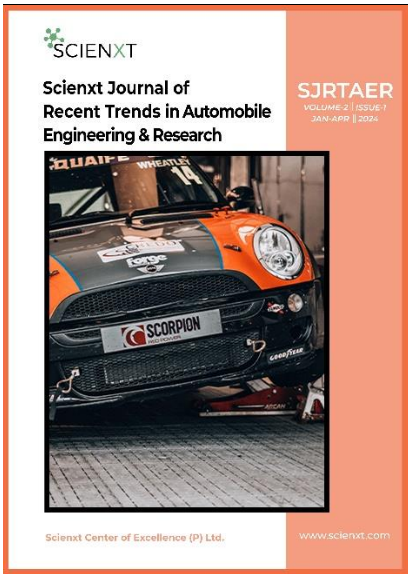


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# *Driving towards tomorrow: exploring the evolution and challenges of hybrid electric vehicles*

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## Abstract:

Hybrid electric vehicles (HEVs) represent a piv- otal advancement in automotive technology, blending internal combustion engines with electric propulsion systems to redefine the future of transportation. This review paper comprehen- sively explores the intricate components, diverse types, versatile operation modes, compelling advantages, persistent difficulties, and groundbreaking innovations within the realm of HEVs. HEVs encompass various types, including full hybrids, plug- in hybrids, and mild hybrids, each offering distinct benefits in terms of efficiency, range, and environmental impact. Innovative powertrain architectures, next-generation batteries, regenerative braking systems, predictive energy management, and electrification of auxiliary systems, vehicle-to-grid integration, and advanced driver assistance systems are among the cutting-edge innovations shaping the evolution of HEV technology. However, challenges such as cost barriers, battery degradation concerns, weight con- straints, maintenance requirements, infrastructure limitations, and consumer adoption hurdles persist, underscoring the need for collaborative efforts to overcome obstacles and accelerate the transition to a sustainable transportation paradigm. Through an in-depth analysis of HEV components, types, operation modes, advantages, innovations, and difficulties, this review paper pro- vides valuable insights into the current state and future prospects of hybrid electric vehicles in the automotive industry.

# 1. Introduction:

Hybrid electric vehicles (HEVs) combine the environmental advantages of electric propulsion systems with the efficiency of internal combustion engines, marking a revolutionary development in automotive technology [1][2][3]. This review paper provides an in-depth analysis of HEVs, breaking down their complex parts, various varieties, and adaptable modes of operation, attractive features, enduring difficulties, and revolutionary inventions. The paper explores the subtleties of each HEV type, shedding light on their distinct characteristics and contributions to sustainable mobility. From full hybrid electric vehicles (HEVs) that can seamlessly switch between electric and internal combustion modes to plug-in hybrid electric vehi- cles (PHEVs) that offer extended electric-only driving ranges and mild hybrid electric vehicles (MHEVs) that improve fuel economy through electric motor supplementation. The review also explores the basic elements of hybrid electric vehicle (HEV) technology, such as power electronics, transmissions, traction batteries, electric motors, and internal combustion engines (ICEs). The foundation of HEV propulsion systems is made up of these parts, which facilitate effective energy storage, power delivery, and vehicle control. The study also examines the dynamic operating modes of HEVs, clarifying how each mode maximises powertrain performance and efficiency in a range of driving situations. These modes include series and parallel hybrid configurations as well as series- parallel hybrid modes. The paper highlights the transformative potential of hybrid electric vehicles (HEVs) in shaping a cleaner, greener transportation future by analysing the benefits of electric vehicles, including environmental sustainability, energy efficiency, lower operating costs, The review paper also looks at the difficulties that HEVs face, including initial costs, battery deterioration, weight restrictions, maintenance needs, infrastructure constraints, and barriers to consumer adoption. Notwithstanding these obstacles, continuous advancements in HEV technology—including sophisticated powertrain designs, batteries of the future generation, regenerative braking systems, energy management prediction, electrification of auxiliary systems, integration with advanced driver assistance systems (ADAS), and vehicle-to-grid integration—keep pushing efficiency, performance, and sustainability gains. This review paper seeks to educate and motivate progress towards cleaner, more efficient, and more sustainable mobility solutions by navigating the opportunities and complexities present in hybrid electric vehicle technology.

# 2. Types of hybrid electric vehicles:

## 2.1. Full hybrid electric vehicles (HEVs):

Strong hybrids, sometimes referred to as full hybrid electric vehicles (HEVs), can run solely on electricity, only on an internal combustion engine (ICE), or both. These cars use advanced powertrain control systems to smoothly transition between modes of propulsion according to road conditions


***Figure. 1: HEV***

And energy requirements. Full HEVs can run entirely on electricity when idling or travelling at low speeds in cities, which lowers emissions and fuel use. The Ford Fusion Hybrid and Toyota Prius are two examples of full hybrid vehicles. Prius in particular is well known for being a trailblazer in the popularisation of hybrid technology, providing a reliable, adaptable, and fuel-efficient combination [4].

## 2.2. Plug-in hybrid electric vehicles (PHEVs):

Unlike conventional hybrids, plug-in hybrid electric vehicles (PHEVs) have an internal combustion engine in addition to an electric motor and a larger battery pack. The capacity of PHEVs to be refilled from an external power source, like a regular electrical outlet or a charging station, sets them apart. This enables plug-in hybrid electric vehicles (PHEVs) to run entirely on electricity for a predetermined amount of time, usually 20 to 50 miles, before starting their internal combustion engines. Because of this, PHEVs provide more versatility and the possibility to save fuel, particularly for drivers who have short commutes or access to charging stations. The Chevrolet Volt and Mitsubishi Outlander PHEV are well-known PHEV models that combine extended range with electric-only driving and the assistance of a petrol engine [5].

## 2.3. Mild hybrid electric vehicles (MHEVs):

Unlike full hybrids, mild hybrid electric vehicles (MHEVs) cannot run the car entirely on electricity. Instead, they use an electric motor and a small battery pack to supplement the internal combustion engine. Instead, by producing extra torque during acceleration and cruising, the electric motor mainly enhances fuel economy and power delivery. In order to save even more fuel, MHEVs frequently have start-stop systems that turn off the engine when the car stops. While MHEVs are more efficient and reduce emissions than full hybrids or plug-in hybrid electric vehicles (PHEVs), they usually have lower levels of electrification. The Honda Accord Hybrid and Chevrolet Malibu Hybrid are two examples of MHEVs that use hybrid technology to improve performance without sacrificing affordability.

## 3. Components of hybrid electric vehicles:

### 3.1. Internal combustion engine (ICE):

One of the main power sources in hybrid electric vehicles (HEVs) is the internal combustion engine (ICE). Fueled primarily by petrol (though some hybrid electric vehicles, or HEVs, may run on diesel or other fuels as well), the internal combustion engine (ICE) generates mechanical power through burning fuel. Because it functions in tandem with an electric motor in HEVs, the internal combustion engine (ICE) is frequently more compact and efficient than in conventional cars. Depending on the vehicle's operating mode and power requirements, the ICE can either drive the wheels directly or function as a generator to charge the traction battery while in use [10].

### 3.2. Electric motor:

Electric motors, which can function independently or in conjunction with internal combustion engines to provide propulsion, are essential parts of hybrid electric vehicles. These motors drive the wheels of the vehicle by converting electrical energy from the traction battery into mechanical power. Electric motors have many benefits, such as quiet operation, great efficiency, and instantaneous torque delivery. Electric motors are essential to regenerative braking in hybrid cars because they store kinetic energy during slowing down and transform it into electrical energy to recharge the battery.

### 3.3. Traction battery:

In hybrid electric cars, the traction battery is a rechargeable energy storage device that stores electrical energy for the electric motor or motors. Lithium-ion (Li-ion) and nickel- metal hydride (NiMH) are two common battery chemistries; Li-ion batteries are becoming more and more popular because of their lighter weight and higher energy density. In order to maximise

Fuel efficiency and lower emissions, the traction battery works in conjunction with the internal combustion engine to power the electric motor during acceleration. Furthermore, the traction battery in plug-in hybrid electric vehicles (PHEVs) can be recharged externally, extending the vehicle's range when running on electricity alone.

## 3.4. Power electronics:

In hybrid electric vehicles, power electronics parts like inverters, converters, and controllers are in charge of controlling the flow of electrical energy between the traction battery, electric motor(s), and other vehicle systems. These components control frequency, voltage, and current to guarantee the electric propulsion system operates effectively. Bidirectional energy flow is another feature of power electronics, which makes it possible for PHEVs to perform tasks like regenerative braking and traction battery charging from an external power source or internal combustion engine.

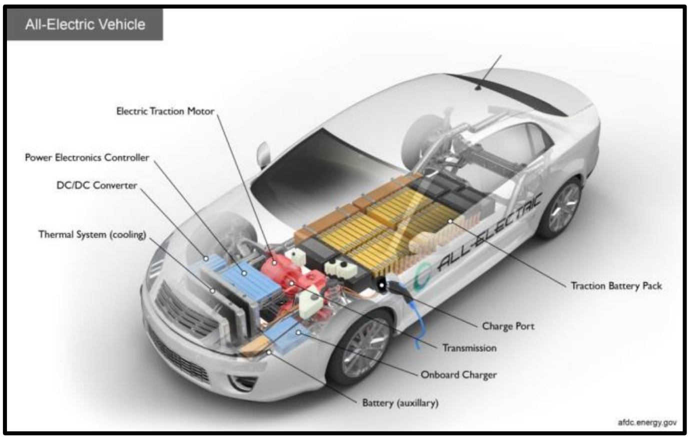


***Figure. 2: Components of Hybrid Vehicle***

## 3.5. Transmission:

In hybrid electric vehicles, the gearbox controls speed and torque in addition to transferring power from the internal combustion engine and electric motor(s) to the wheels. Hybrid gearboxes can range from conventional automatic or manual gearboxes to continuously variable transmissions (CVTs) or dual-clutch transmissions (DCTs), depending on the design of the vehicle. The gearbox is an essential component in hybrid vehicles as it regulates gear ratios and handles the changeover between various propulsion modes to maximise power delivery, fuel efficiency, and vehicle performance.

# 4. Operating modes of hybrid electric vehicles:

## 4.1. Series hybrid mode:

The internal combustion engine (ICE) does not drive the wheels directly when operating in series hybrid mode. Rather, it functions as a generator, generating electricity to run the electric motor or motors and also to replenish the traction battery. By transforming electrical energy from the battery into mechanical power to drive the wheels, the electric motor(s) provide propulsion. This mode is usually engaged when driving at low speeds or when the car needs little power, like when cruising or driving through cities. By avoiding inefficient engine load conditions, series hybrid mode lowers fuel consumption and emissions by enabling efficient operation of the internal combustion engine at its optimal operating point [11].

## 4.2. Parallel hybrid mode:

The internal combustion engine (ICE) and/or electric motor(s) provide propulsion simultaneously in the parallel hybrid mode. While the electric motor(s) help to provide extra power during acceleration or high-load situations, the internal combustion engine (ICE) drives the wheels directly through the gearbox. When accelerating quickly, turning onto a high- way, or ascending a steep grade, this mode is frequently used because it requires the combined output of the internal combustion engine and one or more electric motors to meet performance standards. By utilising the advantages of both propulsion systems, the parallel hybrid mode maximises powertrain efficiency and produces lower emissions and better fuel economy than conventional vehicles [7].

## 4.3. Series-parallel hybrid mode:

Aspects of both series and parallel modes are combined in the series-parallel hybrid mode, which provides flexible power delivery based on driving circumstances and energy requirements. In this mode, the internal combustion engine (ICE) can power the wheels directly through the gearbox while also serving as a generator to power the electric motor(s) or recharge the traction battery. Additionally, the electric motor or motors can operate independently by obtaining power from the ICE or by drawing energy from the battery. Through the dynamic adjustment of the ICE and electric motor(s) contribution based on variables like speed, load, and battery state of charge, series-parallel hybrid mode maximises powertrain efficiency and delivers improved fuel efficiency and performance in a variety of driving scenarios.

# 5. Advantages of electric vehicles:

## 5.1. Environmental sustainability:

Since EVs have no tailpipe emissions, there is a noticeable decrease in air pollution, noise pollution, and greenhouse gas emissions. Countries can reduce the negative effects of vehicle emissions on the environment and public health by switching to electric propulsion, supporting international efforts to fight climate change and enhance air quality [6].

## 5.2. Energy efficiency:

Since they can convert a larger proportion of electrical energy from the battery into mechanical power to drive the vehicle, electric motors are by nature more efficient than internal combustion engines. Because of this efficiency advantage, less energy is used per mile of travel, which lowers the demand for fossil fuels overall and the transportation sector's corresponding carbon footprint.

## 5.3. Lower operating costs:

For a variety of reasons, EVs are less expensive to operate than traditional cars. On a per-mile basis, electricity is typically less expensive than petrol or diesel, which lowers fueling expenses. Additionally, compared to cars with internal combustion engines, electric vehicles have fewer moving parts, which lowers maintenance and repair costs over the course of ownership.

## 5.4. Performance and driving experience:

Instantaneous torque is produced by electric motors, enabling smooth and responsive acceleration from a stop. With its rapid acceleration and steady power delivery over a broad speed range, this feature makes driving more enjoyable. Furthermore, the lack of engine noise makes the ride for passengers quieter and more comfortable...

## 5.5. Energy independence and security:

Numerous energy sources, including renewable ones like solar, wind, and hydroelectric power, can power electric vehicles. By utilising domestic renewable resources, this diversification of energy supply improves energy security and lessens reliance on imported fossil fuels. Through vehicle-to-grid (V2G) technology, EVs also present opportunities for energy storage and grid stabilisation, strengthening the foundation of a more robust and sustainable energy infrastructure.

## 5.6. Incentives and subsidies:

To promote the use of electric vehicles, numerous governments provide tax credits, rebates, and exemptions from road taxes and vehicle registration fees. These financial incentives speed up market adoption and promote economies of scale in battery and vehicle manufacturing by offsetting the higher upfront cost of electric vehicles and making them more accessible to consumers.

## 6. Difficulties in hybrid vehicles:

### 6.1. Cost:

When it comes to initial costs, hybrid cars are typically more expensive than cars with traditional internal combustion engines. Higher manufacturing costs are a result of the hybrid powertrain's additional complexity, which includes electric motors, batteries, and power electronics. The initial purchase price still acts as a barrier for some customers, even though the overall cost of ownership may be lower over time due to lower fuel consumption and maintenance costs.

### 6.2. Battery degradation and replacement costs:

Age, temperature changes, and charge-discharge cycles are some of the factors that cause the traction batteries used in hybrid cars to deteriorate over time. Degradation of batteries can result in lower performance, a shorter electric range, and eventually the need for replacement—a costly process. Potential buyers of hybrid cars may be discouraged by worries about the traction batteries' longevity and durability [9].

### 6.3. Weight and packaging constraints:

Electric motors, batteries, and power electronics are common extra parts found in hybrid cars, which increase the vehicle's weight. The additional weight may have an impact on overall driving dynamics, braking effectiveness, and handling. Furthermore, it can be difficult for manufacturers to incorporate hybrid components into a vehicle's design without sacrificing interior space or cargo capacity, which limits the flexibility and creativity of design.

### 6.4. Complexity and maintenance requirements:

Compared to traditional internal combustion engines, hybrid powertrains are more complicated, necessitating specific maintenance and repair techniques. In order for service technicians to properly diagnose and repair hybrid components, they might need extra equipment and training. Furthermore, the combination of various propulsion systems and control algorithms raises the possibility of possible malfunctions or failures, which can cost owners more in maintenance and cause downtime.

## 6.5. Infrastructure limitations:

Hybrid vehicles still need access to petrol or diesel filling stations even though they do not exclusively depend on charging infrastructure like plug-in hybrid or battery electric vehicles do. For long-distance driving in particular, hybrid owners may have trouble locating convenient refuelling options in areas with a lack of alternative fuel sources or charging infrastructure. To encourage the widespread use of hybrid vehicles, the infrastructure for fueling must be made more easily accessible and reliable.

## 6.6. Consumer perception and adoption:

Hybrid cars have advantages for the environment and the economy, but some consumers might be reluctant to use this technology because of worries about dependability, resale value, and lack of experience with hybrid powertrains. Furthermore, consumers' preferences and purchase decisions may be influenced by false information regarding the durability, performance, and range of hybrid vehicles in comparison to conventional vehicles or fully electric alternatives.

# 7. Innovations in hybrid electric vehicles:

## 7.1. Advanced powertrain architectures:

In order to maximise the integration of internal combustion engines, electric motors, and energy storage systems, automakers are constantly creating new powertrain architectures. More flexibility in power delivery and increased overall efficiency are made possible by innovations like power-split devices, multi-mode transmissions, and series-parallel hybrid configurations [8].

## 7.2. Next-generation batteries:

Technological developments in batteries form the basis of HEV innovation. In order to boost energy storage capacity, de- crease weight, and extend lifespan, manufacturers are investing in the development of high-energy-density battery chemistries, such as lithium-ion, solid-state, and lithium-sulfur batteries. Compared to conventional nickel-metal hydride (NiMH) batteries, these next-generation batteries have a higher power output, quicker charging times, and greater safety.

## 7.3. Regenerative braking systems:

When braking and decelerating, regenerative braking systems absorb kinetic energy and transform it into electrical energy, which replenishes the traction battery. The utilisation of regenerative braking algorithms, motor-generators, and energy management systems has led to advancements in efficiency and energy recovery, which have expanded the range of electric vehicles and decreased dependence on internal combustion engines.

## 7.4. Predictive energy management:

Using real-time data, GPS navigation, and predictive algorithms, predictive energy management systems optimise powertrain performance according to road conditions, topography, traffic patterns, and driver behaviour. These systems can intelligently distribute power between the internal combustion engine and electric motor to minimise fuel consumption and emissions while maximising performance and driving range. They do this by anticipating future road conditions and energy demands.

## 7.5. Electrification of auxiliary systems:

Vehicle efficiency is increased when auxiliary systems like water pumps, air conditioning, and power steering are electrified. This lowers parasitic losses. Novel approaches, like electrically powered pumps and compressors, do away with the requirement for mechanical belts and lessen the strain on the internal combustion engine, which lowers fuel consumption and improves driving.

## 7.6. Vehicle-to-grid integration:

Vehicle-to-grid (V2G) integration makes it possible for HEVs and the electrical grid to exchange energy in both directions, transforming cars into mobile energy storage devices. V2G technology advancements allow HEVs to release stored energy back into the grid during periods of high demand. This reduces dependency on fossil fuels and promotes the integration of renewable energy sources while offering grid stabilisation, demand response, and potential revenue streams for vehicle owners.

## 7.7. Integration of advanced driver assistance systems:

In order to improve safety and convenience, hybrid electric vehicles (HEVs) are progressively integrating advanced driver assistance systems (ADAS), such as automated emergency braking, adaptive cruise control, and lane-keeping assistance. By integrating with hybrid powertrain controls, advanced driver assistance systems (ADAS) can maximise vehicle performance and efficiency, minimise driver workload, and enhance the overall driving experience.

## 8. Conclusion:

In summary, hybrid electric vehicles (HEVs) are a huge development in automotive technology, providing a flexible and environmentally friendly mode of transportation that tackles issues related to emissions, fuel consumption, and environmental effect. Internal combustion engines, electric motors, traction batteries, power electronics, and transmissions are just a few of the parts that HEVs use. These parts all work together to maximise powertrain performance and efficiency. There are several varieties of these cars, such as plug-in hybrids, mild hybrids, and full hybrids, each with unique benefits related to emissions reduction, driving range, and fuel economy. Different driving conditions can be accommodated by HEVs through their ability to operate in multiple modes, including series, parallel, and series-parallel hybrid modes. This allows for dynamic power delivery.

The efficiency, performance, and sustainability of HEV technology are also continuously being improved by ongoing innovations like next-generation batteries, advanced power- train architectures, regenerative braking systems, and electrification of auxiliary systems, vehicle-to-grid integration, and integration with advanced driver assistance systems. HEVs do, however, have certain drawbacks, such as greater upfront costs; battery deterioration and replacement costs; limitations on weight and packaging; maintenance needs; restricted infrastructure; and barriers to consumer adoption and perception. In order to overcome technical, financial, and regulatory obstacles and expedite the widespread adoption of hybrid electric vehicles as a crucial element of the shift towards a cleaner, greener, and more sustainable transportation future, automakers, legislators, researchers, and industry stakeholders will need to work together.

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