A Review on the Development of Hybrid Powertrain Systems and Alternative Clean Energy Engines

T.He, IEEE

Abstract-**This review examines hybrid powertrain systems and renewable-fuel internal combustion engines as transitional and long-term solutions for low-carbon transportation. As the global energy structure shifts from fossil fuels to cleaner and more sustainable energy sources, hybrid powertrain systems currently serve as an important transitional technology that combines benefits of internal combustion engines and electric motors. Therefore, this review first compares series, parallel, and series-parallel hybrid architectures in terms of energy flow, efficiency characteristics, application scenarios, and technical limitations. It then discusses energy management strategies, with particular attention to reinforcement learning methods for real-time power allocation. Finally, hydrogen and ammonia engines are reviewed as potential carbon-free combustion pathways, with a focus on combustion characteristics, storage challenges, emissions, and future development trends. Overall, this study aims to summarize the current status, key technological bottlenecks, and future development trends of hybrid and alternative clean energy engine technologies for automotive powertrains.**

Index Terms—**Ammonia engine, Hybrid vehicles, Hydrogen engine, Reinforcement learning**

I. INTRODUCTION

SINCE the development of the first automobile by Carl Benz in 1886, our demand for automobiles has exponentially increased. We are able to transport people and goods across greater distances in a shorter time, but it causes issues such as global warming from the release of greenhouse gases. Currently, the transportation sector accounts for 24% of total greenhouse gas emissions, with 74.5% from road vehicles, including passenger and freight [1]. While advancements in engine efficiency and exhaust aftertreatment systems have significantly reduced emissions over the past decades, further progression on conventional internal combustion engines are becoming increasingly limited, indicating the need for more fundamental changes in the design automotive powertrain systems [2].

Although battery electric vehicles have emerged as a potential alternative with no tailpipe emission, it faces major challenges that prevent their widespread adoption. These include raw material availability, charging infrastructure/speed, and operational limitations in long-haul scenarios and cold regions [3]. These limitations highlight the importance of hybrid powertrain systems to provide a practical intermediate solution by combining the advantages of conventional ICEs and electric vehicle systems to improve fuel economy, reduce emissions, while maintaining high reliability and practicality. Beyond both ICE-based and battery-based systems, clean alternative energy forms such as hydrogen and ammonia systems may play an important role in the future, acting as the ultimate goals to achieve zero emissions [4]. However, because these technologies are not yet fully developed, hybrid systems remain especially important at the current stage of automotive powertrain evolution, acting as a transition between traditional, mature powertrain systems and underdeveloped alternative powertrain systems [5]. In large-scale energy transitions, these alternatives play a critical role, enabling gradual emission reduction while preserving system reliability and user convenience. In the automotive sector, the hybrid powertrain system fits this description well, as it has higher efficiency and lower emissions compared to traditional fossil fuel powertrains while maintaining high convenience and reliability.

As a transition between fossil fuel-powered internal combustion engines and electric battery-powered motors, hybrid systems incorporate multiple energy conversion and storage components, greatly increasing system complexity. This interaction among mechanical, electrical, and chemical systems makes efficient energy management a central challenge. This not only means that more physical space is required in the vehicle to place these parts, but more development is required in order to achieve optimal fuel economy, emission performance, and component durability. Each type of hybrid powertrain, consisting of different components, is apt for different scenarios and has specific limitations. Therefore, there is ongoing development and research to establish the hybrid type that performs best across all environments.

Energy management in hybrid powertrain systems is central to how hybrid vehicles achieve lower fuel use and emissions [6]. In a hybrid system, a control unit constantly decides how to split the required wheel power between the internal combustion engine and the electric motor, as well as when to charge or discharge the battery or when to switch the engine on or off. The goal is to keep each component in its highest efficiency while meeting the demand of the driver [7]. However, trade-offs are also present; battery limitations, conversion losses, and driving conditions (city vs highway) can change which strategy is the most efficient overall.

At the same time, the generation of electricity, commonly through the burning of fossil fuels, poses a limitation for this powertrain form and underscores the need for a zero-emission powertrain. These constraints suggest that a single option for a cleaner drivetrain is unlikely to satisfy the unique and diverse requirements of future transportation systems, highlighting the importance of maintaining multiple powertrain development routes. Hybrid, in the long term, will also be able to coexist with current and future powertrain types, providing a cheap and reliable powertrain option.

This review examines hybrid powertrain systems as a transition within the current trend of powertrain systems towards a cleaner energy source. It first discusses the environmental limitations of conventional ICE vehicles and the potential challenges of BEVs, which limit their widespread adoption. It then introduces hybrid powertrain systems as a transitional solution and compares the architectures, characteristics, and limitations of the three mainstream types of hybrid powertrain systems-series, parallel, and series-parallel. Building on this, the essay focuses on energy management systems because the efficiency of a hybrid system depends not only on its hardware but also on its computer, which calculates the distribution of power between the motor and the ICE. Furthermore, the review explores the growing application of **reinforcement learning** in energy management to calculate the optimal ratio in real time based on the current scenario. Finally, it considers the future roles of hydrogen and ammonia systems, analyzing their potential future applications as a low-carbon automobile powertrain. The importance of this research lies in how improving powertrain design and control strategies can provide meaningful emission reduction in the near term. In the longer term, these systems also contribute to the wider development of sustainable transportation technologies, enabling a greater reduction in carbon emissions.

Therefore, this review aims to answer three questions: first, how different hybrid architectures influence powertrain efficiency and application scenarios; second, how energy management strategies, especially reinforcement learning, improve hybrid system performance and efficiency; and third, how hydrogen and ammonia engines may contribute to future carbon-free combustion systems.

II. Hybrid Electric Vehicle

Hybrid powertrain systems are systems that use two or more distinct power sources in order to improve fuel economy, reduce emissions, and optimize energy use. Most commonly, it combines an internal combustion engine, electric motor, battery pack, and power electronics. Hybrid powertrain systems can be classified into three main architectures: series, parallel, and series-parallel. Each configuration presents unique mechanical complexities, operational advantages, and distinct driving scenarios where its efficiency is maximized. The following sections will systemically explore the mechanical characteristics and energy dynamics of these three primary layouts, beginning with the series hybrid configuration.

II.A Series Hybrid

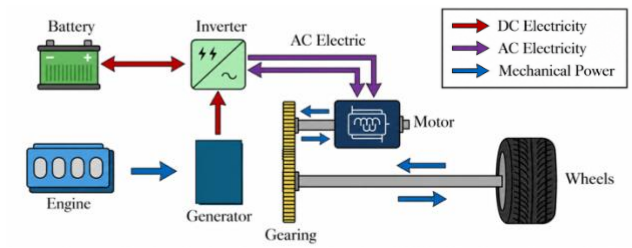

Fig. 1 Schematic Diagram of a Series Hybrid Electric Vehicle

The series hybrid architecture, as shown in Figure 1, derives its name from its sequential energy flow path, analogous to a series electrical circuit [10,12]. This architecture represents the simplest layout among the three primary hybrid types. In a series configuration, the internal combustion engine (ICE) is mechanically decoupled from the drive wheels. Instead, the ICE is exclusively used to drive a generator, converting mechanical energy into electrical energy. This electricity is then either stored in a high-voltage battery pack or routed directly to an electric traction motor, which is solely responsible for propelling the vehicle [9, 15, 17].

Compared to conventional ICE-powered vehicles, packaging a series hybrid powertrain presents greater spatial and weight challenges. The system requires housing an engine, a dedicated generator, a traction motor, a battery pack, and a power control unit (PCU) [8,10]. Furthermore, as the traction motor is solely responsible for delivering the required driving performance without direct mechanical support from the engine, it is generally sized larger compared to motors in parallel hybrid architectures. Consequently, this configuration often increases the vehicle's overall mass and volume, which can lead to higher baseline energy consumption during propulsion.

Despite the increased system mass, the main advantage of a series hybrid lies in the mechanical decoupling of the internal combustion engine (ICE) from the wheels. This enables the engine to operate near its optimal efficiency region, typically around the minimum Brake-Specific Fuel Consumption (BSFC) point, as shown in Fig. 2.

In conventional ICE powertrains, the engine operating point varies significantly with driving conditions, often leading to inefficient operation at low loads or high speeds due to frictional and pumping losses. In contrast, a series hybrid allows the engine to operate along a more efficient region and to be shut down when not required.

In addition, the absence of a multi-speed transmission reduces mechanical losses associated with clutches and gear meshing, further improving overall efficiency [10].

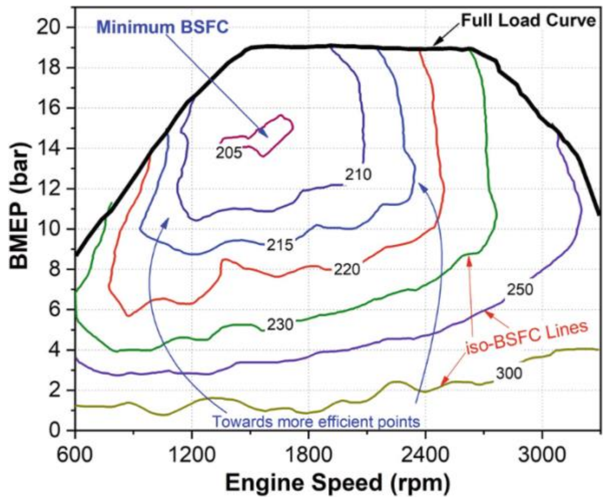

Fig.2. Brake-Specific Fuel Consumption (BSFC) Map of an internal combustion engine [80]

Due to packaging constraints and the specific power-flow characteristics of the series architecture, the internal combustion engine and the generator are typically downsized [11].

Because the traction motor must propel the vehicle independently without mechanical assistance from the engine, it must be sized to meet the vehicle's peak torque and power requirements. While this decoupling limits the vehicle's sustained high-power output compared to parallel architectures, it is exceptionally well-suited for urban driving scenarios characterized by low speeds and frequent stop-and-go traffic. In these environments, the system can heavily rely on pure electric propulsion and recover substantial kinetic energy through regenerative braking, maximizing overall urban efficiency [11].

An important component that ensures the capability of powering the motors is the inverter. The inverter acts as a converter for changing the type of electricity from DC (direct current) in the battery to AC (alternating current) which is required for powering the motors. Similarly, in regenerative braking, the inverter is also relied on for converting the AC currents generated from the motors back into DC form that is recharged and reused [18].

However, series hybrid powertrains are less efficient on highways due to energy lost as heat through multiple phases of conversion: engine, generator, battery, and motor. Representative values suggest that the motor and generator typically have an efficiency of about 90-96%, the inverter of about 95-99%, and the battery charge/discharge of about 95% [19, 20, 21]. Using the mean of these values, the efficiency is roughly 90% ($0.93 * 0.97 \approx 0.90$) if the power goes directly from the generator to the motor or around 86% ($0.93 * 0.97 * 0.95 \approx 0.86$) if it is also buffered through the battery, meaning that 10-14% of the energy can be lost before final-drive losses are considered [19,21]. When efficiency decreases, more work is lost, which decreases the amount of useful work from a fixed total work.

$$W_{\text{Total}} = W_{\text{Useful}} + W_{\text{Lost}}$$
$$\text{so} \quad W_{\text{Useful}} = W_{\text{Total}} - W_{\text{Lost}}$$

Therefore, when efficiency increases, there is less work lost and therefore more useful work produced.

In real-world applications, series hybrid powertrain systems have been used the most in Nissan's e-POWER system, in which the electric motors are powered by the ICE and drive the wheels [15]. Nissan states that this system has developed through three generations since its introduction in 2016 and has expanded across multiple vehicle classes, including compact cars, minivans, and SUVs. Some models that currently use this powertrain include the Nissan Qashqai, Nissan X-Trail, and Mazda MX-30 e-Skyactiv R-EV. More broadly, reviews suggest that they are still primarily used in urban duty vehicles such as buses and specialized urban vehicles but may become more competitive in passenger vehicles as battery systems, power electronics, and other low-loss components continue to improve. Overall, it is unlikely that series powertrain systems will dominate over the other two types. Instead, its future most likely involves continued development in niches where urban efficiency is especially valuable [16].

II.B Parallel Hybrid

In contrast to series hybrid systems, a parallel hybrid system allows both the ICE and electric motor to provide mechanical energy to the wheels, so the total torque is the sum of the ICE and motor.

$$T_{\text{Total}} = T_{\text{Engine}} + T_{\text{Motor}}$$

Therefore, a parallel hybrid usually provides higher peak torque than a series hybrid, making it better suited to power-demanding conditions such as accelerating, overtaking, and driving uphill. At low speeds or during acceleration, the electric motor gives instant torque, helping the engine overcome low-RPM inefficiency. As vehicle speed increases, the engine gradually becomes the main source of power, while the motor provides less assistance or switches off.

The two power sources can drive the wheels simultaneously or separately, allowing torque distribution to change according to driving conditions. Therefore, the term "parallel" comes from the idea that energy can flow through more than one path, as shown in Figure 3.

Similar to traditional ICE powertrains, the power from the ICE is first passes through the gearbox. Then, the energy leaves the gearbox and is joined with the motor via a driveshaft, using clutches, gears, or a torque-coupling system.

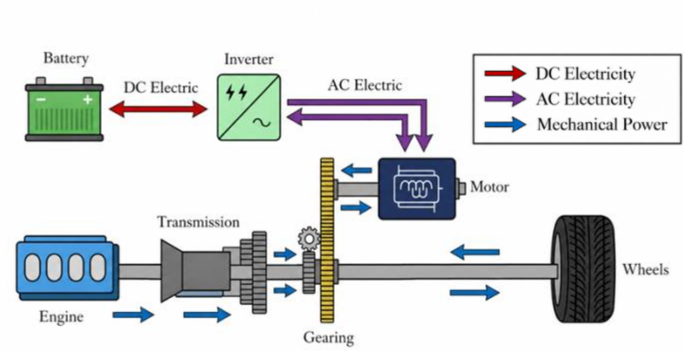

Fig.3. Schematic Diagram of a Parallel Hybrid Electric Vehicle

Parallel hybrids are especially efficient during cruising because the engine provides most of the energy, leading to fewer energy conversions and less energy loss than in series systems, even though series hybrids can allow the engine to operate near its optimal RPM. In a series hybrid, energy typically flows through the engine, generator, motor, and wheels, resulting in conversion losses. In contrast, a parallel hybrid can use the simpler path of engine → transmission → wheels. During sustained cruising, these fewer conversions can improve overall efficiency. Since the motor mainly assists during acceleration, it can also be smaller, reducing the overall size and weight of the system.

However, parallel hybrids are less efficient in stop-and-go traffic, where engine-on/off cycles reduce smoothness, which can lead to higher city emissions than other hybrid systems that rely more heavily on electric drive.

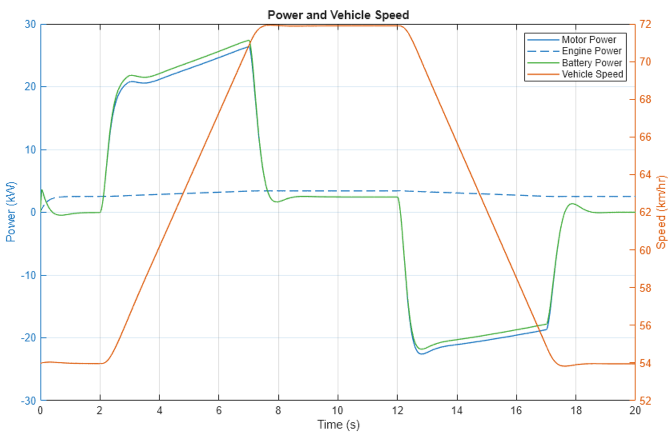

Fig.4. Distribution of the Engine, Motor, and Battery During Acceleration, Cruising, and Deceleration [79]

Figure 4 shows how the ICE, motor, and battery power change during acceleration, cruising, and deceleration. During the acceleration phase from 2.5 s to 9.5 s, both the engine and motor produce power, allowing maximum combined torque. During cruising from 9.5 s to 12 s, the engine provides most of the power, while the motor provides little to no assistance. During deceleration, the motor works as a generator, converting mechanical energy into electrical energy and storing it in the battery.

II.C Series-Parallel

A series-parallel powertrain system combines the operating principles of both series and parallel systems, granting the system more flexibility

II.C.1 Basic Principle

Like its name, the series-parallel hybrid powertrain system is a blend of series and parallel systems. Compared to parallel hybrid systems, which are structurally similar to series-parallel systems, series-parallel hybrid systems add a power-split device, usually a planetary gearset, that divides engine power into a mechanical path to the wheels and an electrical path to the generator/motor. Because of this, series-parallel combines characteristics of both series and parallel hybrids, making it a more flexible choice. According to Toyota's own description of the original Prius system, the planetary gear "constantly reallocates" engine power, keeping the engine closer to its efficient operating range [24,25].

For mass-produced passenger cars, Toyota is most influential in the development of series-parallel hybrid systems. Early since the 1990s Toyota's Prius development team built the Toyota hybrid system around a planetary-gear power-split device, and launched that production in 1997 [22,23]. However, despite the proven technical efficiency of this architecture, its wider adoption by other manufacturers did not immediately follow due to the key hybrid power-split designs and control methods being protected by patents [26]. Toyota and Ford entered licensing agreements related to hybrid systems in 2004, Toyota reaching a settlement with Paice in 2010 and Ford also licensing Paice's hybrid technology in 2018 [27,28,29,24].

It is important to note, however, that the main legal barrier was not around the planetary gear set itself, but hybrid power-split architectures and control methods built around it instead. This heavily influenced the early development trend of hybrid vehicles because it was difficult for other manufacturers to commercialize similar systems without licensing agreements or alternative designs [26]. As a result, power-split hybrid development in early periods condensed around companies with strong patent positions or licensing access, whereas other manufacturers without these patents continued to focus on simpler or alternative hybrid layouts [27,28,29].

However, this barrier weakened over time, especially after Toyota announced in 2019 that it would provide 23740 hybrid technology patents royalty-free. This helps shift the series-parallel development market away from legal restriction and towards technical refinement, cost reduction, and control optimization [30].

II.C.2 Advantages

Efficiency-wise, the power-split layout in series-parallel hybrid systems usually improves control flexibility and can keep the engine in a more efficient region compared to parallel hybrid [31]. However, the actual gain may not show as a large value due to the extra electrical path also creating losses from imperfect efficiencies. In one matched comparison, the series-parallel hybrid had slightly higher engine efficiency than the parallel hybrid: 38.18% vs 37.98%. The fuel economy was also slightly higher at 28.66 km/L vs 28.59 km/L [32]. Because this system can smoothly shift between energy sources at lower power demand, blend power output between the ICE and motor, and predominantly use mechanical engine output combined with an active electromechanical power split at higher vehicle speeds, this architecture is especially suitable for urban stop-and-go driving. This makes it suitable for daily driving and follows mainstream passenger vehicles that require both efficiency and drivability [31,33].

Another important advantage of a series-parallel hybrid is its highly efficient ability to charge the battery while the vehicle is driving. This is enabled by the planetary gears, which divide the output between a mechanical path to the wheels and an electrical path to the generator. Therefore, this system can propel the vehicle and generate electricity simultaneously, not needing to rely entirely on regenerative braking [36,9]. This feature helps address a key limitation of parallel hybrid systems. While parallel hybrids can charge the battery using the engine during propulsion, their engine speed is mechanically locked to the wheel speed. This mechanical coupling means the engine may be forced to operate outside its optimal efficiency range to generate electricity [35]. In contrast, the series-parallel system decouples the engine speed from the wheels, allowing the internal combustion engine to consistently operate at its most efficient point while simultaneously driving the vehicle and charging the battery [35,36]. As a result, the series-parallel system increases flexibility and can better maintain the battery state of charge during mixed driving conditions, allowing smoother mode switching, more frequent electrical propulsion, and more stable overall efficiency [36,22].

II.C.3 Limitations

However, the same flexibility that gives the series-parallel its advantages also creates important limitations [31,33]. The planetary gear piece is compact, but the full system usually relies on two larger motors, a more advanced inverter and control system, and more complex energy flow management than simpler parallel architectures. As a result of the increased complexity, electrical conversion losses can become significant. In one comparison, the energy losses due to electrical conversion of series-parallel systems were almost double that of the parallel system, mainly due to the two large motors [31]. This means that series parallel systems gain fuel economy and performance benefits at the cost of greater complexity, higher cost, and more difficult control [33].

Despite its high flexibility, series-parallel hybrids still face two fundamental bottlenecks. First, although the efficiency of internal combustion engines has significantly improved since their introduction, it is still far from perfect. Recent hybrid-engine development papers report brake thermal efficiency around 44%, while 50% is considered a major frontier in the field rather than an easily achievable next step [37,38]. Second, the power-split architecture inevitably introduces conversion losses because part of the engine output passes through electrical components such as the generator, inverter, motor, and battery before reaching the wheels. Therefore, although the system improves operating flexibility, it cannot eliminate the tradeoff between wider operating adaptability and additional energy-conversion losses [39].

II.C.4 Recent Development

Under the needs for a more efficient systems, recent research is increasingly focused on dedicated hybrid transmissions (DHTs) and multimode power-split mechanisms as ways to reduce these losses and widen the high-efficiency operation range. DHTs are described as a major development trend in the field because they integrate hybrid functions into the transmission itself and can offer lower cost and better performance than traditional add-on layouts [39]. In this transmission specialized for hybrid systems, clutches, fixed gears, and electric motors are used instead of relying only on a planetary power-split device [40,41]. Therefore, it is more advantageous as it can often provide a more direct mechanical connection between the engine and wheels at higher speeds, reducing electrical conversion losses compared with a conventional power-split system [42].

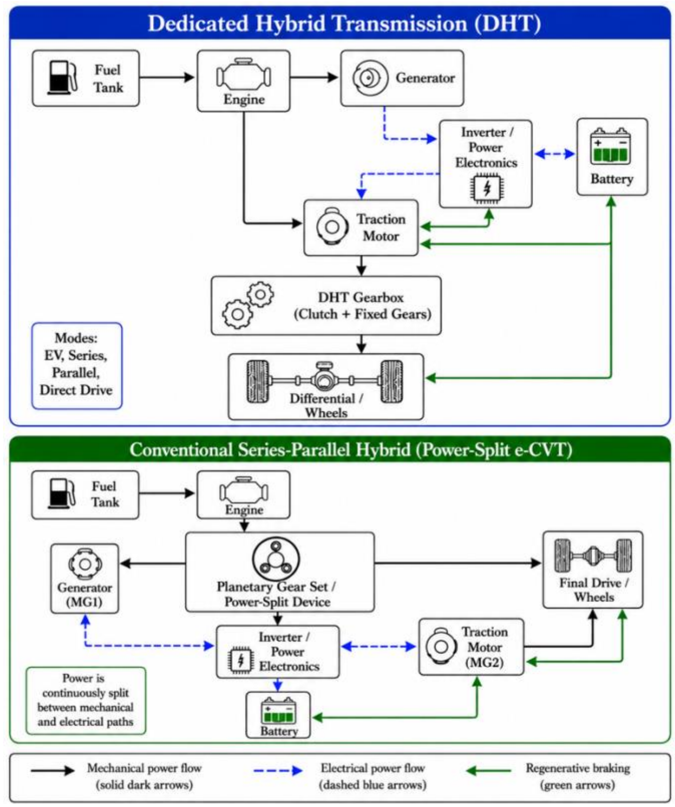

Fig.5. Energy flow comparison of DHT and e-CVT

Furthermore, more recent studies have proposed two-mode and multimode power-split e-CVT architectures that improve matching between the engine, motors, and battery across different driving conditions, while also expanding the usable efficient region of the transmission [40,41]. This is significant because in single mode systems, the same basic power-split relationship is used across most driving conditions, so at some speeds or loads the engine and motors may not be matched especially well. This can be resolved through two-mode or multimode systems, which allow switching between different power-flow arrangements. This allows the transmission use one mode that is better for low speed launch or urban driving and another than is better for medium or high speed cruising. In simple terms, the newer designs try to keep more operating in a high efficiency zone, instead of forcing one compromise layout to do everything [40.41].

Under steady highway driving conditions, the efficiency of series–parallel hybrid systems is slightly lower than that of parallel hybrids. This difference is not primarily due to the mechanical losses of the planetary gearset, which is highly efficient (typically 96%– 98%) [42,43]. Instead, it arises from the inherent power-split mechanism. In such systems, part of the engine power is typically routed through the electrical path to satisfy kinematic constraints of the planetary gearset. This results in energy flowing through multiple conversion stages, introducing additional losses compared to direct mechanical transmission. In contrast, parallel hybrid systems can operate in a mode where the engine is mechanically coupled to the wheels via clutches at cruising speeds, allowing most of the power to be transmitted through a high-efficiency mechanical path with minimal electrical conversion losses [42,43].

Currently, Toyota still remains the most prominent user of the series-parallel hybrid system, with its present hybrid lineup continuing to include mainstream models such as the Prius, RAV4 Hybrid, Camry Hybrid, and Highlander Hybrid [44]. Similarly, Toyota's luxury brand, Lexus, produces many mainstream hybrid models with systems derived from the same general power-split concept [45]. Apart from Toyota, Ford remains an important current user of series-hybrid systems in models including the Maverick Hybrid and Escape Hybrid [46]. Therefore, despite series-parallel systems being more complex than simpler hybrid layouts, they are still widely used in practical passenger vehicles due to their strong flexibility, smooth operation, and competitive efficiency across urban and mixed driving conditions [47].

II.D Energy Management Systems

In conventional ICE vehicles, because the engine is the only source of propulsion, efficiency is mainly improved by optimizing the combustion process, primarily by improving the physical components of the engine and transmission. However, hybrid systems often require more advanced energy management systems because they have multiple power sources. Specifically, efficiency also depends on how the system distributes power between the engine, motor, battery, and generator. This makes software-based energy management systems essential, as the system must constantly decide whether to use electric drive, engine drive, combined drive, or regenerative braking. Therefore, as road and driving conditions constantly change, a hybrid energy management system is essential to continuously calculate the most efficient power split to achieve the highest efficiency.

II.D.1 Equivalent Consumption Minimization Strategy (ECMS)

One common approach for optimizing efficiency is ECMS, which converts fuel use and battery electricity into a shared value, allowing the controller to compare these values over the same metric.

In hybrid energy management systems, the engine and battery are not directly compared in their original units of liters and kilowatt-hours. Instead, these systems convert electrical and gasoline consumption into an equivalent energy cost metric, enabling the controller to determine the optimal power split [48,49]. A widely used formulation is the Equivalent Consumption Minimization Strategy (ECMS), where the instantaneous objective is written as

$$m_{ECMS}(t) = m_{engine}(P_e(t)) + S_{equ}\big(P_b(t)\big)$$

$m_{ECMS}(t)$ represents the instantaneous total equivalent fuel consumption at t and is the value the controller tries to minimize [n]. $m_{engine}(P_e(t))$ shows the actual fuel consumption rate of the engine in the car, usually in per second or per hour units. The $P_e(t)$ inside the brackets, the term depends on the instantaneous engine power, with the term increasing when the engine is working harder [48,49].

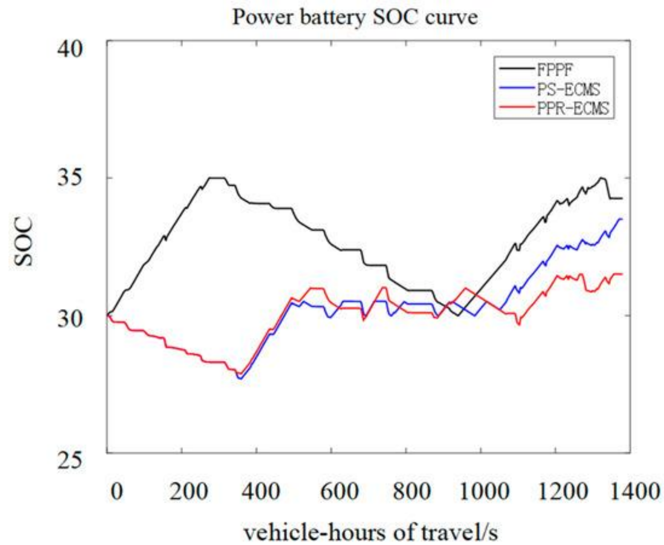

Fig.6. Battery State of Charge Over Time Across Energy Management Strategies [50]

Because battery electricity is measured in electrical units and gasoline is measured as fuel, they cannot be added directly, the term $S_{equ}(P_b(t))$ represents the battery power converted into an equivalent fuel consumption term. Inside, $P_b(t)$ represents the battery power at time *t* [m]. Usually, when $P_b > 0$ the battery is discharging, it sends power to drive the vehicles, and when $P_b < 0$ the battery is charging, it does so through regenerative braking or engine-generated electricity [48,49].

This equation can also be displayed in a simplified battery-conversion form $m_{ECMS}(t) = m_{engine}(P_e(t)) + S(t) * \frac{P_b}{\eta * Q_{flhv}}$, where $S(t)$ tells the controller how costly battery electricity is at the time compared with gasoline [48,49]. If $S(t)$ is larger, electricity is treated as more expensive, so it tends to use the engine more. If $S(t)$ it is smaller, electricity is treated as cheaper, so it tends to use the battery more [m]. P_b also represents the battery power, serving the same purpose as P_b in the other equation form. Additionally, Q_{flhv} in the denominator, it represents the fuel's lower heating value, meaning how much usable energy is contained in the fuel per unit of fuel. This allows conversion between the energy from the battery and the amount of fuel that would contain the same energy [48]. Finally, η the efficiency term, showing how energy conversion is not perfect as some energy is lost as heat in the battery, motor, inverter, generator, and other components [48,49]. When $\eta = 1$ no energy is lost, but when $\eta < 1$ only a portion of the energy becomes useful output [48,49]. This makes the equivalent fuel term larger, meaning you need more input energy to get the same useful output. Therefore, $\frac{P_b}{Q_{flhv}}$ represents "how much fuel energy this battery power is equivalent to," and $\frac{P_b}{\eta * Q_{flhv}}$ represents "how much fuel energy would really be needed after accounting for losses" [48,49].

II.D.2 Comparison of the Equivalent Consumption Minimization Strategy with the Fixed-Point Power-Following Method

Furthermore, by comparing other energy management systems to ECMS, we can visualize their efficiency. The Fixed-Point Power-Following (FPPF) is a traditional baseline strategy that runs at a fixed efficient point and follows the vehicle's power demand rather than adapting intelligently to predicted future conditions, as for ECMS methods. Fig 6 shows how each strategy affects battery state of charge (SOC) over time. This graph shows that ECMS-based control strategies are more stable than FPPF strategies in controlling SOC. This is significant in a hybrid vehicle because if it is too low, the motor cannot provide much electric assistance, so fuel economy and performance drop. Conversely, an excessive SOC may leave the battery without enough room to store energy recovered from regenerative braking. Therefore, it is important for the EMS to maintain the SOC within a healthy, stable range [50].

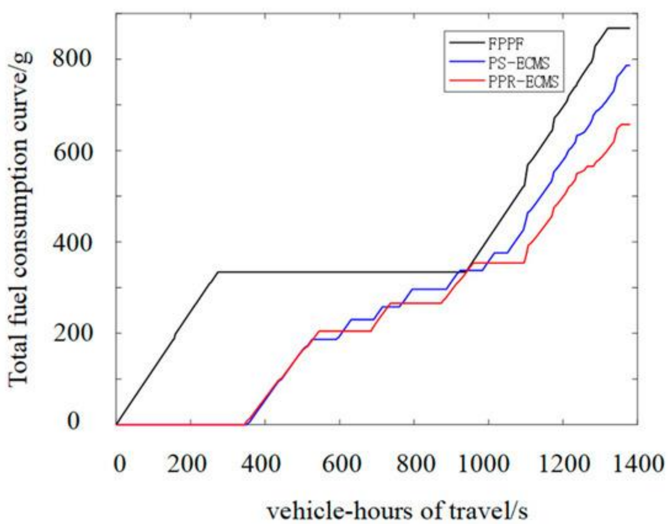

Fig.7. Total Fuel Consumption Over Time Across Energy Management Strategies [50]

Similarly, another factor that measures the efficiency of energy management strategies is the total fuel consumption, shown in Fig 7. Specifically, both ECMS strategies are shown to have consistently lower fuel consumption than FPPF systems, suggesting that ECMS methods allocate engine and battery power more efficiently than conventional FPPF strategies. The steeper sections of each curve indicate periods of faster fuel consumption, while flatter sections show lower consumption. Overall, the figure suggests that predictive ECMS methods can improve hybrid vehicle fuel economy [50].

II.D.3 Reinforcement Learning and Edge-Cloud Energy Management Systems

While ECMS is proven successful in adjusting real-time power distribution, it still depends heavily on the accuracy of its equivalent fuel-cost factor and system model. Therefore, learning-based methods such as reinforcement learning (RL) have been explored to improve adaptability under more uncertain vehicle dynamics. Unlike ECMS systems, which optimize energy distribution through a defined equivalent consumption equation, RL can study patterns from driving habits and use patterns to make decisions on power distribution. However, because many RL models are trained primarily in simulation, gaps may arise between simulation and real-world road conditions, leading to inaccuracies and inefficiencies. Furthermore, energy source values, such as temperature, state of health, and initial SOC, are also important enough to affect controller performance [51]. In addition, neural network-based controllers may introduce additional computational time, which can weaken instantaneous response if the onboard processor is limited. Therefore, many recent studies have combined RL with model predictive control (MPC) to reduce excessive learning time, improve adaptability, and strengthen real-time performance [51,52].

As energy management strategies become more advanced, the computational requirements also increase. Basic EMS methods can make decisions using simple equations and calculations, whereas learning-based methods such as RL and MPC require more sophisticated calculations and pattern analysis. However, the onboard Electronic Control Unit (ECU) has limited processing power and must handle safety-critical tasks, so an alternative strategy is needed that provides greater processing power whilst maintaining flexibility, allowing safety task calculations to be left on the vehicle for rapid response.

A promising solution under research is through edge-cloud energy management systems. In this system, energy management calculation tasks are split across three levels of computation: vehicle, edge, and cloud. At the vehicle level, the car measures speed, driver power demand, battery SOC, and engine/motor states, and makes safety-related decisions, such as object detection, emergency braking, and lane-keeping maneuvers to ensure low latency of under 10ms. At the edge level, a nearby roadside or local server handles larger tasks that are too heavy for the ECU but still need quick updates, such as short-horizon traffic-speed prediction and near-term torque or power-split optimization, with latencies of 10-50ms. At the central cloud level, much larger computations are done using broader information, such as global path planning, model training, and predictive maintenance, with latencies of 100-500ms+. In conclusion, the vehicle sends operating data upward, the cloud computes long-term strategies, the edge refines that into more instantaneous control actions, and the vehicle executes the final command locally [53].

III Concluding Comparison of Hybrid Architectures

Overall, each of the three major hybrid architectures provides a unique balance between efficiency, performance, complexity, and cost. The series hybrid is best suited for low speeds and urban environments, as the wheels are only driven by the electric motor, enabling smoother operation and strong regenerative braking in stop-and-go traffic. However, energy lost over multiple conversion phases reduces its efficiency in high-speed scenarios [54,55]. The parallel hybrid is better suited to highway and high-load conditions because the engine can directly drive the wheels, reducing conversion losses and improving high-speed efficiency. Its structure, which allows the motor and engine to drive the wheels simultaneously, delivers stronger torque, making it better suited for acceleration, overtaking, and climbing [54,55,56]. The series-parallel hybrid combines the advantages of the previous systems and is therefore the most flexible option, performing well across urban and other mixed conditions. However, this flexibility comes with greater control complexity, more components, and higher production costs [57]. Therefore, no single architecture is universally best; instead, each hybrid type is optimized for different driving demands and design priorities [54,55,56,57].

Table 1
A Performance Comparison Between the Mainstream Hybrid Architectures

Category	Series	Parallel	Series-parallel
Complexity	Medium+	Medium-	High
Cost	Medium–high	Medium	High
High-speed performance	Low–medium	High	Medium–high
Low-speed performance	High	Medium	High
Energy efficiency	High in city, lower on highway	High on highway, moderate in city	High overall
Best Scenario	Urban / stop-go traffic	Highway / high-load driving	Mixed / daily driving

Energy management systems are essential in hybrid vehicles because the vehicle's efficiency depends not only on its physical structure but also on how power is distributed between the engine, motor, and battery. A well-designed hybrid system should allow reduced emissions and fuel consumption while maintaining battery health and vehicle performance [54,58].

Especially as hybrid systems become more complex and require higher emission standards, advanced approaches such as RL become increasingly valuable because they can adjust power allocation in real time in response to changing driving conditions [54,55,58]. For example, Yang et al. integrated RL into a model predictive control framework and used LSTM-based speed prediction to address two key weaknesses of conventional energy management systems (EMSs)- excessive learning time and poor adaptability- while improving real time performance, currently with both simulation and hardware tests supporting the method [51]. Additionally, Han et al. developed a battery-life-constrained reinforcement learning EMS to solve the trade off between fuel economy and battery degradation, allowing continuous adjustments in distribution between the engine and battery under driving conditions while still operating in real time [59]. Furthermore, Xu and Lin proposed a safe RL method specifically addressing another major limitation of RL: safety. Their method was designed to keep battery state of charge and other constraints within safe limits while simultaneously handling continuous actions such as engine torque, gear shifting, and clutch engagement [60].

Although hybrid systems are providing meaningful reductions in fuel use and emissions, they are still a transitional technology rather than a final endpoint [61]. Specifically, their main importance lies in bridging the gap between conventional fossil fuel vehicles and future zero-emission powertrains. In the long run, the ultimate aim is to transition to powertrains with zero emissions, so hybrid vehicles support this transition rather than replacing the long term goal of cleaner transportation [62,63]. This is why growing attention is now being directed toward hydrogen and ammonia engines, which may play an important role in achieving future powertrains with zero emissions [61,62].

IV Decarbonized Alternative Clean Energy Engines

Although hybrid powertrains reduce carbon emissions and fuel consumption by combining the ICE with electrical propulsion, these systems still partly depend of fossil fuels and therefore remain a transitional rather than a final solution. The ideal future automotive powertrain should be both highly efficient and with little to no emissions. Therefore, decarbonized clean energy engines, especially hydrogen and ammonia, have attracted increasing attention from both industry and academia. Among the possible pathways, hydrogen engines are regarded as one of the most promising options because hydrogen is a carbon-neutral energy carrier, has high energy density, and is well compatible with existing engine manufacturing and powertrain infrastructure. In this sense, hydrogen engines are important not only as a possible widespread clean energy powertrain, but also as a route that can bridge the gap between conventional ICE systems and zero-emission systems.

IV.A Hydrogen Powertrain Systems

In hydrogen powertrain systems, hydrogen is used as fuel and clean energy source for combustion and vehicle propulsion. During the chemical process $2H_2 + O_2 == 2H_2O$ where two hydrogen molecules are combined with two oxygen molecules to form two water molecules, the formation of new oxygen-hydrogen bonds in water releases more energy than is needed to break the original hydrogen-hydrogen and oxygen-oxygen bonds [64]. Therefore, the reaction is exothermic, releasing energy as heat and increasing gas pressure, which pushes the pistons, as in ICE engines. Based on fuel form, hydrogen systems can be divided into pure hydrogen systems and dual-fuel systems, and based on injection strategy, they include intake manifold injection and direct in-cylinder injection. Pure hydrogen systems use hydrogen alone and produce mainly water vapor during combustion, while dual-fuel systems blend hydrogen with conventional fuels to reduce carbon emissions while maintaining high combustion efficiency

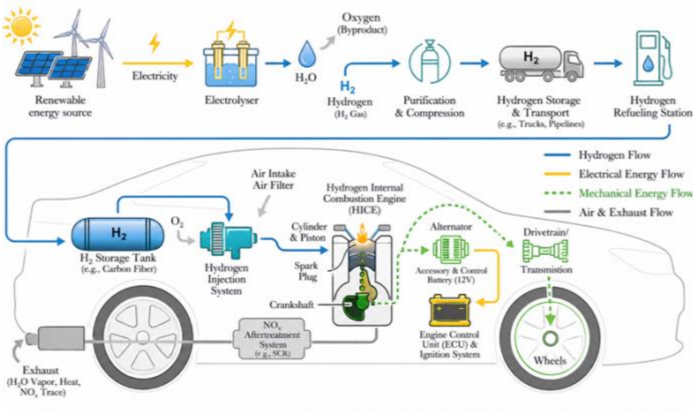

Fig.8. Energy Flow for Hydrogen Powertrain Systems

The widespread hydrogen powertrain system is structurally similar to a conventional pure ICE system. Shown in fig 8, hydrogen is first produced externally, then purified, compressed, stored, and transported before being filled into the vehicle's hydrogen tank. Inside the vehicle, hydrogen flows from the hydrogen storage tank to the hydrogen injection system, where it is mixed with oxygen and delivered into the cylinders through valves. Inside the cylinder, a spark plug ignites the hydrogen-air mixture, and the combustion releases heat, increasing gas pressure and pushing the piston [64]. This piston motion is converted by the crankshaft into rotational mechanical energy, mostly to spin the wheels and partly to an alternator that produces electrical energy for the engine control unit (ECU) and ignition system [64]. After combustion, waste gas is directed through a NOx aftertreatment system, where a majority of NOx harmful gases can be filtered out, and other products, such as water, will be released through the exhaust [64]. Therefore, the main energy pathway follows as hydrogen chemical energy, combustion heat energy, piston motion, crankshaft rotation, drivetrain, and finally wheel propulsion.

Hydrogen has several important fuel properties that explain its appeal. Firstly, it has a low calorific value (LCV) of 119.7 MJ/kg, significantly higher than 49 MJ/kg in conventional fossil fuels. LCV refers to the heat produced by combusting a unit quantity of fuel, so greater energy density allows hydrogen engines to produce more energy per unit of fuel than gasoline engines. Secondly, Hydrogen's minimum ignition energy (MIE) of 0.02 mJ is significantly lower than gasoline's 0.24 mJ, meaning less energy is required to ignite the fuel. Additionally, hydrogen has a very wide flammability range of 4-76% and a rapid laminar burning velocity of 1.85 m/s. These properties allow hydrogen to burn rapidly, operate under lean conditions, and achieve high thermal efficiency. However, the properties also create important technical challenges. Hydrogen's fast flame speed and high reactivity increase the risks of abnormal combustion, including backfire, pre-ignition, and knock, while its high combustion temperature can also promote NOx formation [64,65]. NOx pollution refers to nitric oxide (NO) and nitrogen dioxide (NO_2), formed when nitrogen and oxygen in the air react under high-temperature combustion. This is significant because although hydrogen combustion does not directly produce carbon-based emissions, it can still generate NOx due to its high flame temperature. Emissions of NOx are important because they contribute to smog, acid rain, ozone formation, and respiratory harm.

One way to combat this is through ultra-lean combustion, which can raise brake thermal efficiency, an engine's effectiveness in converting fuel's chemical energy into useful mechanical work, to 45%. Other engine technologies proven successful for reducing combustion temperatures, mitigating knock, and reducing NOx emissions include cooled Exhaust Gas Recirculation (EGR), Selective Catalytic Reduction (SCR), and water injection, which have been shown to reduce NOx by up to 97% [64,66]. Overall, these cases show that control strategies are essential for making hydrogen combustion practical [64,65,66].

Another major limitation lies outside the cylinder itself: hydrogen production and storage remain difficult. Hydrogen does not freely exist in nature, so it can only be produced through chemical processes. Traditionally, Methane and water are processed through a steam reformer and a water-gas shift reaction. However, because carbon molecules are also formed as a byproduct, cleaner methods, such as water electrolysis, are being developed [65,67]. In this method, electricity, often from clean sources such as solar or wind, is used along with water to form separate hydrogen and oxygen molecules.

Hydrogen is stored in three forms: compressed gas, liquid hydrogen, and solid hydrogen. Compressed gaseous hydrogen is the most mature and widely used vehicle option at the current stage and typically requires high-pressure tanks of about 350-700 bar. However, hydrogen gas has very low volumetric energy density at ambient conditions, so these tanks are relatively large and costly [68]. Conversely, liquid hydrogen offers a higher volumetric energy density but must be kept at cryogenic temperatures near -252.8 °C. This requirement increases energy consumption, insulation requirements, and boil-off losses- heat leaks causing partial evaporation [68]. Lastly, solid hydrogen is stored either on the surface of solids by adsorption or within materials by absorption. For instance, metal hydrides store hydrogen by absorbing it into a metal or alloy, and chemical storage materials store hydrogen through chemical bonding. This approach is attractive because it can operate under milder pressure conditions and offer improved safety and storage density. However, it is currently limited by slow absorption/desorption rates, material costs, and incomplete technological maturity for larger vehicles [68,69,70]. Therefore, while compressed gas remains the dominant short term solution, liquid and solid form storage continue to be important research directions for improving practicality [68,70].

In addition to form, onboard storage is challenging because hydrogen's small molecular size can cause permeation and embrittlement of storage materials, while its flammability imposes strict safety requirements. Current stage approaches mainly include high-pressure gaseous storage, cryogenic liquid storage, and solid-state storage, with high-pressure gaseous storage, often up to 350-700bar, currently the dominant solution for vehicles [64,66]. Therefore, hydrogen engines have strong decarbonization potential, but their wider adoption will depend on continued progress in hydrogen production, storage, combustion control, and NOx mitigation [71].

IV.B Ammonia Powertrain Systems

Similar to hydrogen, Ammonia, chemically written as NH_3, is another promising clean energy fuel for future internal combustion engines. Similar to hydrogen powertrain systems, the gas is also directly injected into the cylinder, where it is compressed and burned. But unlike hydrogen, ammonia is not mainly attractive because of its fast combustion characteristics, but because it is easier to store and transport. Hydrogen normally requires high pressure or cryogenic storage, while ammonia can be liquified under milder conditions and already has an established global production and transport system because of its long-term use in the fertilizer industry [63,71]. Ammonia is mainly produced through the Haber-Bosch process, where nitrogen from air and hydrogen are reacted under high temperature and high pressure in the presence of an iron-based catalyst $N_2 + 3H_2 == 2NH_3$. Therefore, ammonia is often interpreted as a more practical energy source for some transport applications, especially where long-distance storage and high onboard energy demand are more important than compact packaging in passenger cars. The ideal combustion reaction of ammonia is $4NH_3 + 3O_2 == 2N_2 + 6H_2O$, so similar to hydrogen powertrain systems, no carbon atoms are released upon combustion.

Ammonia has several fuel properties that make it different from both hydrogen and gasoline. Ammonia has a lower heating value of about 18.6MJ/kg, which is far below hydrogen at 119.7 MJ/kg and fossil fuels at 49 MJ/kg. However, ammonia is easier to store because it can be liquefied at about -33.4°C under atmospheric pressure or at about 0.99 MPa ($0.99 * 10^6$ pascals) at room temperature [72]. This makes ammonia more practical for storage and transport than hydrogen, especially for large-scale or heavy-duty applications. However, ammonia has weaker combustion properties; its flammability range in air is only about 15-28%, much narrower than hydrogen's 4-76%, and its auto-ignition temperature is about 650°C, making it difficult to ignite [73]. Its laminar burning velocity is also very low, with values usually under 0.1m/s, greatly dipping compared to 1.85m/s for hydrogen, which leads to issues such as reduced power output, slower combustion, and inconsistent burning [73,74]. Therefore, ammonia's fuel properties create a clear trade-off: it is easier to store and has carbonless potential, but it has lower energy content and is much harder to ignite and less efficient compared to hydrogen.

Because of these limitations, ammonia is often blended with more reactive fuels such as hydrogen or diesel to improve ignition and flame propagation [71,75]. Most commonly, diesel is used as a pilot fuel to make ammonia burn more consistently. During the compression stroke, the ammonia-diesel mixture reaches high temperature and pressure; the diesel ignites first, and the heat from this pilot combustion helps ignite the ammonia. In spark-ignition engines, ammonia can also be blended with hydrogen because hydrogen's high reactivity and rapid flame speed help compensate for ammonia's slow combustion characteristics [73,76]. Therefore, ammonia engines often rely on another fuel, not mainly for energy supply, but to stabilize ignition and improve combustion speed, compensating for the limitations of pure ammonia fuel.

Another major limitation of ammonia powertrain systems is the emission of NOx, which is caused by the fuel's high nitrogen content likeliness to produce nitrogen oxides during combustion, especially under high-temperature conditions. In addition, incomplete combustion may lead to NH_3 slip, where unburned ammonia leaves the exhaust system [71,63]. This is significant because ammonia is toxic, irritating, and corrosive, so exhaust aftertreatment must ensure control of both NOx and unburned ammonia. As a result, technologies such as optimized injection timing, fuel blending, exhaust gas recirculation, and aftertreatment systems are important for making ammonia engines practical [63,76].

Overall, ammonia engines are less suitable as a final endpoint for passenger vehicles compared to hydrogen engines due to ignition difficulties, toxicity, corrosion, and the complexity of emission control. However, ammonia may be more suitable for ships, heavy trucks, and other heavy-duty applications where energy demand is high, and its easier storage compared with hydrogen becomes valuable [71,63]. Therefore, while hydrogen engines are mainly limited by storage and abnormal combustion, ammonia engines are mainly limited by ignition stability, NOx formation, ammonia slip, and safety handling.

V Conclusion

In summary, the review firstly examined hybrid powertrain systems as transitional solutions and their various architectures, then discussed clean alternative fuel internal combustion engines, including hydrogen and ammonia, as potential long-term solutions. Whilst ICE systems are often viewed as mature technologies, its efficiency is only 40-41%, with dedicated hybrid engines showing potential near 45%, with future hybrid engines targeting 50% thermal efficiency [77,78].

Series, parallel, and series-parallel hybrid architectures each offer different energy flow, efficiency characteristics, and technical limitations. Their performance not only depends on hardware, but also on Energy Management System (EMS), which optimizes power distribution between the engine, motor, battery, and generator. For clean alternative fuels, Hydrogen offers the strongest potential to achieve zero-carbon emissions, but is limited by storage challenges. Meanwhile, Ammonia is not suitable for passenger vehicles due to poor combustion performance but may be more practical for industrial applications because of easier storage and existing infrastructure.

Overall, no single powertrain system can meet all performance, efficiency, cost, and sustainability requirements. Therefore, future development should continue through diverse routes, including improved hybrid efficiency, advanced EMS strategies, and future development of clean alternative fuel engines.

In the future, hybrid powertrain systems and clean alternative internal combustion engines can be further improved in several suggested ways:

1. For hybrid powertrain systems, improving the efficiency of the internal combustion engine itself through achieving higher compression ratios, thermodynamic optimization such as the Miller cycle and other advanced combustion cycles, and improving thermal insulation, lubrication, and other mechanical efficiency measures.
2. Using Safe Reinforcement Learning (Safe-RL)to optimize energy management systems whilst incorporating control barrier functions that ensure EMS control actions, such as battery SOC range, engine/motor torque limits, and thermal constraints, remain within acceptable operational limits. Another possible path is the development of next-generation EMS algorithms to achieve this purpose.
3. From a time-scale perspective, hybrid powertrains are likely to remain the most practical solution in the short and medium run, especially when combined with advanced EMS algorithms such as reinforcement learning. However, in the long run, the development of solid-state hydrogen storage and fuel cells will support the widespread adoption of clean alternative fuel solutions. Therefore, both solutions should be continued to be developed, ensuring that there are valid solutions in both the short run and long run.
4. In the long run, continuation in developing clean renewable internal combustion engines will reduce carbon emissions and provide a clean alternative for consumers.

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