of HEVs in developing or rising economies. Hossain et al. [11] conducted a comprehensive assessment of the incorporation of EVs in order to promote sustainable development. The findings suggested that the increased complexity of sustainable development results in a comparatively delayed adoption of EVs. The study revealed that EVs have the potential to serve as a sustainable energy source, hence aiding in the reduction of CO_2 emissions. Nevertheless, the advancement of EV sustainable development needs robust policy backing. This study reviewed the trends in conventional HEV technologies in the context of environmental sustainability.

1.1 | Historical Evolution of Hybrid Electric Vehicles

In 1900, Ferdinand Porsche invented the first gasoline-electric hybrid automobile, marking the beginning of a new era in hybrid cars in the late 19th century. In the 1920s, the idea of HEVs grew with the development of the Lohner-Porsche Mixte Hybrid, which Ferdinand Porsche engineered. This vehicle was equipped with an electric motor powered by batteries. Additionally, it had a gasoline engine that could replenish the batteries or supply extra power. The Lohner-Porsche Mixte Hybrid was a pioneering advancement that showcased the possibilities of integrating electric and ICE technology in automobiles. During the 1930s and 1940s, more tests and advancements were conducted in HEVs. An exemplary instance is the Woods Dual Power, a HEV with an electric motor and a gasoline engine. The Woods Dual Power was an early example of a hybrid electric car that was offered for purchase and demonstrated the advantages of integrating electric and ICE technology. During the 1960s and 1970s, the popularity of HEVs declined as attention switched towards enhancing the efficiency of ICEs.

Nevertheless, the oil crisis that occurred in the 1970s sparked a renewed fascination with alternative fuel technologies, such as HEVs. During this period, many automobile manufacturers, such as General Motors and Toyota, initiated investigations into the possibilities of HEVs as a viable response to the increasing costs of gasoline and growing environmental issues. During the 1980s, improvements in battery technology and the efficiency of electric motors made HEVs more feasible and suitable for large-scale manufacturing. The popularity and broad use of HEVs did not occur until the late 20th century [12]–[14]. The emergence and development of HEVs throughout the early 1990s were pivotal in the automotive sector. During this period, there was an increasing recognition of the ecological consequences of conventional gasoline-fueled automobiles and a determination to decrease reliance on non-renewable energy sources. As a result, HEVs developed effectively incorporated the advantages of gasoline and electric power sources.

The first generation of the Toyota Prius in 1997 marked a significant milestone in the history of hybrid electric cars. The Prius was the inaugural commercially manufactured HEV and promptly emerged as an emblem of eco-conscious mobility. The success of this vehicle opened doors for other car manufacturers to develop their HEVs, resulting in a significant increase in the number and diversity of hybrid models available on the market. HEVs have experienced substantial expansion and advancement in recent decades. In the early 2000s, HEVs became increasingly popular as a greener substitute for conventional gasoline-powered cars. The Toyota Prius rapidly became an emblem of the environmental sustainability movement. With the rising concerns about climate change and air pollution, many manufacturers started investing in HEV technology. This resulted in a consistent growth in the variety of HEV models that are now accessible to customers. In the 2000s, improvements in battery technology and electric motors enabled HEVs to achieve greater efficiency and affordability. Government incentives, such as tax credits and rebates, played a significant role in stimulating the sales of HEVs. By 2010, HEVs had gained widespread popularity among consumers seeking to minimize their environmental impact and reduce gasoline expenses. During the 2010s, manufacturers made advancements in HEVs to enhance fuel efficiency and decrease emissions [15]–[18]. Subsequently, Plug-in Hybrid Electric Vehicles (PHEVs) cars were developed, allowing drivers to recharge their vehicles using power sourced from the grid. This technique enabled extended electric-only driving ranges and significantly diminished the need for fuel. The HEVs market has experienced significant growth in recent years as many manufacturers have expanded their product offerings to cater to the rising customer demand. The emergence of electric cars has also impacted the advancement of HEVs since several car manufacturers have redirected their attention towards fully electric versions. HEVs continue to be a preferred option for consumers who are not yet prepared to transition to completely electric cars [8], [19]–[21].

1.2 | Advancements in Hybrid Electric Vehicles

Zakaria et al. [22], Hossain et al. [23], and Fantin and Appadurai [4] noted that the earliest advancements in HEVs may be attributed to the development of the first hybrid car by Ferdinand Porsche. This pioneering hybrid car established the groundwork for further advancements in hybrid technology. A significant breakthrough in the early 1990s was the advancements made in battery technology, enabling HEVs to achieve longer driving ranges and enhanced performance. Early HEVs were constrained by the capacity and performance of their batteries, leading to restricted electric-only range and overall efficiency.

Nevertheless, progress in battery technology, as shown by the development of Li-ion batteries, has notably enhanced the efficiency and distance capabilities of HEVs [24], [25]. Battery technology developments in the early 2000s were essential for improving the performance of HEVs. The subsequent significant breakthrough in battery technology was Nickel-Metal Hydride (NiMH) batteries. This innovation enabled better energy density and enhanced power output, resulting in increased efficiency and reliability of HEVs. The improved batteries are characterized by reduced weight, smaller size, and increased energy density. As a result, HEVs can now cover greater distances using only electric power and achieve enhanced fuel economy. During this period, another significant technological breakthrough in HEVs was the emergence of regenerative braking systems. Regenerative braking enables the car to harness and retain energy that would otherwise be dissipated during braking and utilize it to replenish the batteries. This technique greatly enhances the efficiency of HEVs and contributes to the expansion of their operating range. Advancements in powertrain technology have also had a notable impact on improving the performance and efficiency of HEVs. Modern HEVs are outfitted with modern powertrain technologies, including dual-motor configurations and continuously variable gearboxes. These enhancements enable the vehicles to provide power more smoothly and efficiently. These technological developments have improved the driving experience of HEVs and made them more competitive with conventional gasoline-powered automobiles.

Automobiles equipped with bi-directional charging capability can provide electricity to power the electrical appliances in a home or smaller EVs, such as scooters or e-bikes. There are widespread concerns about how people will handle the extra expenses of charging EVs, especially given the recent surges in energy costs [26]. This innovation enables the utilization of a backup HEV battery to supply electricity to our residence at the user's discretion, therefore mitigating this issue. The user can reroute power to their HEVs at any time they choose. The cell-to-pack technique enhances efficiency by reducing the overall resistance of the battery pack and eliminating intermediate components. This revolutionary technology has significantly improved the range and reduced the charging time of electric cars. Cell-to-pack technology enhances HEV performance by reducing the weight of the battery pack. The production time for battery packs is decreased, and the process is simplified. Integrating cell-to-pack technology into HEV battery packs enhances reliability [27]–[30].

2 | Key Components of Hybrid Electric Vehicles

Un-Noor et al. [21], Broussely [31], Elwert et al. [32], and Singh et al. [33], in their investigative study, reported that modern HEVs utilize an ICE together with one or more electric motors that draw energy from batteries. It integrates the advantages of superior fuel efficiency and less exhaust emissions with traditional automobiles' performance and driving distance capabilities. HEVs consist of several components (*Fig. 1*) that enable its functionality, some of which are highlighted as follows:

I. An auxiliary battery in an electric drive vehicle supplies low-voltage electricity to initiate the ignition before engaging the main traction battery. It is also responsible for powering other vehicle accessories.

II. A DC/DC converter is a device that converts high-voltage DC power from the traction battery pack into low-voltage DC power required to operate vehicle devices and replenish the auxiliary battery.

III. An electric generator is a device that converts the kinetic energy generated by the revolving wheels during braking into electrical energy, which is then sent back to the traction battery pack. Certain cars utilize motor generators that serve dual purposes by performing both the driving and regeneration operations.

IV. An electric traction motor propels the vehicle's wheels by utilizing electricity from the traction battery pack. Certain vehicles use motor generators that fulfil propulsion and energy recovery tasks.

V. The exhaust system directs the engine's exhaust gases to exit through the tailpipe. A three-way catalyst is specifically engineered to minimize the engine's emissions before they are released into the exhaust system.

VI. The fuel filler is the part of the vehicle where the nozzle from a fuel dispenser is connected to fill the tank.

VII. The fuel tank, specifically designed for gasoline, serves as a reservoir on the vehicle, storing the fuel required by the engine.

VIII. An ICE with spark ignition operates by injecting gasoline into the inlet manifold or the combustion chamber. The fuel combines with air, and the resultant air-fuel mixture is ignited via a spark generated by a spark plug.

IX. The power electronics controller regulates the transmission of electrical energy from the traction battery and effectively governs the speed and torque output of the electric traction motor.

X. The thermal system, specifically designed for cooling purposes, ensures that the engine, electric motor, power electronics, and other components operate at the appropriate temperature level.

XI. The traction battery pack stores power that the electric traction motor will utilize.

XII. The transmission is responsible for transferring the torque produced by the engine and/or electric traction motor to the wheels that drive them.

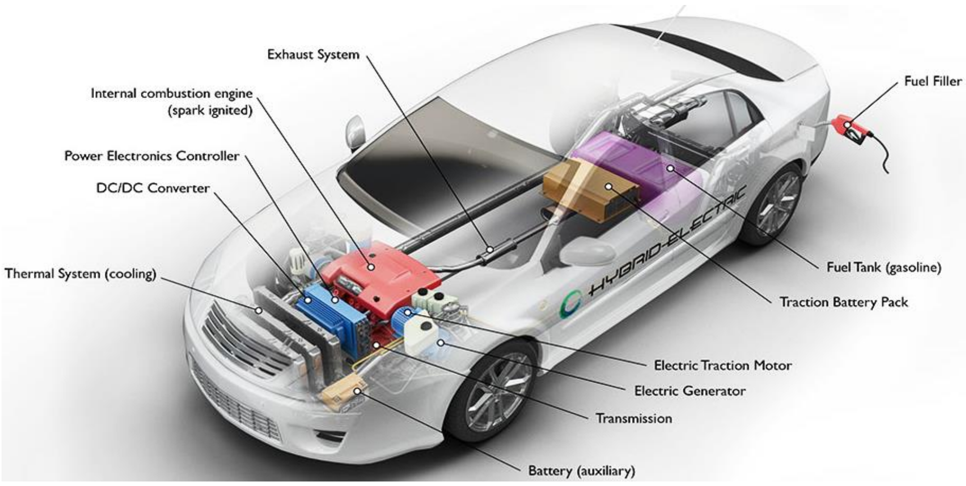

Fig. 1. Key components of modern hybrid electric vehicle [34].

2.1 | Types of Hybrid Electric Vehicles

Lulhe and Date [35], Zarma et al. [36], Hannan et al. [37], Lyati [38], and Pielecha et al. [39] opined that there are three primary categories of hybrid vehicles: 1) full hybrids, 2) mild hybrids, and 3) plug-in hybrids. These three hybrid vehicle categories share common features to enable their functionality. The vehicle's fuel economy is enhanced while harmful emissions are minimized. This is because electric motors are more efficient than ICEs and do not generate any pollution.

I. Full Hybrid Electric Vehicles (FHEVs) combine an ICE with an electric motor and battery to improve fuel efficiency and reduce emissions. Unlike mild hybrids, which primarily use the electric motor to assist the engine, FHEVs can run on electric power alone for short distances at low speeds. One of the key components of a FHEV is the battery pack, which stores energy generated by regenerative braking and the ICE. This energy can then be used to power the electric motor, reducing the load on the engine and improving overall fuel efficiency. The electric motor also provides additional acceleration power, reducing fuel consumption. FHEVs also feature a sophisticated control system that manages the power flow between the engine and the electric motor. This system determines the most efficient way to use the available energy based on driving conditions, such as speed, load, and terrain.

II. Mild Hybrid Electric Vehicles (MHEVs) are a type of hybrid vehicle that combines a traditional ICE with an electric motor and a small battery pack. Unlike full hybrid vehicles, which can run on electric power alone for short distances, MHEVs primarily rely on the ICE for propulsion, with the electric motor providing additional power and efficiency. One of the key features of MHEVs is their ability to capture and store energy during braking and deceleration. This energy is then used to assist the ICE during acceleration, reducing fuel consumption and emissions. This regenerative braking system is a key component of MHEVs, allowing them to achieve better fuel efficiency than traditional gasoline or diesel vehicles.

III. Another important aspect of MHEVs is their start-stop system, which automatically shuts off the ICE when the vehicle is stationary, such as at a traffic light or in heavy traffic. This helps to reduce fuel consumption and emissions, especially in urban driving conditions where frequent stops and starts are common. MHEVs are also equipped with a belt-driven starter generator, which allows the ICE to be restarted quickly and smoothly when needed. This system helps improve overall efficiency and performance and reduce wear and tear on the engine [40], [41].

IV. PHEVs are a type of vehicle that combines the benefits of both traditional ICEs and electric motors. These vehicles can run on electricity alone for a certain distance before switching over to the ICE, allowing drivers to use either power source depending on their needs. One of the key features of PHEVs is their ability to be charged from an external power source, such as a wall outlet or charging station. This allows drivers to recharge the vehicle's battery pack at home or work, reducing the need to rely solely on gasoline. Using electricity as a primary power source, PHEVs can help reduce GHG emissions and dependence on fossil fuels. With lower fuel costs and potential tax incentives for purchasing an EV, PHEVs can save money in the long term. Furthermore, PHEVs typically have a longer driving range than fully EVs, making them a more practical option for drivers needing to travel longer distances. PHEVs combine the benefits of electric and gasoline power to provide drivers with a versatile and environmentally friendly option for their daily transportation needs [42]–[44].

3 | Powertrain Architectures for Hybrid Electric Vehicles

Anselma and Belingardi [15], Wu et al. [45], and Lanzarotto et al. [46] during their investigative study, reported that HEVs have gained significant attention in recent years as a promising solution to reduce GHG emissions and dependence on fossil fuels in the transportation sector. There are different powertrain architectures for HEVs, including series, parallel, and series-parallel configurations (See *Fig. 2*), highlighted as follows:

I. Series HEV Architecture: The series HEV architecture is characterized by the electric motor being the sole source of propulsion for the vehicle, with the ICE acting as a generator to charge the battery or provide additional power when needed. This is also known as a range extender since the engine does not directly power the wheels; the engine powers the electric motor and the battery pack. This architecture offers the advantage of operating the ICE at its most efficient operating point, improving fuel efficiency. However, the series HEV may suffer from limited electric-only range and reduced performance compared to other architectures.

II. Parallel HEV architecture: The parallel HEV architecture allows the ICE and electric motor to drive the wheels directly, providing better performance and range than the series architecture. In other words, the engine and electric motor synergistically provide optimal power for the effective operation of the vehicle. The parallel HEV architecture also allows for regenerative braking, where the electric motor acts as a generator to recharge the battery during deceleration. However, the parallel architecture may be less efficient than the series architecture due to the need to operate both the ICE and electric motor simultaneously [46], [47].

III. Series-parallel HEV architecture: The series-parallel HEV architecture combines elements of both the series and parallel architectures, allowing for greater flexibility in powertrain operation. In this architecture, the ICE can drive the wheels directly, or the electric motor can provide propulsion independently or in conjunction with the ICE. In other words, the electric motor has the capability to operate either in cooperation with other motors or alone [48], [49]. The power delivery or power distribution system optimizes the vehicle's power output or fuel economy, resulting in maximum efficiency. This flexibility allows optimal powertrain operation under varying driving conditions, improving fuel efficiency and performance [33], [50]. Itemized cost analysis for several powertrain alternatives in EUR is presented in *Table 1*, while *Table 2* summarizes HEV architectures.

Table 1. Itemized cost analysis for several powertrain alternatives in EUR [51].

Costs Type (In EUR, Year 2020)	ICV	HEV	PHEV 15	PHEV 30	EREV	BEV	FCEV
Purchase price (Excluding CO_2 penalties)	27,946	29,963	30,805	31,941	37,093	36,390	46,456
Resale value	- 9503	- 11,916	- 12,252	- 12,704	- 14,756	- 10,335	- 15,809
Net depreciation	18,443	18,047	18,554	19,237	22,337	26,054	30,647
Energy cost	4016	2142	1739	1564	1637	1235	2587
Maintenance and repair cost	2892	2720	2704	2692	2124	2348	2548
Other operation cost (e.g., motor tax and inspection)	330	160	160	160	160	53	53
Total cost of ownership	25,680	23,069	23,157	23,653	26,257	29,690	35,835

Table 2. Summary of hybrid electric vehicle architectures [52].

Architectures	Complexity	Efficiency	Hybridization	Computation Time
Series	Low	Low	Full HEV and PHEV	Low
Parallel	Medium	Medium	Micro-, mile, and full HEV	Medium
Series-parallel	High	High	Full HEV and PHEV	High

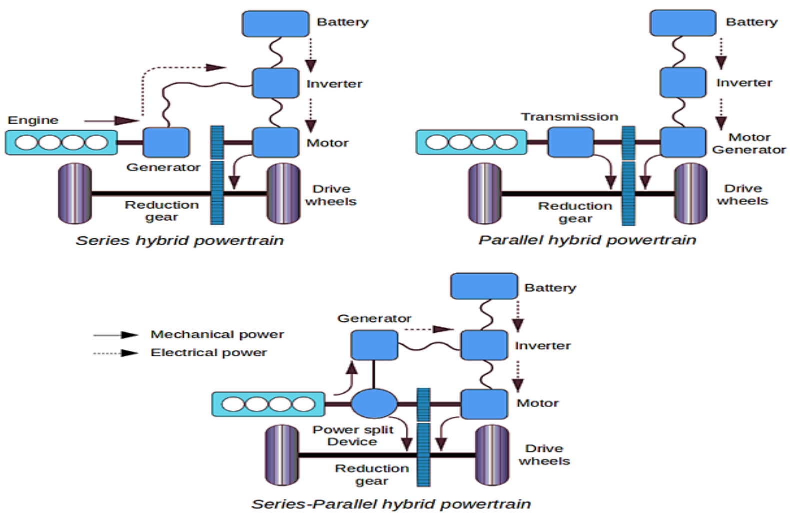

Fig. 2. Powertrain architectures for hybrid electric vehicles [53].

3.1 | Classification of Batteries in Hybrid Electric Vehicles

Zhang et al. [54] and Xue et al. [55] opined that the key component of HEVs is the battery, which stores and provides electrical energy to power the car's electric motor. There are several classifications of HEV batteries, each with its pros and cons. These include the following:

I. NiMH battery: NiMH batteries are among the most commonly used batteries in HEVs due to their reliability and lengthy lifespan. However, unlike their battery counterparts, they are relatively heavy and have a lower energy density, which can minimize the vehicle's range.

II. Li-ion battery: Li-ion batteries are lighter and have higher energy density than NiMH batteries, which enables longer driving range. However, unlike NiMH batteries, Li-ion batteries are more costly and have a minimal lifespan.

III. Lithium-ion Polymer (LiPo) battery: LiPo batteries are similar to Li-ion batteries but have a higher energy density and are quite flexible in shape and size. However, unlike NiMH batteries, they are relatively expensive and have a shorter lifespan.

IV. Solid-state battery: This type of battery uses a solid electrolyte instead of a liquid electrolyte. This integration eradicates the dangers of leakage and thermal runaway associated with traditional Li-ion batteries, making them safer and more reliable. They have higher energy density with faster charging features, which can improve the performance of HEVs. However, their expensive production cost and limited scalability constitute the general issues that must be resolved before widespread adoption in HEVs.

V. Lithium-sulphur batteries: Unlike traditional Li-ion batteries, lithium-sulphur batteries provide higher energy density at a lower cost. They can greatly increase the range of HEVs and minimize CO_2 emissions. However, their low cycle life and ineffective stability tend to limit their adoption in HEVs [56].

3.2 | Electrification Process in Hybrid Electric Vehicles

The electrification process in HEVs entails integrating electric powertrain components with contemporary IC engines, resulting in enhanced fuel economy and diminished pollutants. This technique is essential for environmental impact mitigation in transportation systems. The battery system and electric motor are key to the HEV electrifying process. The electric motor operates with the IC engine to provide the required supplementary power during acceleration or uphill travel [57], [58]. The battery system accumulates energy produced during braking or coasting, which may also be employed in the operation of the electric motor and alleviate unwanted load on the IC engine. Another crucial mechanism of the electrification process is the application of regenerative braking technology, which enables regenerative braking in events where the electric motor functions as a generator, converting the available kinetic energy during braking into electrical energy. This electrical energy can subsequently be channelled and stored in the battery system for future use. This improves fuel efficiency and minimizes the strain effect on the braking system, prolonging the vehicle components.

Furthermore, the electrification process in HEVs often implies the application of efficient power electronics and control systems, which control heat transfer across the IC engine, electric motor, and battery system to improve vehicle performance. In other words, they contribute to seamless transitions between multiple driving modes, including electric-only, hybrid, or engine-only operations [57]–[59]. *Fig. 3* illustrates the electrification process in HEVs and BEVs.

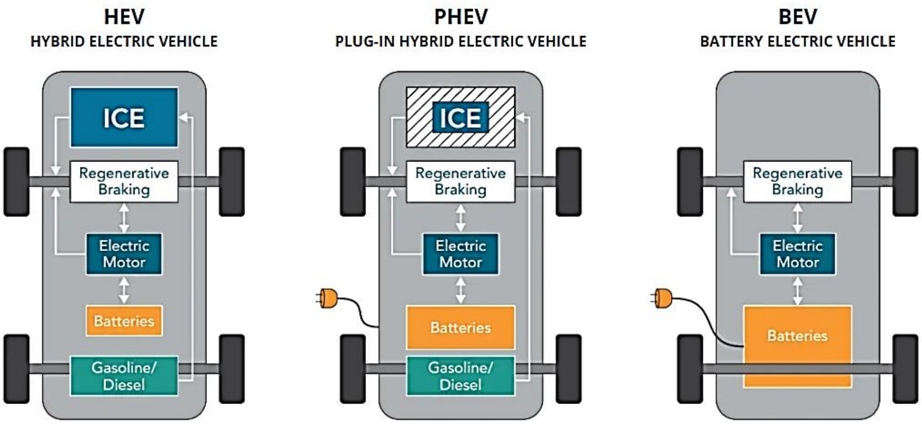

Fig. 3. Electrification process in hybrid electric vehicles and battery electric vehicles [60].

3.3 | Performance Measurements of Hybrid Electric Vehicles

HEVs have gained significant acceptance in recent years due to their potential to reduce GHG emissions and dependence on fossil fuels [61]. However, comprehensive performance measurements are essential to fully understanding and optimizing these vehicles' performance. This section presents a detailed procedure for conducting such measurements, focusing on laboratory and on-road testing.

I. The first step in measuring the performance of a HEV is to establish a baseline for comparison. This can be done by conducting a series of tests to determine the vehicle's fuel efficiency, emissions, and overall performance under usual driving conditions. These tests should be conducted in a controlled environment, such as a laboratory or test track, to ensure accurate and reliable results. Once the baseline performance has been established, the next step is to conduct a series of tests to evaluate the vehicle's electric propulsion system. This includes measuring the efficiency of the electric motor, battery performance, and regenerative braking capabilities. These tests can help identify potential issues with the vehicle's electrical system and provide valuable data for optimizing its performance.

II. In addition to laboratory testing, on-road performance measurements are also essential for evaluating the real-world performance of a HEV. This can include driving the vehicle on various road conditions, such as highways, city streets, and hilly terrain, to assess its fuel efficiency, handling, and overall performance. On-road testing can provide valuable insights into how the vehicle performs in everyday driving situations and help identify areas for improvement.

Through a combination of laboratory and on-road testing, it is possible to identify areas for improvement and work towards minimizing fuel efficiency and maximizing the environmental benefits of HEVs [61]–[63]. Fuel savings in some EV models are presented in *Table 3*.

Table 3. Fuel savings in some electric vehicle models [64].

Technology	Nonhybrid/Nonelectric Base Model (BEE* Fuel Efficiency Star Rating)	Hybrid/Electric Model (BEE Fuel Efficiency Star Rating)	Gasoline Equivalent Fuel Consumption Reduction Over Base Model
Diesel-based mild hybrid	Maruti Ciaz VDI (5 star)	Maruti Ciaz VDI-shvs (5 star)	7%
Diesel-based mild hybrid	Maruti Ertiga VDI (4 star)	Maruti Ertiga VDI-shvs (5 star)	15%
Gasoline-based strong hybrid	Toyota Camry at 2.5 l (2 star)	Toyota Camry Hybrid (5-star)	32%
Battery-operated electric	Mahindra Verito d2 (4 star)	Mahindra E-verito d2 (5 star)	68%
Battery-operated electric	–	Mahindra e2o (5 star)	–

3.4 | Analysis of Hybrid Electric Vehicle Systems

According to Awadallah et al. [65], Tran et al. [66], and Minh et al. [67], a thorough examination of the HEV system is essential for a complete understanding of its performance and efficiency. This process comprises the following stages:

I. The initial stage of analyzing an HEV system involves comprehending the fundamental components and their respective roles. The ICE supplies power to the vehicle as required, while the electric motor aids in accelerating and recovers energy during the braking process. The battery is an energy reservoir for the electric motor and may be recharged through regenerative braking or the engine. Power electronics regulate the energy transfer among the engine, motor, and battery, enhancing efficiency and performance.

II. It is crucial to examine the energy flow inside the HEV system thoroughly. This entails analysing energy generation, storage, and utilization under various driving situations. The electric motor can supply extra power to support the engine during acceleration. Conversely, energy is caught and stored in the battery during braking for future use. A comprehensive understanding of these energy fluxes is essential for maximizing the vehicle's performance and efficiency.

III. Another crucial factor in analyzing an HEV system is assessing the vehicle's overall efficiency and emissions. This entails comparing the fuel efficiency and emissions of the hybrid system with those of a regular ICE vehicle. Research has demonstrated that HEVs may substantially decrease fuel consumption and emissions, particularly in urban driving situations with frequent stops and starts. The effectiveness of a HEV system can fluctuate based on variables such as driving habits, vehicle dimensions, and battery technology.

IV. Although HEVs may need a larger initial investment than traditional automobiles, the savings in long-term fuel and maintenance expenses can compensate for this greater upfront cost. Moreover, the progress in battery technology and the implementation of government incentives for electric cars are enhancing the affordability and appeal of HEVs for customers.

Researchers and policymakers may make well-informed judgments on transportation prospects by comprehensively analyzing the constituents, energy transfer, effectiveness, emissions, and expenses associated with HEVs [68]. *Fig. 4* depicts the battery prices over the next 12 years, and it can be inferred that by 2022, EVs will likely cost the same as the ICE vehicle equivalent.

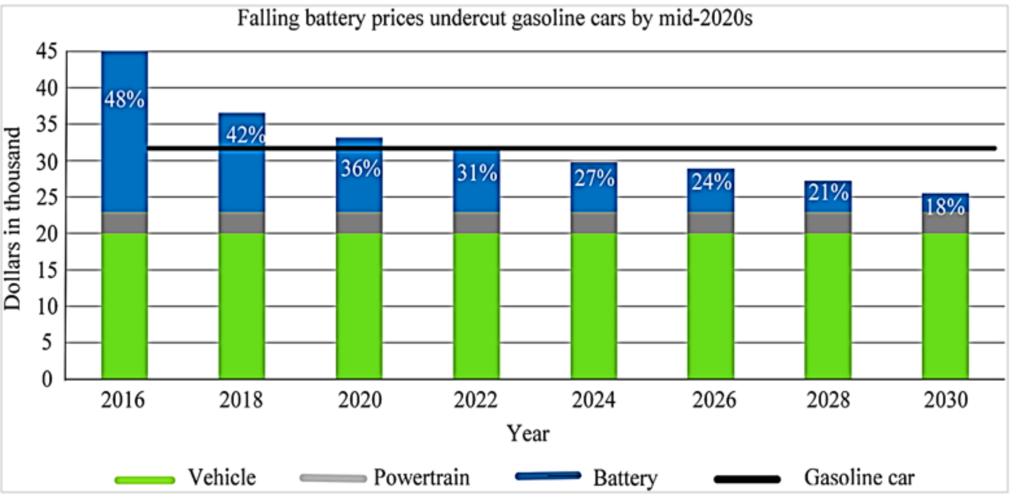

Fig. 4. Price forecast of hybrid vehicles [33].

4 | Designing and Sizing of Hybrid Electric Vehicles

Anselma and Belingardi [15], Huang et al. [69], and Anselma et al. [70] outlined the design and sizing of an HEV in their report. This process involves a complex process that requires careful consideration of various factors such as vehicle performance, energy efficiency, and cost. This section presents a comprehensive approach to designing and sizing HEVs, focusing on maximizing energy efficiency and performance.

I. The first step in designing an HEV is to define the vehicle requirements, including the desired performance characteristics such as acceleration, top speed, and range. This information is crucial for determining the powertrain configuration and sizing the components such as the engine, electric motor, and battery. The next step is to select the appropriate powertrain architecture, which can vary from a parallel hybrid to a series-parallel hybrid, depending on the vehicle's specific requirements.

II. Once the powertrain architecture is chosen, the next step is to size the components based on the vehicle requirements. This involves calculating the power and energy requirements of the engine, electric motor, and battery and determining the optimal operating points for each component. The sizing process also includes selecting the appropriate control strategy to optimize the energy flow between the components and maximize overall efficiency.

III. In addition to component sizing, the design of an HEV also involves optimizing the vehicle's aerodynamics, weight distribution, and rolling resistance to minimize energy consumption. This can be achieved through advanced simulation tools and optimization techniques, which allow engineers to evaluate different design options and select the most efficient configuration.

The design and sizing of HEVs require a multidisciplinary approach that integrates knowledge from various fields, such as mechanical engineering, electrical engineering, and control systems. By following a comprehensive process, engineers can develop HEVs that are energy-efficient and environmentally friendly and meet the performance requirements of modern vehicles [71], [72].

4.1 | Control Systems in Hybrid Electric Vehicles

Enang and Bannister [73], Cao et al. [74], Xu et al. [75], and Lü et al. [76] studied the control systems in HEVs and outlined their crucial role and operation as they are responsible for managing the power flow between the ICE and the electric motor. These systems are designed to optimize fuel efficiency, reduce emissions, and enhance overall vehicle performance. Detailed description of the control systems used in HEVs and their importance in the advancement of sustainable transportation are as follows:

I. The Powertrain Control Module (PCM) in HEVs acts as the vehicle's brain. The PCM continuously monitors parameters such as vehicle speed, engine load, battery state of charge, and driver input to determine the most efficient power distribution between the engine and the electric motor. By adjusting the throttle response, transmission gear ratios, and regenerative braking, the PCM ensures that the vehicle operates in the most fuel-efficient manner possible.

II. The Battery Management System (BMS) in HEVs monitors the state of charge and the health of the battery pack. The BMS regulates the charging and discharging of the battery to prevent overcharging or deep discharging, which can reduce the battery's lifespan. By optimizing battery usage, the BMS helps to maximize the vehicle's range and efficiency.

III. The traction control system in HEVs manages the power delivery to the wheels to optimize traction and prevent wheel slip. This system uses sensors to monitor wheel speed and adjust power distribution between the front and rear wheels as needed. The traction control system improves the vehicle's stability and handling by effectively managing traction, especially in slippery road conditions.

IV. The regenerative braking control system in HEVs is designed to capture and store energy typically lost during braking in traditional vehicles. When the driver applies the brakes, the regenerative braking system converts the vehicle's kinetic energy into electrical energy, which is then stored in the vehicle's battery for later use. This system improves the vehicle's overall efficiency and helps extend the driving range of HEVs. By providing additional power during acceleration, regenerative braking systems can help improve the overall responsiveness and agility of HEVs, making them a more enjoyable and engaging vehicle to drive. Additionally, regenerative braking can also help reduce wear and tear on traditional friction brakes, leading to lower maintenance costs and longer brake life.

V. The hybrid power control unit in HEVs acts as the vehicle's brain, coordinating the operation of the ICE and electric motor to optimize fuel efficiency and performance. This unit constantly monitors various parameters such as battery charge level, engine load, and driving conditions to determine the most efficient power source at any given time. The hybrid power control unit ensures that the vehicle operates at peak efficiency by seamlessly switching between the ICE and the electric motor.

These systems work together to maximize fuel efficiency, reduce emissions, and improve vehicle performance under different driving conditions. For example, the traction control system helps to prevent wheel slip during acceleration. In contrast, the regenerative braking system captures energy during deceleration and stores it in the battery for later use [76].

4.2 | Factors Influencing the Efficiency of Hybrid Electric Vehicles

Lai et al. [77], Tu and Yang [78], and Li et al. [79] investigated the efficiency of HEVs, which depend on a variety of factors that can impact their overall performance and effectiveness. These factors can range from the design and technology of the vehicle itself to external influences such as driving conditions and maintenance practices. These factors are crucial to maximize the efficiency and benefits of HEVs as follows:

I. Some key factors that influence the efficiency of HEVs are driving behavior and conditions. Factors such as speed, acceleration, and braking patterns can affect the fuel efficiency of HEVs. Driving at high speeds or accelerating aggressively can increase fuel consumption, while steady driving and optimum speeds can enhance fuel efficiency. Furthermore, driving in stop-and-go traffic or hilly terrain can also affect the efficiency of HEVs, as these conditions may require constant use of the ICE mode.

II. Maintenance practices also contribute to HEVs' efficiency. Regular maintenance, such as oil changes, tire rotations, battery checks, tire inflation, and engine tune-ups, is important for maximizing efficiency and prolonging the vehicle's lifespan. Neglecting maintenance can lead to decreased performance and efficiency, as well as potential mechanical issues that may impact the overall lifespan of the vehicle.

III. Another key factor that can influence the efficiency of HEVs is the size of the vehicle. Larger vehicles typically require more power to operate, resulting in decreased efficiency compared to smaller vehicles. This is because larger vehicles have more weight to move, requiring more engine and battery energy. In contrast, smaller vehicles are generally more aerodynamic and require less power, making them more efficient overall [79].

IV. The type of battery technology used in the vehicle is another important factor that can impact the efficiency of HEVs. The efficiency of a hybrid vehicle is largely dependent on the performance of its battery, which stores and releases energy to power the electric motor. Advances in battery technology have led to improvements in the efficiency of HEVs, with newer Li-ion batteries offering higher energy density and longer driving ranges compared to older NiMH batteries [33].

4.3 | Energy Management Systems in Hybrid Electric Vehicles

Energy Management Systems (EMS) are essential for the functioning of HEVs. The task required implementing control techniques, which might be practicality-based, based on real-time application, or development and evolution. *Fig. 5* provides a comprehensive overview of the ecology of EMS approaches, as described by Munsi and Chaoui [80].

These systems optimize energy utilization from the ICE and the electric motor, aiming to maximize fuel economy and minimize emissions. EMS in HEV regulates the energy transfer between the ICE, the electric motor, and the battery [61].

This entails monitoring many data, including vehicle velocity, engine burden, battery charge level, and driver input, to ascertain the optimal method of power distribution. The EMS utilizes this data to determine the optimal use of the electric motor, ICE, and battery recharging.

A crucial obstacle in developing a successful EMS for HEVs is the requirement to harmonize conflicting goals, such as optimizing fuel efficiency, enhancing performance, and reducing emissions. For example, the EMS must prioritize utilizing the electric motor to achieve optimal fuel efficiency or utilize the ICE for improved performance.

These tasks necessitate using advanced algorithms and control techniques considering many parameters, such as driving conditions, traffic patterns, and battery state. Another crucial element in EMS design is the use of regenerative braking. Regenerative braking enables the electric motor to function as a generator, transforming the energy of motion into electrical energy that can be stored in the battery. The EMS should be able to smoothly transition between regenerative braking and conventional friction braking to optimize energy recuperation while maintaining vehicle safety. To achieve better fuel economy and fewer emissions compared to traditional ICE cars, the design and implementation of EMS in HEVs require a thorough comprehension of vehicle dynamics, powertrain architecture, and control theory [52], [81].

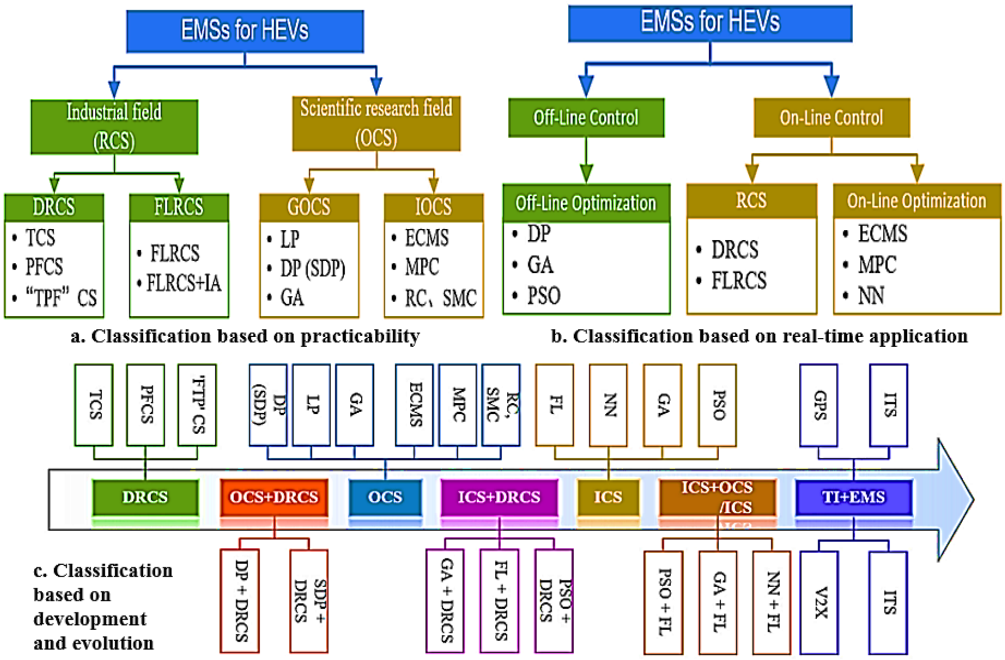

Fig. 5. Classification of the energy management system for hybrid electric vehicle Systems [55].

4.4 | Start-Stop System in Hybrid Electric Vehicles

An important characteristic of HEVs is the start-stop system, which automatically turns off the engine when the vehicle stops after the driver presses the brake pedal and then turns it back on when the driver releases the brake pedal. This device enhances fuel economy and mitigates pollutants by eliminating the practice of idling when the vehicle is not in motion.

The start-stop system in HEVs employs sensors and control units to oversee many metrics, including vehicle velocity, engine temperature, and battery charge status. Upon the driver using the brake pedal and the vehicle coming to a halt, the system immediately ceases the engine operation to reduce needless fuel consumption and emissions. Upon the driver's release of the brake pedal, the system initiates the engine restart, facilitating a seamless and prompt movement of the vehicle [82–84].

An important advantage of the start-stop system in HEVs is its capacity to decrease fuel consumption and emissions, particularly in urban driving scenarios characterized by frequent stops and starts. Another benefit of the start-stop technology is its capacity to enhance the overall driving experience by diminishing noise and vibration while the vehicle is not in motion. By turning off the engine, drivers can have a more serene and pleasant journey, particularly in urban regions with frequent traffic congestion.

Although HEVs offer advantages, certain drivers may see the start-stop system as difficult or bothersome, as the engine restarts each time the vehicle halts. Nevertheless, manufacturers have implemented enhancements to the system to achieve a higher level of integration and minimize the driver's awareness of it [85]–[87].

5 | Power-Split Transmissions in Hybrid Electric Vehicles

Power-split transmissions are essential in HEVs since they enable the smooth combination of power generated by both ICE and electric motors. It has many benefits, such as enhanced fuel economy, seamless acceleration, and decreased emissions [80]. A power-split transmission utilizes a planetary gear set to combine and transmit power from ICE and electric motor to the wheels. This enables the utilization of several operating modes, such as electric-only, engine-only, and a hybrid mix of both.

The primary element of a power-split transmission is the planetary gear set, comprising sun gear, ring gear, and several planet gears [88]–[90]. The sun gear is linked to the electric motor, the ring gear to the wheels, and the planet gears to the ICE. By varying these components' velocity and trajectory of rotation, the transmission may smoothly transition between various operational modes. A key benefit of a power-split transmission is its capacity to maximize the use of both ICE and electric motors.

When the vehicle moves slowly or often stops and starts, the electric motor can supply energy to the wheels, resulting in lower fuel usage and emissions. Under high-speed highway driving circumstances, the ICE can assume control, delivering enhanced power and efficiency. One additional benefit of power-split transmissions is their capacity to capture and store energy when braking. During deceleration, the electric motor functions as a generator, transforming kinetic energy into electrical energy and storing it in the battery. The energy may be utilized to operate the electric motor while accelerating, enhancing fuel efficiency [88], [89].

5.1 | Electric Motors Used in Hybrid Electric Vehicles

Electric motors are essential for the functioning of HEVs since they supply the required power to propel the vehicle and enhance fuel economy. HEVs often utilize the following types of electric motors: Brushless DC (BLDC), Permanent Magnet (PM), Switched ReluctanceReluctance, and Polyphase Induction motors.

I. BLDC motors are extensively utilized in HEVs because of their notable efficiency, small dimensions, and low maintenance needs. These motors employ electronic commutation instead of brushes, minimizing friction and wear and enhancing efficiency and durability. Moreover, BLDC motors accurately regulate speed and torque, rendering them well-suited for HEV applications needing adjustable power output.

II. In contrast, PM motors employ magnets to generate a magnetic field that interacts with the stator windings to generate motion. PM motors are renowned for their exceptional power density and efficiency, which makes them a highly favoured option for HEVs. Utilizing rare-earth magnets in PM motors significantly improves their performance by delivering more torque and power output in a smaller, more efficient design.

III. Switched Reluctance motors are a frequently employed form of electric motor in HEVs. These motors function based on magnetic ReluctanceReluctance, wherein the rotor is drawn towards the stator poles when power is applied. Switched Reluctance motors are recognized for their simplicity, durability, and ability to generate high torque in a compact form, making them well-suited for HEV applications that demand high torque at low speeds.

IV. Polyphase induction motors are utilized in HEVs as a cost-efficient and dependable method for electric propulsion. These motors function based on the theory of electromagnetic induction. The stator windings generate a rotating magnetic field, which induces a current in the rotor, resulting in motion. *Table 4* provides a summary of the different electric motors utilized in HEVs.

Table 4. Comparison of various electric motors used in hybrid electric vehicle [91].

Electric Motors	BLDC	PM	Switched Reluctance	Polyphase Induction
Type	AC	DC	AC	AC
Family	Synchronous excited PM.	Separately excited	Synchronous unexcited.	Induction slip ring squirrel cage.
Power to rotor	PM	DC	Induced	Induced
Power to stator	Pulsed DC	PM	Pulsed DC	AC
Overall cost	High	Medium	Medium	Medium
Weight	Low	Medium	Medium	Medium
Commutation method	Internal electronic	Mechanical commutation	External electronic	External electronic
Controller cost	Very high	Medium	High	High
Pros	Outstanding torque and speed, fast responses, tremendous power, and long life.	High starting torque	Low inertia can be tailored for specific applications and runs cool.	High efficiency
Cons	Very expensive, limited economy to small-sized motors.	Susceptible to damage if dropped, requires maintenance, bulky and limited rotation speed.	It is not very powerful full, ripple in torque and requires position sensing.	Expensive controller
Maintenance requirement	Low	Brushes wear	Low	Low
Speed control method	Frequency-dependent	PWM	Frequency-dependent	Frequency-dependent
Starting torque	[175% of rated torque	[200% of rated torque	Up to 200% of rated torque	High
Speed range	Excellent	Limited by brushes, easy control.	Controllable	Controllable
Efficiency	High	High	Less than PMDC	High
Application	HEVs, EVs and ICVs	HEVs, EVs and ICVs	ICVs	HEVs, EVs and ICVs
Efficiency with motor only (%)	80	97	94	90
Efficiency with power electronic devices only (%)	98	93	90	93
Efficiency with motor and power electronic devices (%)	78	90	85	84

6 | Environmental Impact Benefits of Hybrid Electric Vehicles

Franzò and Nasca [92], Petrauskienė et al. [93], and Balali and Stegen [94], in their investigative studies, reported the environmental impact of HEVs when compared to traditional gasoline-powered vehicles. The environmental impact benefits of HEVs are highlighted as follows:

I. HEVs emit minimal CO_2 compared to other contemporary vehicles. The combined effect of ICE and electric motors in HEVs allows for better fuel efficiency, reducing GHG emissions.

II. By utilizing both gasoline and electricity as power sources, HEVs minimize reliance on fossil fuels while minimizing total gasoline consumption. This helps conserve finite fossil fuel resources and reduces the environmental impact associated with extracting and burning fossil fuels.

III. HEVs contribute to improved air quality. Their reduced emissions result in reduced levels of harmful pollutants such as NOx and particulate matter, which limits the rise in respiratory diseases and other health challenges associated with poor air quality.

IV. As the demand for cleaner and more efficient vehicles increases, HEVs offer a viable option to traditional gasoline-powered vehicles, leading to sustainable transportation. Adopting HEVs can help transition toward an effective, sustainable transportation system that is less dependent on fossil fuels [95]. *Table 5* presents a comparative presentation of emissions for different driving cycles.

Table 5. Comparative presentation of emissions for different driving cycles [96].

Parameters	Conventional	EV	Series Hybrid	Parallel Hybrid
Control complexity	NA	Simple	Medium	Complex
Weight (kg)	Very low	High	Medium	Low
NOx (g/km)	High	NA	Medium	Low
CO (g/km)	High	NA	Medium	Low
HC	High	NA	Low	Medium
Fuel consumption (km/L)	High	NA	Medium	Low
Amount of energy supplied or depleted (MJ)	NA	Low	Medium	High

6.1 | Benefits of Hybrid Electric Vehicles

Alanazi [26] and Muratori et al. [97] highlighted the significant benefits of HEVs. They enunciated the surge in their popularity in recent years due to their numerous advantages over traditional gasoline-powered vehicles, which are as follows:

I. Electric motors in HEVs allow for regenerative braking, which captures energy that would otherwise be spent as heat during braking and stores it in the battery for later use. This results in a better fuel economy and reduced emissions of harmful pollutants such as CO_2, NO_x, and particulate matter, contributing to air pollution and climate change.

II. Although HEVs may have a higher initial cost than traditional vehicles, they offer long-run cost savings for car users via efficient fuel usage. This is because they combine gasoline and electric power to operate, allowing them to achieve optimum fuel efficiency and offset total fuel costs.

III. HEVs contribute to a better fuel economy compared to contemporary vehicles. The electric motor in HEVs plays a vital role in supplementing the gasoline engine, enabling the car to operate with minimum fuel. This improved fuel economy saves car users fuel costs and minimizes the total CO_2 emissions from the vehicle.

IV. Noise reduction and pollution are two key benefits HEVs offer that improve ride comfort for drivers and passengers. One of the main sources of noise in vehicles is the engine, which can be loud and disruptive, especially during acceleration. However, HEVs can operate in electric-only mode at low speeds, substantially decreasing engine noise. This contributes to ride comfort and a quieter driving experience for occupants while minimizing noise pollution in urban areas.

As the automotive industry moves towards sustainable transportation alternatives, HEVs are gaining more advantages in terms of becoming suitable choices for vehicle users who prioritize minimal vehicle emissions and fuel expenses.

6.2 | Drawbacks of Hybrid Electric Vehicles

Cao et al. [74] reported the problems encountered by HEVs despite their potential. Their limitations are presented as follows:

I. HEVs have a higher initial cost compared to traditional vehicles. They are comparably costlier than their gasoline vehicle counterparts, which may serve as a deterrent for many consumers. Furthermore, maintenance and repair costs for HEVs are equally on the rise due to their complicated dual powertrain systems.

II. HEVs have a limited range compared to gasoline-powered vehicles. While they have the potential to switch between electric and gasoline power, they still depend widely on gasoline for long-distance traveling. This may cause discomfort to drivers who frequently travel long distances and may not have access to charging stations.

III. While HEVs generate less emissions compared to traditional vehicles, they still depend upon fossil fuels for power.

IV. The production and disposal of HEV batteries can have a detrimental environmental effect [98].

Consumers should carefully weigh the pros and cons of HEVs before deciding whether to purchase one [99].

7 | Conclusion and Recommendations

The results of this study, which reviewed conventional HEV technologies in terms of their impact on the environment, have presented some insight into the benefits and challenges related to implementing HEV technologies. Although HEVs have been considered a greener alternative to conventional gasoline-powered cars, the findings from this study revealed that their environmental impacts are not as benign as usually perceived. One of the findings from this study showed that the ecological advantages of hybrid cars are hampered by factors such as the power source used to charge the battery, the driving conditions, and the manufacturing process of the car. For example, in events where the electricity required to recharge the battery is generated from fossil fuels, the ecological footprint of the car may not considerably differ from that of contemporary gasoline-powered vehicles.

In addition, this study also emphasized the difficulties associated with the disposal of hybrid car batteries, which may include hazardous substances that may lead to the depletion of environmental aesthetics if not appropriately addressed. These findings suggest that hybrid cars are viable for long-term usage, but alternative battery technologies with minimal detrimental environmental impact should be sought. While hybrid cars may minimize the emission of damaging pollutants like nitrogen oxides and particulate matter, improving air quality in metropolitan regions, their environmental consequences are more complex than often assumed. Therefore, further research is required to unravel HEV technologies' environmental challenges and devise more sustainable transportation alternatives for the future. Based on the perspectives above, the following suggestions are suggested for future studies and policy development in the area of HEV technologies and environmental sustainability:

I. Continued research on advanced hybrid technologies: Future research should focus on developing advanced hybrid technologies that improve fuel efficiency and reduce emissions. This could include integrating renewable energy sources such as solar or wind power and developing more efficient battery technologies.

II. Incentives for hybrid vehicle adoption: Policymakers should consider implementing incentives for hybrid vehicle adoption, such as tax credits or rebates. This can help accelerate the transition to more sustainable transportation options and reduce reliance on fossil fuels.

III. Infrastructure development: Investments in infrastructure, such as charging stations for PHEVs, are essential to supporting the widespread adoption of hybrid technologies. Policymakers should prioritize infrastructure development to facilitate the transition to a more sustainable transportation system.

By implementing the recommendations outlined in this systematic review, policymakers, researchers, and industry stakeholders can work together to accelerate the adoption of hybrid technologies and create a more sustainable transportation system for future generations.

Author Contribution

Aniekan Ikpe: Conceptualization and development; Michael Bassey: Investigation, supervision, and delivered resources; Imo Akpan: Review editing and proofreading.

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Data Availability

All data supporting the reported findings in this research are provided in the paper. All authors have read and agreed to the publication of this research work.

Conflicts of Interest

The authors declare no conflict of interest with the findings and publication of this research work.

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