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Article

Advancing combustion technologies and alternative fuels in hybrid electric vehicles: a pathway to high-efficiency, low-emission propulsion systems

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ABSTRACT

In the pursuit of reducing carbon emissions and enhancing fuel efficiency, the integration of advanced combustion technologies and alternative fuels in internal combustion engines (ICEs) remains pivotal, especially when paired with electrified powertrains. This study offers a comprehensive analysis of cutting-edge combustion strategies—Gasoline Direct Injection (GDI), Gasoline Compression Ignition (GCI), and Low-Temperature Combustion (LTC)—and their transformative potential in hybrid electric vehicles (HEVs). Through a detailed examination of these technologies, we assess the thermodynamic optimizations achieved via variable valve timing, variable compression ratio, and cylinder deactivation systems. Additionally, the study investigates the viability of alternative fuels, including compressed natural gas (CNG), liquid petroleum gas (LPG), biodiesel, and hydrogen, as cleaner and more efficient energy carriers. The synthesis of these technologies with HEV platforms not only addresses emission regulations but also pushes the boundaries of thermal efficiency. We provide a critical evaluation of the hybridization benefits, focusing on fuel consumption reductions, particulate matter (PM) mitigation, and overall system efficiency improvements. By coupling multi-mode combustion with electrification, this work underscores a promising trajectory toward achieving near-zero emissions in both light and heavy-duty vehicle sectors. Furthermore, this study offers insights into future propulsion architectures, advocating for a synergistic approach between advanced ICE technologies and electric powertrains to meet stringent global climate targets.

1. Introduction

A wide range of recent technologies such as gasoline direct injection (GDI), gasoline compression ignition (GCI), Atkinson cycle engine, and low-temperature combustion (LTC) have been introduced in recent decades to be suitable replacements for conventional spark ignition (SI) and compression ignition (CI) engines [1]. Along with all these recent technologies, optimizations have been done on traditional engines to keep them alive. Researchers mostly support the former, while car manufacturers consider the latter option. These optimizations are extensive, while this section mostly refers to the optimizations used in HEVs. The optimizations in the field of ICEs include valve actuator systems such as variable valve timing (VVT) [2], variable valve timing & lift electronic control (VTEC which stands for valve timing electronically Control) [3], the electro-hydraulic valvetrain system (EHVS) [4], BMW's valvetronic system [5], the Fiat MultiAir system [6], the continuous variable valve duration system (CVVD) by Hyundai [7], Camless engine (Freevalve) [8], and the others like continuously variable transmission (CVT) [9], variable compression ratio (VCR) [10], cylinder deactivation (CDA) [11], turbocharging [12] and plasma ignition system [13].

1.1. Gasoline direct injection (GDI)

Gasoline direct injection (GDI) is one of the latest engine generations. The engine revolutionized the automobile industry due to direct fuel injection and has attracted the attention of car manufacturers. GDI was developed by Bosch for the first time, introduced with Goliath and Gutbrod in 1952 by Borgward [14]. Three years later, the Mercedes SL300, as a sports car, was introduced with GDI. Finally, in 1996, GDI entered the automotive industry, and it was launched by Mitsubishi in Japan; then, lots of car manufacturers showed a desire to employ it. GDI provides lean combustion, which fills homogeneously in all combustion layers and improves fuel efficiency by 30% and reduces emissions by 25%. GDI responds quickly to the changes in timing and the amount of injected fuel. GDI challenges include the complexity of adjusting to different speeds, the complexity of fueling control, the high cost of fuel (gasoline with more than 95 octane rating), the high cost of GDI system components, the complex electronic system, wearing increase in fueling system, the accumulation of carbon behind the inlet valve, sedimentation around the spark plug and increase in the electricity required for the spark ignition. One of the main challenges of GDI is the high amount of HC emission in the start-up process, which is aggravated by incomplete combustion and misfire due to dilute combustion and low cylinder temperature [14]. Another challenge of this combustion is the high emission of PM. This technology doubles the challenge of HC emissions when used alongside HEV. Because the control of transient conditions of quick start in this series is prone to this happening [15]. Many researchers have tried to solve these challenges. It has been shown that the optimized demands of injection and ignition as a function of coolant temperature, engine speed, and fuel temperature can progress the combustion and emissions of GDI in HEVs, especially in cold start-ups [16]. Engine re-start in GDI-HEV emits about 70% of the total particulate number (PN). By increasing the injection pressure by 300 bar, the sum of PN averages drops by 87.2%. By retarding the ignition timing by 15 degrees in crank angle, the PN average drops about 65.3%, and NO_x emission can be reduced by 85.6%, while HC and CO are stubborn and do not reduce much [17].

1.2. Gasoline compression ignition (GCI)

Ignition under high pressure is the bullet point in high efficiency in diesel engines, which provides about 40% higher efficiency than gasoline ICEs ignited by spark plugs [18]. Almost 27% of the advantage comes from compression ignition (CI) compared to spark ignition (SI), and 13% comes from higher diesel fuel density. To understand, the ability of a gas to store heat energy through combustion is enhanced by increasing pressure, which makes a compression ignition flexible in various equivalence ratios, while SI engines operate under stoichiometric conditions. Therefore, lean burning is possible in CI engines. Gasoline CI or GCI can provide both high efficiency and low emissions while even defeating diesel engines. GCI engines have lower pumping losses compared to diesel engines and throttle losses compared to SI engines [19]. Achates Power, Argonne National Laboratory, and Delphi Automotive were awarded for the design and development of opposed-piston gasoline compression ignition engines (OPGCI). Achates Power has spent about 12 years improving OPGCI. This award was the largest grant or financial investment that the Advanced Research Projects Agency-Energy (ARPA-E) has given in its history [20]. The combination of these two technologies (opposed pistons and GCI) can be a solution to the SI ICE restrictions. OPGCI engines have proved to be 50% more efficient than SI engines with comparable power, torque, noise, vibration and toughness, and dimensions. OPGCI engines eliminate the cylinder head, thus improving the surface-to-volume ratio of the combustion chamber (less surface area relative to the volume) to reduce heat transfer and repulsion, which causes earlier and more efficient combustion. The engine has more power density by reducing displacement volume and lower brake mean effective pressure (BMEP), which leads to lower NO_x emission, advance in combustion, and enhanced efficiency. Due to uniflow scavenging, fuel pump performance is independent of the engine speed; therefore, at low loads, high exhaust rates can be fixed by reducing turbocharging and improving efficiency. Achates Power recently released the engine results showing a 30% improvement in combined urban and highway MPG over the diesel engine, while the engine achieves U.S. EPA Tier 3 emission standards (over the period from 2017 through 2025) [20]. Low-temperature combustion in GCI is its main drawback for CO_2 and HC emissions. To overcome this, the integration of GCI and HEV could be a suitable option. Research has shown that GCI-HEV performance is dependent on battery size. CO_2 emission in non-PHEV integrated with GCI engine drops up to 37% and 45% compared to the referenced GCI engine and modern SI engine, respectively. For PHEV, the reduction could be achieved by up to 75% compared to both, although heavier batteries should be utilized [21].

1.3. Atkinson cycle

The Atkinson cycle is one of the important technologies registered in 1882 by British inventor James Atkinson. In the beginning, the Atkinson cycle was very mechanical, which resulted in complex kinematics, which failed in the first decade of its construction and was abandoned. The stroke length of the pistons was variable, and these motion changes applied to the pistons were made by a connecting rod or branched connecting rod between the piston and the flywheel. All this meant that the expansion ratio of the piston was much higher than its compression [22]. However, since the introduction of the variable valve timing (VVT) system and the abandonment of mechanical systems, the Atkinson cycle has regained attention. In this case, there was no change in the compression and expansion of the engine, and the engine could work with both Atkinson and Otto cycles if necessary. The intake valve opening has a longer duration than the Otto cycle. This difference causes some air-fuel mixture to pass away from the cylinder as the compression starts. Therefore, less air-fuel mixture is ignited, and as a result, fuel consumption is also reduced [23]. Today, the Atkinson cycle engines have spread significantly into HEVs. The main advantage of the Atkinson cycle over the conventional Otto cycle is the higher efficiency. The higher efficiency means that the engines will be able to produce more power using less energy. However, the output power of the engine at low speeds is less than the same engine in the Otto cycle, making the Atkinson cycle a relative technology that can optimize fuel consumption only at medium and high speeds. Therefore, engineers consider the Atkinson cycle suitable for hybrid vehicles since, when the output power decreases, the electric motor helps the engine to compensate for the lack of power [24]. Various degrees of compression and expansion can be achieved by controlling the intake valve opening phases, which was proposed by Ralph Miller and registered in 1956. The Miller cycle tends to achieve greater efficiency and lower compression ratios with low-octane fuels. Miller designed systems to close the intake valve earlier (early inlet valve closing, EIVC) or later (late inlet valve closing, LIVC), as well as to compensate for lack of air or to maintain air return to the intake manifold. Unlike Atkinson, Miller used a boosting system like turbocharging. Mazda Millenia and Mercedes W163 can be seen as the most notable commercial vehicles that use the Miller cycle for their propulsion system [25]. Atkinson cycle engines have been so successful in HEVs that Toyota has been tempted to use this integration in its all petrol HEV versions after the Prius and Lexus HEVs, including the Tacoma, C-HR, Camry Hybrid, UX250h, and RX 450h. Mazda's SKYACTIV engine is another famous example of Atkinson cycle usage in HEVs. It uses a high compression ratio of 14:1 and VVT technology to enable more accurate combustion phasing. It consumes 15% less fuel and produces 15% more torque than its same-displacement diesel engine [26]. Detailed research has been done on the performance of the Atkinson cycle engine in HEVs. As an example, the results on the parallel HEV architecture with this engine show a 12.3% and 7.22% fuel improvement in Manhattan and modified FUDS (Federal Urban Driving Schedule) driving cycles, respectively, compared to the Otto cycle engine. In another research, the minimum brake-specific fuel consumption (BSFC) of a series HEV with the Atkinson cycle engine was decreased from 250 g/(kW.h) to 234.5 g/(kW.h) compared to the Otto cycle engine. In specific research, a REEV with an Atkinson-cycle engine showed 4.58% fuel improvement compared with the same Otto-cycle engine, while NO_x and CO_2 emissions dropped by about 46.1% and 18.37%, respectively [27]. Decoupling the engine from the drivetrain can enable the engine to operate at its maximum efficiency since the road load would not affect it. Therefore, REEV could be the best HEV platform for implementing this integration. Also, other simplifications are allowed; for example, there is no need for VVT and VCR systems, and the engine is downsized [1].

1.4. Low-temperature combustion (LTC)

Low-temperature combustion (LTC) technology has been the most interesting combustion approach in recent years. After years of using gasoline and diesel engines, a new idea was formed based on the combination of these two engines [28]. The principles of the new idea are based on entering a premix air-fuel mixture (almost homogeneous) (Otto principle) into the combustion chamber, then compressing in a compression stroke so that the temperature and pressure of the mixture reach the auto-ignition limit (diesel principle) and eventually starting combustion. Theoretically, a flame front is not observed in this idea, and ignition would be placed simultaneously in all regions [29]. Homogenous charge compression ignition (HCCI) was the first example of this technology, proposed by Onishi et al. in 1979 for a two-stroke engine. In an HCCI engine, the ideal approach is LTC fuel and air are mixed before the start of combustion, and this mixture spontaneously ignites in several places of the combustion chamber, which leads to a decrease in the combustion temperature and, as a result, a decrease in NOx emissions, as well as a decrease in fuel consumption. In addition, due to the homogeneous mixing of fuel and air, fuel-rich regions and the formation of PM would be eliminated [30]. Another LTC approach is the reactivity control compression ignition (RCCI) concept developed at the University of Wisconsin. RCCI engine can deliver up to 60% thermal efficiency; This means that the engine converts 60% of its fuel into power. Such a value is a huge leap for engine thermal efficiency compared to the Toyota Prius with 42% and the Mercedes AMG F1 with 50% thermal efficiency. The engine uses two types of fuel, with a low reactivity, such as gasoline, which is a port injection, and high reactivity fuel, such as diesel, which is a direct injection. The main advantage of RCCI over HCCI is that it is more effective in controlling combustion phasing. Premixed charge compression ignition (PCCI) engine is a concept between them [31]. LTC's main challenges are narrow operating range, combustion phasing control, cold start, high CO, and HC emissions [29]. Therefore, integrated LTC with HEV could be an option. Much research has been done to introduce a suitable LTC-HEV platform. By improving the hybridization degree (from ICE to REEV), the fuel-saving benefits of HCCI-HEV drop. The reason could be found in the engine running time shortening, so the unstable situation causes the continuous cold start and the combustion phasing control challenges, which causes fuel penalties and torque fluctuations. However, decoupling the engine from the road load causes the engine to overcome the narrow operating range. Therefore, choosing an appropriate platform for LTC-HEV is a trade-off of fuel saving and preventing misfires or engine knocking, which makes the power-split HEV an ideal solution. The research proposed fuel improvements by about 12.6% to 18% for an appropriate HCCI-HEV platform. The appropriate RCCI-HEV platforms showed fuel savings of about 6.5%, 14.2%, and 3% compared to diesel engine, SI-HEV, and CI-HEV platforms, respectively, while NOx, CO2, and soot emissions dropped significantly [1]. Multi-mode LTC-HEV, which brings both HCCI and RCCI into one platform, showed more satisfactory results than single mode. A multi-mode SI-RCCI-HCCI engine, in comparison with single-mode HCCI and RCCI engines in the HEV platform, indicated about 1.4% to 2% in fuel savings. LTC-HEV technology is justified when performance and fuel consumption due to engine downsizing limitations at high power are obstacles. There are fundamental similarities and differences between Atkinson cycle-HEV and LTC-HEV. LTC-HEV technology can be implemented when, due to the high-power demand, downsizing is a limitation, especially in heavy vehicles, while Atkinson cycle-HEV is the best platform for urban use since the powertrain size would be compact. However, their best deployment platform would be series HEV (REEV) and power-split HEV for Atkinson cycle-HEV and LTC-HEV. Both technologies could improve fuel saving and drop emissions, besides dominance the engine challenges [32].

1.5. Variable valve timing (VVT)

The variable valve timing propulsion system, or VVT, is designed to increase the engine's volumetric efficiency at speeds above 3000 RPM. The valve opening and closing time in a 4-stroke engine is always constant and determined by the rotation of the cams placed on the camshaft [2]. This monotony restricts maximum efficiency to only one specific engine speed. For example, at high engine speed, since the cylinder is not filled completely with the fuel-air mixture, the engine performance is not efficient. Therefore, the necessity of a valve-controlling system is felt. The best performance of the VVT system significantly improves the spark ignition engine when integrated with the Miller cycle when throttle control is not required [7]. However, VVT systems have been tested on other modes of ICEs as well. Plenty of HEV configurations with a naturally aspirated (NA) and a turbocharged (TC) with a VVT system were investigated on various degrees of hybridization. The operation of the VVT system is clearly illuminated when the engine works at part-load due to the reduction of pumping and throat losses. The brake efficiency has been enhanced by about 40% since these losses dropped. The VVT system provides more acceleration. As the degree of hybridization (DOH) progresses, the engine-required power drops. From 0 to 50% of DOH, the total required system power of turbocharged ICE and NA ICE with VVT system and Atkinson cycles drops about 13.8% and 29.2%, respectively. With DOH improvement, the engine downsizes, and the engine would be responsible for the detailed commands of the programmed driving cycle. From the perspective of fuel consumption, despite the improved situation, the performance of the VVT system in HEVs is weaker than in ICEs alone. The conditions will become more unfavorable with the increase of DOH. 4% to 9% improvement in fuel consumption for ICEs, compared to 3% to 4% for 10 DOH and 1% to 2% for 30 to 60 DOH, based on the engine performance, is proof of this fact [23]. Homogeneous Charge Compression Ignition (HCCI) engine concept is one of the LTC strategies. The main challenge of HCCI is the narrow operating range and combustion phasing. VVT system could be an optional solution to overcome these challenges [30]. The VVT system could moderate the charge mixing process, which led to controlling the auto-ignition timing and combustion phasing by affecting the charge mixture's composition, temperature, and pressure [10].

1.6. Variable valve timing & lift electronic control (VTEC)

The emission restrictions forced Japanese car manufacturers to investigate new ways to increase engine power without changing the engine displacement. The Japanese engineers responded to these strict regulations. with several methods: turbocharger and supercharger, Toyota Supra, Nissan 300ZX and GT-R, Mazda's rotary engines (Rotary) in RX-7 and RX-8, and Honda's VTEC technology [33]. Unlike conventional VVT technology, where only the valve timing changes, VTEC uses two or three short and long cam surfaces on the camshaft and long and short rocker shaft. VTEC comes into play on the air side of the engine. Honda's VTEC technology optimizes the amount of airflow in the intake and exhaust strokes [34]. The opening and closing of the inlet and outlet valves depend on the camshaft's design. According to the length of the cam and the rotation of the valve shaft, the number of valve openings and closings can be adjusted. The more opening of the intake valve, the more power is produced. In higher engine speeds, more power is required; in these conditions, the VTEC technology activates the long cam surfaces. Comparing VVT and VTEC technologies, there are fundamental differences, VVT is operated by a hydraulic system, while VTEC is controlled by the electronic control unit. The purpose of using each one is different; VVT technology is to increase efficiency and reduce emissions and fuel consumption, while VTEC technology is designed to increase engine power. VVT technology is mostly used by Toyota, while VTEC is unique to Honda [33]. The new generation of Honda Civic Type R uses the VTEC design of the exhaust valve, which is different from the other models. The reason is the presence of a turbocharger, which ensures maximum intake of air while the VTEC optimizes the exhaust valve. Intelligent variable valve timing and lift control system i-VTE coupled with the Atkinson cycle significantly improves the engine's maximum torque, power, and idle stability by optimizing the valve overlapping. Hybrid Honda Civic Type R will be introduced in 2024, although its 2023 turbocharged ICE version can attain 9 hp and 15 lb.-ft improvements in the maximum power and torque, respectively, compared to its previous VTEC version. I-VTEC enhances valve timing flexibility to achieve lean burning conditions and improves fuel economy; therefore, pumping losses and ISFC are reduced [34].

1.7. Electro-hydraulic valvetrain system (EHVS)

The electro-hydraulic valvetrain system (EHVS) uses an electronic actuator instead of a mechanical camshaft system. EHVS helps the engine manage the charge mixing process and provides precise air intake and gas programming. EHVS actuators operate according to pumping and bleeding using a solenoid valve to provide hydraulic pressure in one direction and return in the opposite direction. Two solenoid valves provide a high-pressure side for pumping and two low-pressure side valves for bleeding. This technology leads to the optimal engine operating point in extended loads by flexing the valve lift function; therefore, these immediate thermodynamic conditions reduce fuel consumption and increase output power [35]. The most common EHVSes are developed by Bosch and AVL. This technology is compatible with cylinder deactivation, and the results of this integration indicate a significant reduction in BSFC, ISFC, HC, and NOx compared to the conventional mode. Unlike VVT and VTEC, this integrated system performance drops with increasing engine speed [36]. BMW's variable valve lift system, known as Valvetronic, was exclusively developed by BMW. This system changes the intake air valve's progress into the combustion chamber. Velotronic as a part of BMW's TwinPower technology has a positive effect on fuel consumption reduction and the gas pedal response improvement by eliminating throttle, although the throttle remains for precautionary reasons. Velotronic was first released in 2001 on a 2L naturally aspirated four-cylinder engine, N42, BMW 316ti. Valvetronic technology shows its advantages in N55 BMW's 3L six-cylinder engines [37]. The engine is competitive with 4L eight-cylinder engines, while with lower weight, it provides the required torque at the lowest possible engine speed. This engine has 315 hp and 450 Nm of power and torque, respectively, and emits 209 grams CO_2 per kilometer, which is offered in 640i and 740i models. BMW's efforts to keep up with strict regulations led to the introduction of its first full HEV in 2013 by ActiveHybrid 3. BMW ActiveHybrid 3 was the smallest sedan, offering an amazing combination of high performance and sporty characteristics with low fuel consumption. It takes advantage of the N55 engine and lithium-ion high-performance batteries. The total power and torque of this powertrain were reported by 335 hp and 450 Nm, respectively. With hybridization, the overall torque of the drivetrain has not changed, but it has led to a 20 hp improvement in the overall power compared to the non-hybrid BMW 640i and BMW 740i. Proper performance of the TwinPower technology in the hybrid BMW 3 series (ActiveHybrid 3) led to enhance this system into the hybrid version of the BMW 5 Series (BMW ActiveHybrid 5) and BMW 7 Series (BMW ActiveHybrid 7) [37].

1.8. Multi Air system

Fiat powertrain technologies developed MultiAir system to compete with Honda's VTEC and BMW's TwinPower systems. MultiAir is a hydraulically actuated variable valve timing and variable valve lift engine technology enabling control of intake air directly via a gasoline engine's inlet valves [38]. In the MultiAir system, cams charge a small hydraulic pump, which provides the required oil pressure. Oil via this provided pressure controls the solenoid valves which manage the valves opening and closing time. The revolutionary MultiAir system, as well as providing up to 10% higher power and 15% higher torque, guarantees a reduction of up to 10% in CO_2, 60% in NO_x, 40% in particulate emissions, and 10% in fuel consumption, compared to the conventional engine. The main weakness of Fiat's MultiAir system compared to BMW's TwinPower technology is the operating lag, which is somewhat remedied by turbocharging. In 2020, Fiat offered the Panda hybrid and 500 hybrids with a MultiAir system [38].

1.9. Continuous variable valve duration (CVVD)

CVVT, CVVD, and CVVL are three mechanisms affecting the opening and closing of valves in ICEs that change the time and the amount of valve opening. The first three letters of these three mechanisms are common and stand for the continuously variable valve, While T, D, and L stand for the time, duration, and lift, respectively. Figure 1 represents the differences between these three mechanisms [7].

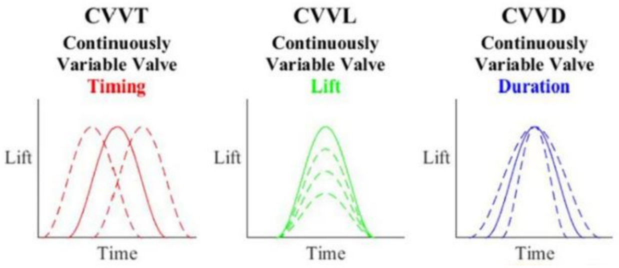


Figure 1. The differences in valve lift timing of the CVVT, CVVL, and CVVD mechanisms

CVVT delays the valve opening and closing at low engine speeds, consuming less energy during the compression stroke and resulting in less fuel consumption. At high speeds, more air must enter the chamber. Therefore, CVVT advances the valve timing to advance charge entry and process before the compression stroke, so the volumetric efficiency improves. CVVL moves the valve shorter at low speeds when less air is needed. On the other hand, at high speeds, the engine needs much more air, during CVVL operation, the valve opens more to allow more air to enter. Therefore, the volumetric efficiency is closer to the ideal value in a wide speed range. CVVD is the latest system in valve opening and closing, which Hyundai worked on for 9 years to finally introduce. It can increase or decrease the valve opening time. CVVD technology in the Hyundai 4-cylinder G1.5 T-GDi engine, with a significant power of 180 hp, a torque of 264 Nm, and 179 to 182 gr/kilometer CO_2 emission, was introduced with the Hyundai Sonata in 2020. The SANTA FE Hybrid uses CVVD which produces a combined output power and torque of 226 hp and 265 Nm, respectively. It emits 146 to 157 g/kilometer of CO_2 based on the WLTP driving cycle [7].

1.10. Camshaft (Free valve) engine

The engine design without a camshaft (Freevalve) was proposed by "Koenigsegg", in which the task of opening and closing the valves is the responsibility of the solenoids, which are controlled by electricity, air pressure, (pneumatic), and oil pressure (hydraulic) [39]. In Freevalve engines, long valve opening time allows more air and gas to enter and exit. There is no necessity for high pressure fuel injection by injector, therefore, the low-pressure multi-point injection system can be served. Freevalve system can completely take all exhaust gases out the chamber, and gas scavenging can be done in the best feasible way [40]. With such changes, the engine volumetric efficiency increases, the engine knocking decreases, the fuel atomization reaches its maximum rate, and the charge temperature decreases. This technology can be integrated with CDA, converting a four-stroke engine to a two-stroke engine at low speeds and working with Flex-Fuel. Detailed research has been done regarding the comparison of HEV-configured Freevalve ICE vehicles against battery electric vehicles (BEVs) and camshaft-induced HEVs. Freevalve HEVs have a 55% lower global warming potential impact than BEVs. The results with renewable fuels become more favorable, Freevalve renewable-fueled HEV concepts have significant potential in achieving global net zero CO_2 emission targets [39].

1.11. Continuously variable transmission (CVT)

CVT, or continuously variable transmission, was registered in 1986. Nissan was the first manufacturer to commercialize CVT on a regular basis. This transmission momentarily adjusts the gear based on the engine speed [41]. CVT has two axles; one is connected to the engine, and the other is connected to the wheels, making transferring power between light and heavy gears smooth. The variable and instantaneous gear ratio in CVT optimizes the engine speed, reducing fuel consumption. CVT makes the engine run at its most efficient point and also smoothly in wide load range and engine speed. Therefore, fuel saving improves, and emissions are reduced. CVT produces a lot of noise at high speeds. A vehicle equipped with a powerful engine and CVT produces unpleasant noise during acceleration, although its main challenge would be lags to deliver power in accelerations [9].

1.12. Variable compression ratio (VCR)

According to Otto's thermodynamic cycle, thermal efficiency improves with increasing the compression ratio since, with increasing the compression ratio, the charge temperature and pressure would increase. Enhancement of the engine speed provides turbulent charge; therefore, the flame speed increases, and the tendency to knock decreases [10]. The variable compression ratio (VCR) system can increase the compression ratio at higher engine speeds (low loads) without causing knocking problems. By instantly changing the bottom dead center, the VCR system, with the help of a motor and two additional arms, increases efficiency in low compression ratio and power in high compression ratio. Recently, Nissan has been using VCR-turbo technology in the Mk6 Altima and Infiniti QX50, which allows changing the compression ratio and increases power and efficiency [42]. VCR shows a proper performance in fuel improvement, reported from 3% to 16% compared to the fixed compression ratio. VCR, VVT, and turbocharging are optimizations applied to the Atkinson cycle to create the Miller cycle, making it an ideal option for HEVs with downsized engines. VCR has worked well in HEVs. In terms of fuel consumption, Mild-HEV with VCR and full-HEV with VCR show reductions of 8% and 20%, respectively, while for emissions, the situation is getting better; particulate matter (PM) and unburned hydrocarbons (HC) drops around 60% and 15%, respectively [10].

1.13. Cylinder deactivation (CDA)

The more cylinder numbers do not necessarily mean an increase in fuel consumption, but the engine displacement is the main determinant. Cylinder deactivation or CDA technology was first used by General Motors in 1981 in Cadillac, which could change the number of active cylinders from eight to six or four, depending on the engine load [43]. This process was carried out by the vehicle's electronic control center or ECU [11]. Later, in the first decade of 2000, many big manufacturers such as Volkswagen Group, General Motors, Mercedes Benz, Mazda, Honda, and Ford also showed interest in using this system. Controlling this system is not easy, and in addition, mechanical problems enter the engine assembly through the balance, which makes it difficult to manage. CDA can reduce fuel consumption and emissions but depends on many factors, especially the degree of throttle opening. This factor directly affects the frictional losses, lubrication, and cooling water temperature. The throttle controls the air, which in CDA causes more air pressure in the active cylinder, making higher friction losses and, therefore, more energy losses. CDA enables up to 80%, 52%, and 72% reductions in particulate matter (PM), NO_x, and soot emissions, respectively, and 40% in fuel consumption. CDA drops the charge flow rate between the intake and exhaust manifolds, which results in less pumping loss [43].

1.14. Turbocharging

Swiss mechanical engineer Alfred Bucci invented the turbocharger. The main challenge that led to the invention of the turbocharger was to produce engines with small dimensions, less weight, and more power. Therefore, a turbine was introduced to utilize the kinetic energy from the exhaust gases. The turbocharger uses a compressor to increase the intake of air and a turbine, which rotates the compressor. One of the most famous hybrid cars that use turbocharging is the BMW i8. The i8 uses a 3-cylinder turbocharged gasoline engine and an electric motor; the total power produced reaches 360 hp, which accelerates in less than 4.5 seconds [12]. The masterpiece of the turbocharger system was in 2014 in Formula 1 races. The engine's exhaust gases cause the turbocharger rotation and store energy in the built-in batteries. Hybrid Formula 1 racing cars use three propulsion systems: the V6 ICE, the MGU-K (motor generator unit-kinetic), and the MGU-H (motor generator unit-heat). The MGU-K and the MGU-H are electric motors whose energy is provided by the exhaust gases. MGU-H, also known as e-turbe, provides the required energy for turbochargers at low speeds. These electric motors with a turbocharger have made Formula 1 racing cars have the power of a V8 engine while saving 35% in fuel consumption. In 2022, MGU-H was removed, and a more powerful MGU-K was replaced [12].

1.15. Plasma ignition system

The air-fuel mixture in an SI engine must be in stoichiometric condition, while its thermal efficiency would not go across 30%, although if it can run in lean-burning conditions, fuel saving improves, and the exceed air makes the combustion cooler, which enhances thermal efficiency. Therefore, plasma ignition was introduced, which produces high voltage with the help of special sparks and causes the formation of gaseous ions. Unlike the traditional spark, a plasma spark does not release thermal energy, but by creating a kinetic force between charged molecules, it causes them to collide and start combustion. In this case, it is possible to dilute combustion even in SI engines [13]. Plasma ignition would be able to enhance thermal efficiency by 20% and drop NO_x emission by 50% [44].

2. Alternative fuels

Excessive emissions of conventional fossil fuels (gasoline and diesel) and dwindling oil reserves have led researchers to develop alternative fuels with better performance [45]. Compressed natural gas (CNG), liquid petroleum gas (LPG), hydrogen (H_2), alcohol fuels (methanol and ethanol), biodiesel, and dimethyl ether (DME) are considered alternative fuels to gasoline and diesel [46]. Alternative fuels and electrification of vehicle propulsion are two potential solutions that could be integrated and considered as two synchronous solutions, known as alternative-fueled HEV (AF-HEV), to enhance efficiency and drop emissions [1].

2.1. Compressed natural gas (CNG)

Compared to gasoline, methane has a higher octane number, which makes it possible to increase the compression ratio and subsequently increase efficiency. Methane is the main component in CNG, which consists of about 96.5% of its density. Compared to gasoline and diesel, CNG does not have a high low heat value (LHV) and is less than a third of its value, which provides lower power and torque for the same CR and the same injection type. The average brake-specific fuel consumption (BSFC) of CNG direct injection (CNG-DI) engines was 0.28% lower than gasoline port fuel injection (gasoline-PFI) engines, respectively. The CNG-DI engine drops 50% NOx emission while increasing about 34% and 48% HC and CO emissions, respectively, as compared to the gasoline-PFI engine. The CNG-DI engine enhances combustion stability compared to the CNG-PFI engine. The CNG-DI engine efficiency would be higher compared to GDI at part loads. CNG-HEV reduces CO_2 and particle emissions by up to 20% and 60%, respectively. Compared to SI-HEV, BSFC reduces between 6.33% and 12.32%, and average efficiency improves between 6.1% and 11.2%. For PHEVs equipped with CNG engines, fuel efficiency increases between 22% and 35% based on the engine load; the maximum power and torque increase, although their average would be shrunk [47].

2.2. Liquid petroleum gas (LPG)

Liquid petroleum gas (LPG) consists of a combination of propane and butane, which turns into a liquid by pressurizing. LPG has a high-octane number, which makes it an anti-knock fuel that increases CR and improves efficiency. The results of direct injection LPG are more significant than port fuel injection LPG. DI systems for LPG (LPDI system) are under research, along with the trend toward gasoline DI technologies. LPDI, in comparison with GDI, produces lower HC, CO, and PN emissions due to the wider spray angle and flash boiling, which provide a more homogenous mixture. HC emission would drop by up to 45%, CO_2 up to 20%, and PN up to 94% [48]. Hyundai introduced the world's first LPG-HEV in 2006. The Elantra LPI was a mild-HEV that delivers fuel consumption of 42 mpg and CO_2 emission of 99 grams/km. The previous petrol version of Elantra 2005, consumed 46.3 mpg gasoline and produced an average CO2 emission of 160.0 gram/km. The comparison declares 9.28% of fuel saving and 38.12% in CO2 emission reduction [49].

2.3. Alcohol fuels (methanol and ethanol)

The use of alcoholic fuels in ICEs is not a new issue. In 1872, when Nicolaus Otto invented ICEs, gasoline was not yet available, and ethyl alcohol was considered this engine's fuel. Methanol (CH_3OH) and ethanol (C_2H_5OH) can be an alternative fuel for petrol and diesel engines. Significant lower LHVs of methanol and ethanol compared to gasoline make them unappropriated in terms of BSFC and brake thermal efficiency without engine modification. However, they have more octane numbers, which is the capability to improve thermal efficiency in higher CR. The engine stability and emissions under cold-start conditions would be their defects due to their higher vapor pressure and lower boiling point than gasoline. Methanol and ethanol have slight benefits over gasoline in emission reduction, especially methanol, which contains oxygen in its structure, although they have higher ignition delay, causing an increase in the combustion duration [50]. The combination of alcoholic fuel with gasoline would be an option, although when these compounds act to improve one characteristic, they weaken another characteristic. For example, by increasing their blend ratio, emissions drop (except NO_x), but BSFC increases. However, oxygen in the structure of methanol causes more complete combustion and improved combustion characteristics compared to ethanol [51]. The engine power and BSFC of methanol/hydrogen blend showed better results compared to gasoline and ethanol. A series HEV bus with a methanol-hydrogen engine was examined. The results showed that the overall CO, HC, and NO_x in the exhaust were reduced by 78% compared to diesel engines [52].

2.4. Biodiesel

Biodiesel is produced by processing and changing the properties of vegetable oils. This fuel was first introduced in the 1970s as an alternative to petroleum diesel but was not well received then. Due to the reduction of oil resources and increasing global warming concerns, biodiesel is suggested as an alternative to petroleum diesel [53]. The size of molecules in biodiesel and petroleum diesel is similar, but these two fuels differ in chemical structure. Biodiesel molecules are almost entirely composed of fatty acid methyl esters that contain olefinic unsaturated compounds. On the other hand, 95% of petroleum diesel (with low sulfur) is saturated hydrocarbons, and the remaining 5% are aromatic compounds [54]. Biodiesel has a lower LHV, which makes it inappropriate for achieving maximum power and torque under full load conditions. Biodiesel as petroleum diesel supplement. The main sources of biodiesel, which could be vegetable oil, yellow grease, cooking oil, or animal fat, have a great impact on its performance. For example, biodiesel blends B10 (10% biodiesel and 90% diesel), and B20, which are produced from waste cooking oil, have higher CO_2 emissions compared to diesel fuel, while B10 and B20 jatropha, algae, and palm-based emit lower CO_2. Generally, CO, HC, CO_2, and smoke emissions are lower for biodiesel mixtures, while NO_x emissions are higher. For the same brake power, increasing the blending ratio degrades fuel-saving benefits by up to 15%. From B10 to B100, the maximum brake torques dropped by 1.57% to 4.7%. The biodiesel engine equipped with HEV showed a proper performance in reducing tailpipe emissions and enhancing the fuel economy. In comparison with diesel-HEV, CO, HC, and NO_x emissions of biodiesel (oil cottonseed)-HEV dropped by 18%, 35%, and 7%, respectively, fuel consumption improved by up to 1%, while power output slightly decreased [55].

2.5. Dimethyl ether (DME)

DME is an isomer of ethanol, although it can be obtained from biomass, ethanol, and fossil fuels. Currently, natural gas is the main source of interest for its production. DME has the same properties as LPG and could be considered a clean alternative to LPG, diesel, and gasoline. DME has a high cetane number, which indicates its efficiency in compression ignition combustion. The energy efficiency and power generation capability of DME is like diesel fuel. DME, in comparison with diesel fuel, led to zero PM emissions and lower NO_x emissions due to the absence of carbon-carbon bonds and higher heat capacity, respectively. The energy density of DME is half that of diesel fuel, making it inappropriate to carry. Comparison of NO_x, CO, and HC emissions on a DME and diesel-fueled engine showed a reduction of 81.8%, 50%, and 66.7%, respectively, while PM emissions were completely removed and BSFC dropped up to 4%. No research has been done yet on DME engine-HEV, but DME has been used as a fuel for fuel cells in FCEVs [50].

2.6. N-Heptane (C_7H_{16})

Normal heptane or n-heptane with the formula C_7H_{16} is a colorless liquid. It is a saturated aliphatic hydrocarbon and insoluble in water, which is prepared by the partial distillation of oil. Heptane is known as a standard zero for the octane rating scale; normal heptane is used as the standard solvent for knocking diesel. N-heptane is mostly used as a pilot fuel to blend with other fuels in LTC engines, including gasoline, alcohol, and n-butanol. with strong adaptability, ignition properties, more stable engine operation, extended operating range, and combustion phasing tuning. By DI of n-heptane, the peak in-cylinder pressure, pressure rise rate, and HRR (heat release rate) are all increased, which leads to improved knock tendency [55].

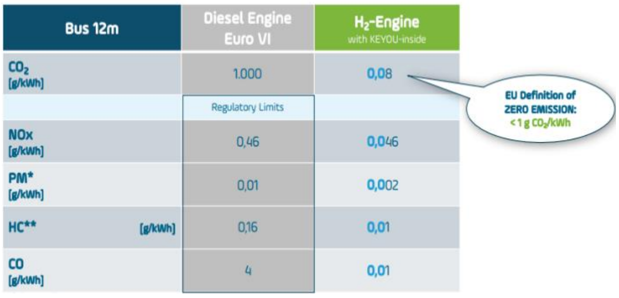
2.7. Ammonia (NH_3)

The main advantages of ammonia over hydrogen are its easier storage and higher safety requirements due to the higher volumetric energy density [56]. Ammonia storage conditions are like LPG either at ambient temperature under high pressure or at -33°C under atmospheric pressure. Its storage cost is significantly lower than that of hydrogen, electricity in batteries, and liquefied natural gas (LNG). Another advantage is the absence of carbon in the chemical structure. Ammonia is susceptible to emitting high levels of NOx emission in NA and low CR engines. High auto-ignition temperature, low flame speed, slow chemical kinetics, low energy density compared to gasoline and diesel, low efficiency, toxicity, and corrosion are other concerning factors that affect ammonia to wide commercialization [57].

2.8. Hydrogen (H_2)

Hydrogen (H_2) has several excellent properties compared to other combustion fuels: high specific energy (energy per unit weight), high flame speed (low combustion duration), wide flammability range (combustion stability), and high-octane number (anti-knock property) [58]. The most interesting internal combustion engine research in recent years is undoubtedly related to the outstanding properties of hydrogen. Exactly the thing that may defeat electric cars in the competition for minimum emissions, maximum efficiency, and reduction of total cost of ownership (TCO) [30]. For the first time about two centuries ago (1807), H_2 was applied to ICE by French-born Swiss inventor Francois Isaac de Rivaz, but his efforts did not yield much result. A century and a half later, Roger Billings used hydrogen gas as fuel for the engine of a Ford Model A. At first, it was thought that hydrogen should only be used as DI, and its PFI efficiency was not very satisfactory because there were problems such as low power density, knocking, backfiring, and air displacement. Batteries have an efficiency of 75-85%, while for H_2-ICEs, it decreases to 30-35%, and the only advantage of hydrogen over lithium batteries was its higher energy per unit weight, but it was true only until the last few years when KEYOU introduced its H_2-ICE technology in 2020. In this technology, DI-H_2 only has an advantage in output power of 30 kW compared to PFI-H_2, and other characteristics such as fuel consumption and emissions of both proposed engines are almost the same, with the insignificant superiority of DI-H_2 [59]. Table 1 compares diesel engines and H_2-ICE in terms of emissions and how modern H_2-ICE meets the EU standard for zero-emission commercial vehicles by 100%.

Table 1. Comparison of emissions in diesel engine and a modern H_2-ICE



Bus 12m	Diesel Engine Euro VI	H_2-Engine with KEYOU-inside
CO_2 [g/kWh]	1.000	0,08
	Regulatory Limits	
NOx [g/kWh]	0,46	0,046
PM* [g/kWh]	0,01	0,002
HC** [g/kWh]	0,16	0,01
CO [g/kWh]	4	0,01

EU Definition of ZERO EMISSION: < 1 g CO_2/kWh

The energy storage potential is the key point that directly controls the powertrain efficiency. By 2025, H_2-ICE's energy storage will be 3.3 kWh/kg, while it would be 0.4 kWh/kg for lithium batteries (more than 8 times), while it costs 300 times less (12 euro/kWh for H_2 and 360 euro/kWh for lithium batteries) This comparison is better understood in the TCO section [30]. BMW, Mazda, Chevrolet, Aston Martin, Ford, and other famous manufacturers have developed H_2-powered ICEs in hybrid and non-hybrid platforms for commercial and racing purposes. Toyota GR Yaris Rally2 is the latest H_2-ICE-powered and is expected to debut in the World Rally Championship-2 in 2024 [59]. Ford's H2RV is the first pure H_2-ICE HEV to deliver a projected fuel economy of 45 mpg and near zero emissions without compromising performance. H_2 in HEVs is usually used as an additive to the main fuel. 10% H2 enrichment to gasoline SI-ICE powered HEV, enhanced 3.6%, 2.38%, 9.4%, and 6.1% for the torque, power, efficiency and heat release rate, respectively. Average BSFC improved by 12.6%, while CO_2, HC, and NO_x emissions were reduced by 29%, 33%, and 14%, respectively. 8% hydrogen addition by volume to diesel engine by port fuel injection showed an average improvement of 4.26% for both power and torque, an average reduction of 14.32%, 15%, and 33% for combined fuel consumption, NO_x, and CO_2 emissions [59].

3. Hydrogen storage systems

Hydrogen, the most abundant element in the universe, has enormous potential as an energy carrier. Hydrogen can be easily generated from renewable energy sources, for example, PV, wind, or hydro, with electrolyzers [46,60]. There are several types of hydrogen storage options [61]:

(1) Compressed H_2 gas storage system: the least complex method of storing pure hydrogen is as a compressed gas in a high-pressure cylinder. The gas can be stored at an ambient temperature, thereby avoiding costly and bulky thermal insulation, and it is easy to pump the gas, i.e., merely opening a valve allows the removal of the gas from the system.

(2) Metal hydride storage: certain materials absorb hydrogen under moderate pressure (less than 1000 psia) at low temperatures, forming reversible hydrogen compounds called hydrides. The storage tank contains powdered metals that absorb hydrogen and release heat when the hydrogen is forced into the tank under pressure. The hydrogen is released from the compound when the pressure is reduced and heat is applied.

(3) Liquid hydrogen storage: hydrogen can be stored as a liquid at extremely low temperatures (-253 C) in highly insulated vacuum containers.

(4) Carbon adsorption: this type of storage system is in the research stage. Here, the hydrogen is forced into a refrigerated tank under pressure, where it adheres to activated carbon. The carbon material is a highly porous material that absorbs hydrogen efficiently.

(5) Sponge iron: hydrogen can be produced onboard a vehicle by oxidation of iron using steam. In this reaction the powered iron stored in the tank is combined with oxygen in the steam to form iron oxide (rust) and liberates hydrogen in the process. Once the iron is completely converted to iron oxide in the vehicle, either the entire tank is replaced or the iron oxide is removed from the tank and replaced with fresh iron. In either case, it takes a few minutes to replace.

The development of adequate on-board energy storage is a major economic and technological barrier to introducing hydrogen vehicles. There are three leading options for fuel storage onboard a fuel cell vehicle: (a) compressed hydrogen gas storage, (b) metal hydride storage, and (c) onboard methanol reformer system. Energy for fuel cell vehicles can be produced from solar power, biomass, or any other means [62]. The calculated energy efficiencies of fuel cell vehicles with assorted options for hydrogen storage and of a battery-powered electric vehicle are shown in Figure 2. The highest efficiency is achieved for the battery-powered electric vehicle. The energy efficiency from the photovoltaic array (electricity) to the wheels of the vehicle is highest for battery-powered electric vehicles (60%) and lowest for the fuel cell vehicle with an onboard methanol reformer system (14%). When we consider regenerative braking in the drive-train system, some of the energy consumed can be saved in the fuel pathway; around 25% of the braking energy is regenerated and stored in the batteries. Due to regenerative braking, the overall fuel efficiency increases in all the storage options [62].

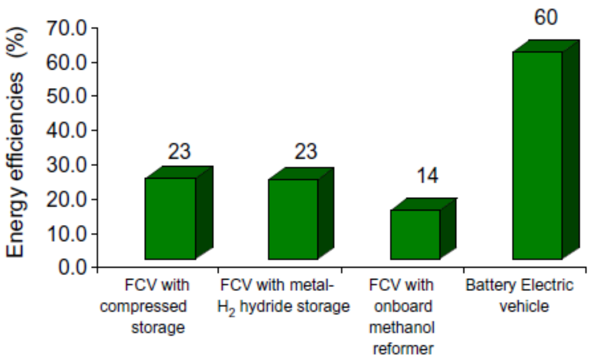


Figure 2. Comparison of energy efficiency of different leading storage options

The driving range per refueling depends on the weight of fuel & fuel tank (W), and it is also largely affected by the storage methods. The dashed lines represent the different speeds of the vehicle (30, 40, 50 and 60 mph). Figure 3 shows that the driving range per refueling does not increase with a linear function and is affected largely by the storage methods. A battery-powered electric vehicle with W 300 kg, which may be the maximum W for practical use, can travel only 100 miles. When a driving range of 300 miles is required, the battery-powered vehicle must carry more than 800 kg of 'fuel'. This result indicates the battery powered vehicle is much inferior in the driving range as compared to the fuel cell vehicles. In the case of a fuel cell vehicle with an onboard methanol reformer storage system, the W 350 kg is required for a driving range of 300 miles. Even in the case of a fuel cell vehicle with metal hydride storage, for a 300-mile driving range, the weight of fuel and fuel tank would be more than 500 kg. It has been found that vehicles with these storage methods must carry much heavier fuel and a fuel tank of more than 300 kg to obtain a driving range of around 300 miles. On the other hand, in the case of a fuel cell vehicle with a high-pressure container at 5000 psi, W 100 kg will give a driving range of 300 miles [60].

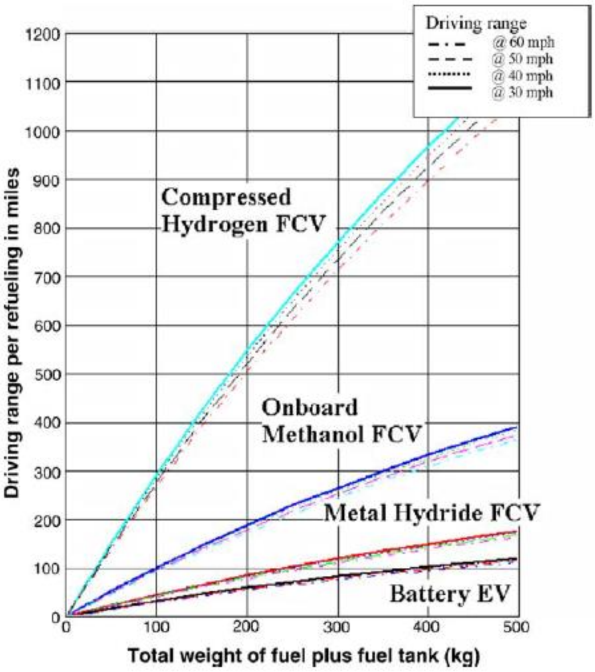


Figure 3. Effect of weight on the driving range

Table 2 shows the vehicle fuel economy on the urban driving cycle and highway driving cycle used by the EPA (US Environmental Protection Agency, 2003) to certify that vehicles meet the Federal emissions and fuel economy standards. To generate these two fuel economy estimates, different tests are used by the EPA to represent typical driving cycles in a city and a highway. The fuel economy is highest for a battery-powered electric vehicle like the two-seater Ford electric vehicle as compared to the hybrid and compressed hydrogen stored fuel cell vehicles (Honda FCX). The fuel economy of battery-powered electric vehicles is based on electricity from an outlet (electrical grid). The higher fuel economy of the battery-powered electric vehicle is due to the direct use of the electricity from the outlet without much loss in energy conversion. In the case of the fuel cell vehicle, the lower fuel economy is due to the losses in energy conversion in the fuel cell stack and losses in the drive train [63].

Table 2. Fuel economy of vehicle

Type of vehicle	City[a]	Highway[a]
	(mpg) gasoline equivalent	(mpg) gasoline equivalent
2001 Ford Th!nk Electric vehicle	106	83
2004 Honda FCX (miles/ kg ≈ mpg)	51	46
2004 Honda Civic hybrid	48	47
2004 Honda Insight	57	56
2004 Toyota Prius	60	51

[a] From www.fueleconomy.gov.

Due to the environmental and resource limitations that have made the use of fossil fuels doubtful, hydrogen as a clean fuel has stepped forward to compete with other alternative methods. Although hydrogen in gaseous and even in liquid form is inherently unrivaled among other fuels due to its highest calorific value and specific energy, so that its LHV is about 3 times higher than gasoline or diesel (120 to 142 MJ/kg vs. 42 to 44 MJ/kg), hydrogen is significantly less efficient than gasoline and diesel on a volumetric basis, the energy density of hydrogen at standard temperature and pressure (STP) is 0.003 kW/lit, compared to 8.9 for gasoline and 10 for diesel. This issue has made the expansion of hydrogen services in transportation a serious challenge [60]. There are three main categories of hydrogen storage methods [64]:

- Physical methods (1-compressed gas at (350–700 bar [5,000–10,000 psi]), 2- cryogenic temperatures (stored at -253°C), 3- liquid H_2)
- Chemical methods (1-Absorbed on interstitial sites, 2-Adsorbed hydrogen, 3-Complex compounds (or), 4-Chemical oxidation of metals with water)
- Hybrid methods (1- cryogenic adsorption)

These storage methods have fundamental challenges, that is why they need a functional system that overcomes these problems. The major challenges are [65]:

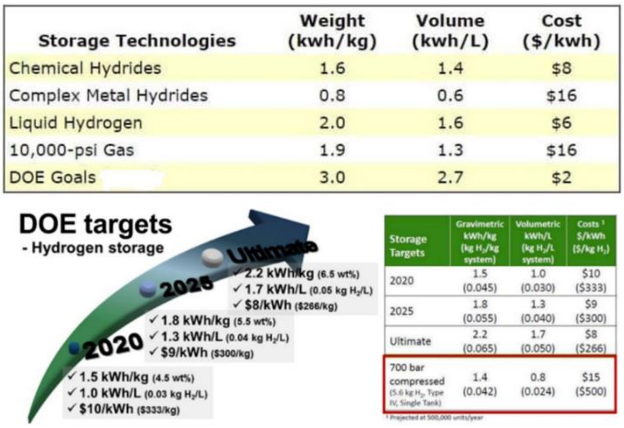
- Working pressure and temperature
- Stability of storage materials
- Hydrogen purity for fuel cell
- Reversibility of hydrogen in absorption and adsorption reactions
- The amount and duration of refueling
- System delivery pressure and temperature
- Safety, toxicity and efficacy, and overall cost of the system

Often, the requirements for a hydrogen storage system, especially in gas or liquid form, in combination with an engine or fuel cell component, are conflicting or, at best, inconsistent. Instead, hydrogen in chemical form has been able to fulfill the requirements despite the challenges of choosing an ideal material to achieve full reversibility in the process of storage and communication systems for transportation purposes. Although, the exact investigation of control bond strength, desorption kinetics, cycle-induced degradation, and the role of nanosize and nanostructure in bonding and kinetics still require extensive research in material sciences.

Currently, there are three hydrogen storage systems to commercialize for transportation [64]:

- The compressed gas at high pressures of 5,000 to 10,000 psi.
- Liquid hydrogen at a cryogenic temperature of -253°C.
- Material storage based on solid materials, including metal hydrides and absorbent carbon-based materials. (Chemical hydrogen storage)

The United States Department of Energy (DOE) is a cabinet-level department of the United States federal government. DOE has set goals for optimal and safe hydrogen storage conditions. The status of various storage technologies and DOE's goals in terms of weight, volume, and cost are given in Figure 4. So far, these systems have performed three to eight times worse in meeting the DOE's goals [64]. To obtain hydrogen from gasoline energy, the tank of a hydrogen vehicle is several times larger than a similar type of gasoline. Apart from this challenge, the safety issue must also be considered, which causes a heavy and large tank to be imposed on the vehicle [66]. High-pressure hydrogen tanks made of carbon fiber may be a solution, but carbon fiber tanks are currently too expensive [67]. Figure 5 is a schematic system of a fibrous composite hydrogen storage tank.



Storage Technologies	Weight (kwh/kg)	Volume (kwh/L)	Cost ($/kwh)
Chemical Hydrides	1.6	1.4	$8
Complex Metal Hydrides	0.8	0.6	$16
Liquid Hydrogen	2.0	1.6	$6
10,000-psi Gas	1.9	1.3	$16
DOE Goals	3.0	2.7	$2

Storage Targets	Gravimetric kWh/kg (kg H_2/kg system)	Volumetric kWh/L (kg H_2/L system)	Costs [1] $/kWh ($/kg H_2)
2020	1.5 (0.045)	1.0 (0.030)	$10 ($333)
2025	1.8 (0.055)	1.3 (0.040)	$9 ($300)
Ultimate	2.2 (0.065)	1.7 (0.050)	$8 ($266)
700 bar compressed (5.6 kg H_2, Type IV, Single Tank)	1.4 (0.042)	0.8 (0.024)	$15 ($500)

[1] Projected at 500,000 units/year

Figure 4. Performance comparison of various hydrogen storage methods with DOE targets

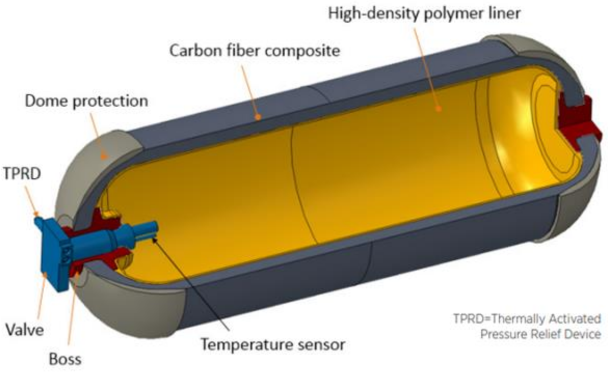


Figure 5. A schematic of a composited pressure vessel designed for compressed hydrogen storage in FCEV

4. Conclusions

This study provides a comprehensive analysis of advanced combustion technologies and alternative fuels, emphasizing their integration into hybrid electric vehicle (HEV) platforms to drive significant advancements in thermal efficiency, emissions reduction, and overall system performance. Key contributions of the research include:

- Integration of Advanced Combustion Technologies: Novel systems such as Low-Temperature Combustion (LTC), Atkinson cycle, Gasoline Compression Ignition (GCI), and Gasoline Direct Injection (GDI) enhance fuel efficiency and reduce NO_x and particulate emissions. Their combination in hybrid systems optimizes performance under varying operational conditions, pushing internal combustion engines to compete with electrified alternatives.
- Combustion Control & Phasing Management: Technologies like variable valve timing (VVT), variable compression ratio (VCR), and cylinder deactivation (CDA), paired with adaptive machine learning algorithms, dynamically optimize combustion phasing and fuel injection, enhancing engine efficiency and reducing emissions across multiple engine loads.
- Fuel Flexibility: Hybrid ICE systems that support dynamic switching between alternative fuels—such as CNG, LPG, biodiesel, and hydrogen—achieve significant emissions reductions and improved energy security, extending operational range and flexibility.
- Hydrogen-ICE Potential: Plasma ignition and lean-burn technologies in hydrogen-powered internal combustion engines (ICEs) elevate thermal efficiency to over 45%, positioning them as competitive alternatives to battery electric vehicles (BEVs) in terms of energy efficiency and emissions.
- Hybrid Systems with Continuous Learning: Integration of continuous learning algorithms in hybrid powertrains allows real-time optimization of power distribution, fuel consumption, and predictive maintenance, improving long-term performance and reducing operational costs.
- Multi-Mode Combustion: Combining GDI, GCI, and LTC technologies in HEV architectures optimizes fuel efficiency and emissions performance, particularly in heavy-duty and long-range applications.

In conclusion, this research illustrates that the fusion of advanced combustion technologies, alternative fuels, and intelligent hybrid systems provides a transformative pathway to achieving low-carbon, high-efficiency propulsion systems. These innovations position internal combustion engines as pivotal contributors to future sustainable mobility, particularly in hybrid configurations.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements and state that the submitted work is original and has not been published elsewhere.

Data availability statement

The datasets analyzed during the current study are available and can be given upon reasonable request from the corresponding author.

Conflict of interest

The authors declare no potential conflict of interest.

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