Proceedings of the 5th International Conference on Materials Chemistry and Environmental Engineering
DOI: 10.54254/2755-2721/124/2025.20046

An Overview of the Development and Energy Management Strategies in Hybrid Electric Vehicles

Teng Zhang[1,a,*]

[1]*School of Energy Systems, Lappeenranta University of Technology, 53900 Lappeenranta, Finland*
a. Teng.Zhang@student.lut.fi
**corresponding author*

Abstract: With the intensification of the global greenhouse effect and the restriction of energy use in countries around the world, hybrid electric vehicle (HEV) is one of the important solutions and has become a research hotspot and development trend in today's automotive field. This study reviews the development history of hybrid electric vehicles, and also discusses key energy management strategies. Hybrid electric vehicles use both motor and internal combustion engines, through a unique power transmission system, significantly reducing fuel consumption while also achieving low emissions and high energy efficiency. The ultimate objective is to transition towards fully electric vehicles. However, the primary challenge currently facing hybrid vehicles is energy management optimization. Enhancing energy efficiency and environmental performance through precise regulation of the power output between the internal combustion engine and the electric motor is the core technology driving the advancement towards a greener and more efficient future.

Keywords: Hybrid electric vehicle, Energy management system, Energy storage

1. Introduction

People's pace of life and convenience for traveling have improved due to the development of the automobile industry, but its related environmental pollution and energy shortage are becoming increasingly serious, and the gas emissions generated by transportation account for 30% of the world's total emissions[1]. With the global attention to environmental protection, the control of gas emissions generated by vehicles has become the focus of countries. Research shows that electric vehicles are being recognized as the best solution to climate change due to their low emissions and high energy efficiency[2]. Electric vehicles are mainly divided into hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), pure electric vehicles (PEV) and fuel cell vehicles (FCV). PEV's performance is limited by factors such as charging time, range and cost; FCV requires proven fuel cell technology and cost performance. Until there is a breakthrough in battery technology, hybrid cars are the effective solution. Combining internal combustion engine and electric motor, the energy management strategy solves the problem the high emissions of traditional internal combustion engine vehicles and the short endurance of battery-powered vehicles. This study focuses on energy management strategies (EMS) and optimization of HEVs, and explores how to further improve energy efficiency and environmental performance of HEVs by analyzing current technological developments and applications. The significance of studying this issue is that, with the increasing global demand for a low-carbon economy, optimizing the EMS of HEVs can not only reduce

DOI: 10.54254/2755-2721/124/2025.20046

greenhouse gas emissions, but also improve fuel economy, thereby contributing to the achievement of global environmental goals. To meet the market demand for green vehicles, precise energy management strategies will help car manufacturers develop more efficient, low-consumption hybrid vehicles. This study also provides a technical basis for policymakers to promote more stringent environmental regulations and policies.

2. The development of HEV

2.1. The history of HEV

Austrian-German engineer Ferdinand Polscher and his partner Ludwig Lohner created the world's first front-wheel-drive hybrid car, the Lohner-Porsche Semper Vivus, 12 years after the birth of the internal combustion engine car (Karl Benz 1). It is short for Lohner-Porsche and combines an internal combustion engine with an electric motor, marking an initial exploration of hybrid technology. Ferdinand Porscher continued to improve the Lohner-Porsche for the next two years, finally presenting the "finished product" at the Paris World's Fair in 1900. Subsequently, Robert Anderson proposed the concept of hybrid electric vehicles and designed the hybrid power system, which promoted HEV development[3].

Robert Anderson repeatedly attempted to develop hybrid cars, but the limited technology and market acceptance at the time prevented mass production. In 1912, Charles Kettering invented the electric starter, which made it easier for conventional fuel cars to start, leading to the decline of electric cars in the market at the time. Until the outbreak of the oil crisis in the 1970s and the global concern for energy security, hybrid vehicles once again became a hot topic. Polypack developed the hydrogen fuel cell in 1971, pushing the boundaries of alternative fuels and revitalizing them. During this period, car manufacturers such as Henry Ford also tried, but hybrid technology was still not mature. The 1990s saw Japanese automakers make a major breakthrough in the hybrid space. In 1997, Toyota launched the world's first mass-produced hybrid vehicle - Prius, with a top speed of 170 km/h and fuel consumption of only 4.7 L/100 km, which simultaneously achieved ultra-low fuel consumption and zero exhaust emission[3]. Its excellent fuel economy and environmental performance have won wide recognition in the market. Subsequently, Honda and other Japanese brands have also launched hybrid models, further promoting the prosperity of the hybrid car market.

After entering the 21st century, with the progress of battery technology and the optimization of control systems, the fuel economy and power performance of hybrid electric vehicles have been significantly improved, and governments have also increased their support for electric vehicles, providing a guarantee for the popularization and development of hybrid electric vehicles.

2.2. Current situation of HEV

According to the current market performance, the performance of plug-in hybrid electric vehicles (PHEV) is particularly outstanding. HEV has become the mainstream of the market in China, Europe, Japan and other countries and regions, and its sales continue to grow globally, which is expected to maintain this trend in the next few years.

As can be seen from Table 1, China is the world's largest sales country, and Japan has strong purchasing power due to its long-term deep cultivation in hybrid technology. Compared with Europe, the United States and Japan, China's hybrid power started late but developed rapidly, the largest market capacity.

Table 1: Countries that hybrid cars are mainly sold in[4]

Country	Continent	Sales (vehicle)	Proportion (%)
China	Asia	2314238	28.23
Japan	Asia	1503360	18.34
USA	North America	954620	11.65
Germany	Europe	821399	10.02
UK	Europe	584249	7.13
Italy	Europe	480983	5.87
France	Europe	457105	5.58
Spain	Europe	217934	2.66
Korea	Asia	209366	2.55
Sweden	Europe	124840	1.52

2.3. Future development

With global sales of pure electric vehicles growing less than expected, global automakers are focusing on hybrid models to meet customer demand and the need for a gradual transition to electrification. The hybrid model can help the car reduce fuel consumption and emissions in the short term by combining the traditional fuel engine system with the electric system, and it has a great advantage in adapting consumer car habits and easing mileage anxiety.

The hybrid model can help the car reduce fuel consumption and emissions in the short term by combining the traditional fuel engine system with the electric system, and it has a great advantage in adapting consumer car habits and easing mileage anxiety. Toyota continues to focus on traditional hybrid models; Ford plans to boost sales of its hybrid V-6 (V-type six cylinder) by 20% by 2024; Chrysler relied on the HEV model transition before launching an electric model; Audi maintains profits in the short term with hybrid models; Kia is putting hybrid and plug-in hybrid models at the heart of its electrification transition (Table 2).

Judging from these strategies, hybrid models will play an important role in the electrification process in the coming years, especially after 2024, when the introduction of hybrid models will further accelerate.

Table 2: The world's major Oems hybrid new plans[5]

Automobile manufacturer	Hybrid strategy
Toyota	Toyota has been focusing on traditional hybrid models.
Ford	In September 2023, Ford announced plans to double V-6 hybrid sales in the United States to about 20 % by 2024.
Chrysler	Its electrification strategy will rely on HEVs until it starts rolling out a range of electric vehicles in 2024.
Audi	In December 2023, in order to maintain operations and stable profits, Audi announced that it would slow down the speed of electric transformation and continue to promote internal combustion engines and plug-in hybrid electric vehicles in the short term.
Kia	In the transition to all-electric, Kia's near - and medium-term goals will be to focus on hybrid and plug-in hybrid models.

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3. Main types and technical characteristics

HEV powertrains can be divided into three main types based on the combination of an internal combustion engine and an electric motor: Series HEV, Parallel HEV, and series-parallel HEV. Each type has its own characteristics in terms of power transmission, energy management and system efficiency.

Figure 1 shows how a series hybrid vehicle works. The internal combustion engine is not directly involved in driving the wheels, but instead drives a generator to generate electricity, which converts mechanical energy into electricity that can either be stored in a battery or fed directly to an electric motor to drive the wheels. The inverter is responsible for converting direct current into alternating current to drive an electric motor. The electric motor converts electrical energy into mechanical energy, which drives the wheels through the transmission system and propels the vehicle forward. When the vehicle needs to accelerate or climb a hill, the electric motor will provide all the power output. In addition, the electric motor can provide additional power when needed to assist the internal combustion engine, thereby improving overall energy efficiency, optimizing energy use, improving fuel economy and reducing emissions, especially for frequent stop-start driving scenarios on urban roads.

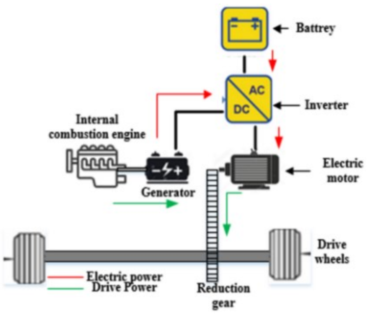

Figure 1: Series HEV[6]

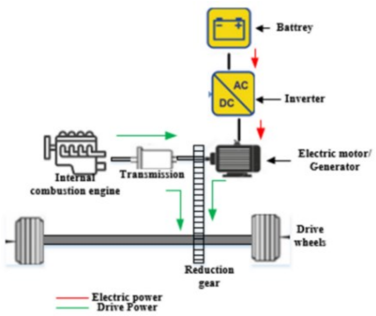

Figure 2: Parallel HEV[6]

An internal combustion engine and an electric motor simultaneously provide the power source in Figure 2, working together to drive the wheels through a mechanical transmission with high transmission efficiency. The internal combustion engine burns fuel to generate power, and the electric motor both drives the wheels and acts as a generator to charge the battery. Both transmit power to the wheels through a transmission, while the battery stores electrical energy to support the motor. The inverter converts direct current to alternating current in this process to suit the motor requirements. The reducer is responsible for adjusting the speed and torque of the motor to ensure that it matches the wheel and optimizes the efficiency of power transmission. The system structure of parallel HEV is simple, the manufacturing and maintenance cost is low, and the fuel economy and power performance can be taken into account[6].

Figure 3 shows the system structure of a series-parallel hybrid electric vehicle. This structure combines the advantages of series and parallel structures to flexibly adjust the power output of the internal combustion engine and the electric motor through the power distribution device. The power distribution unit is the core component of the entire structure, which can precisely control the power distribution between the engine and the electric motor to optimize fuel economy and power performance. The internal combustion engine acts as the traditional power source, driving the generator to produce electricity, which, together with the electricity stored in the battery, drives multiple motors. The bidirectional power inverter realizes the flexible conversion of power between the generator and the motor, and improves the efficiency of energy utilization. In the starting and low speed driving stage, the system uses series mode; In the high-speed driving phase, the system is converted into a parallel mode to achieve a balance between fuel economy and power performance[7]. This structure combines the advantages of series and parallel structures to flexibly adjust the power output of the internal combustion engine and the electric motor through the power distribution device.

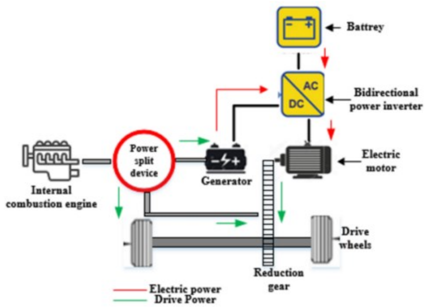

Figure 3: Series-parallel HEV[6]

4. Overview of energy management strategies (EMS) for hybrid electric vehicles

4.1. Basic concepts and objectives of EMS

Energy management Strategy (EMS) is one of the key technologies of hybrid electric vehicles, its core task is to accurately coordinate the power distribution between the engine and the electrical system in the premise of meeting the power demand. The main objective of EMS is to optimize the overall performance of hybrid vehicles, including fuel consumption, pollutant emissions, driving mobility, and the service life of the power source. To achieve these goals, EMS needs to consider the power needs of the vehicle, the real-time operating status of the power system, and the differences between different power sources in terms of work efficiency and load capacity. Artificial intelligence and communication technology are gradually integrating EMS with intelligent transportation systems to enhance energy efficiency, minimize emissions, and enhance vehicle performance. The successful application of EMS can significantly improve fuel economy, reduce emissions, and improve driving performance, providing a guarantee for the sustainable development of future transportation[8].

4.2. Current situation of EMS

4.2.1. Current main EMS technologies

In current hybrid electric vehicles, energy management strategies mainly rely on rule-based control strategies[9]. Most of these strategies are based on the vehicle's real-time state, power requirements, and information such as battery charge (SOC), using preset rules or thresholds to determine the operating mode of the electric motor and internal combustion engine. Although the implementation of this kind of control method is relatively simple, it depends on accurate rule setting and cannot fully adapt to complex and changeable driving conditions [10].

Power following strategy: This strategy is one of the most common energy management methods for hybrid vehicles. The internal combustion engine is usually kept in its most efficient working zone, while the electric motor is used to assist in providing additional power needs[11]. This way, the internal combustion engine can avoid fuel consumption in inefficient operating conditions, while in scenarios with high power requirements such as acceleration, the electric motor can step in in time, thereby improving overall efficiency.

Battery State management strategy: This strategy is mainly based on the State of Charge (SOC) of the battery to control the cooperation of the internal combustion engine and the electric motor. Usually, the internal combustion engine maintains the State of Charge (SOC) within a specific range, and when

DOI: 10.54254/2755-2721/124/2025.20046

the battery level drops below a threshold, it simultaneously provides more power and charges the battery. When the charge is sufficient, the electric motor takes on more driving force, reducing the use of internal combustion engines[12].

Load sharing strategy: When starting and accelerating, the energy requirements of the vehicle are high, and the electric motor usually bears most of the load, the work load of the internal combustion engine is reduced. This can not only reduce the starting load of the engine, but also reduce fuel consumption and emissions, which is especially suitable for frequent start-stop situations in urban driving environments[13].

4.2.2. Advanced EMS technology

With the continuous progress of hybrid electric vehicle technology, energy management strategies based on traditional rules are gradually developing into intelligent, model prediction and real-time optimization strategies, which can improve system flexibility and response speed while making energy management more adaptive[14].

Model-based Predictive control (MPC) : MPC is an advanced control method that can predict the future operating conditions of the vehicle and plan the current energy distribution[15]. With real-time monitoring of the road, driving environment and power needs, the MPC dynamically adjusts the collaboration between the internal combustion engine and the electric motor to maximize the vehicle's energy efficiency. For example, when facing a long downhill road, the MPC can make full use of the kinetic energy recovery system to switch to the energy recovery mode in advance[16]. EMS based on artificial intelligence and machine learning: Today's EMS gradually introduces artificial intelligence (AI) and machine learning (ML) technologies. By analyzing large amounts of historical and real-time data, machine learning algorithms are able to adapt energy management strategies in different driving scenarios[17]. This not only improves the energy efficiency of the system, but also ADAPTS to changing environments, driver behavior patterns, and different road conditions. For example, energy management strategies based on deep learning predict vehicle energy demand using neural network algorithms, optimize real-time power system distribution, and improve fuel economy and vehicle endurance[9]. Another study, based on reinforcement learning, automatically adjusts the vehicle's motor and engine collaboration mode to achieve optimal energy utilization by analyzing different driving conditions[18].

4.2.3. Energy management challenges for hybrid electric vehicles

Although the current EMS has improved the efficiency of hybrid vehicles, there are still many challenges. EMS should consider not only fuel economy, but also power response and driving comfort, and emission control is also an important factor to be considered[19]. How to find a balance between these goals is a big challenge for EMS. Although accurate energy management strategies can extend battery life and optimize usage efficiency to a certain extent, the current battery technology limits the performance improvement of hybrid electric vehicles, especially in terms of battery energy density and charging speed, and restricts the development of EMS[20]. EMS needs to deal with complex and changing driving environments, including urban traffic, suburban roads, and different climatic and road conditions. In such a complex environment, ensuring the reliability of energy management strategies is an important direction for EMS development in the future.

DOI: 10.54254/2755-2721/124/2025.20046

4.3. EMS future development trend

4.3.1. The integration of intelligence and autonomous driving

With the advancement of autonomous driving technology, the energy management strategy (EMS) of hybrid electric vehicles will gradually be deeply integrated with the autonomous driving system. Future EMS not only needs to allocate energy according to vehicle status, but also needs to dynamically adjust to the external environment, such as traffic congestion, road conditions and weather conditions[21]. This way, the system optimizes the vehicle's energy efficiency in real time, ensuring optimal energy use in various driving conditions. The Internet of Vehicles (V2X) and cloud computing technologies will provide EMS with richer real-time data. By communicating with the external environment and other vehicles, EMS can more intelligently manage the vehicle's energy use, such as adjusting power distribution in advance when encountering traffic lights or changes in road conditions ahead. This intelligent energy management helps to further reduce energy consumption and improve the overall performance of hybrid electric vehicles[22]. For example, in an autonomous driving scenario, the vehicle can obtain information such as traffic signals ahead, road slope and weather conditions in advance, so as to adjust the working mode of the internal combustion engine and electric motor. When approaching a red light, the system can enter a low energy mode in advance, thereby reducing unnecessary fuel consumption.

4.3.2. Integrated energy management

The development of EMS is not limited to the optimization of a single vehicle, the future direction of development is to combine EMS with intelligent transportation systems (ITS) to achieve a higher level of energy management optimization. Integrating EMS with ITS effectively improves the energy efficiency of the entire transportation system. For instance, simulating the EMS system in fleet operations significantly reduces fuel consumption and improves traffic flow by analyzing the operating status of all vehicles and coordinating the allocation of energy resources[23]. Another study showed that EMS can dynamically adjust vehicle energy use by obtaining real-time road condition information through vehicle networking technology, thus reducing energy waste and emissions caused by traffic congestion[24]. In the future, the deep integration of EMS and ITS will further promote the intelligent development of transportation systems, especially in fleet management and urban traffic planning, and this integrated energy management scheme will have a wide range of application prospects.

4.3.3. New energy technology combined with EMS

In the future, EMS will be more closely integrated with renewable energy sources such as solar and wind. In addition, hydrogen fuel cell vehicles may also become an important part of hybrid electric vehicles, especially in the field of heavy vehicles and long-distance transportation[25]. EMS will need to have the ability to manage multiple forms of energy to accommodate different energy sources and vehicle needs.

5. Conclusion

In summary, HEV, as a key solution in the transition to all-electric vehicles, has been widely used worldwide due to its fuel economy and low emission characteristics. Despite the competition from pure electric vehicles, HEV can still effectively reduce fuel consumption and emissions in the short term by optimizing energy management strategies. In the future, with the breakthrough of battery technology and the popularization of autonomous driving technology, the energy management of

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HEV will be more intelligent and adapt to diverse driving scenarios. However, the limitation of this paper is the scarcity of studies on multi-objective optimization and real-world driving scenarios, with most literature citations focusing on historical analysis and lacking experimental verification. Future research should deepen the combination of autonomous driving and EMS through simulation and experiments, especially in complex traffic and extreme environment applications, to promote the sustainable development of electric vehicles.

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