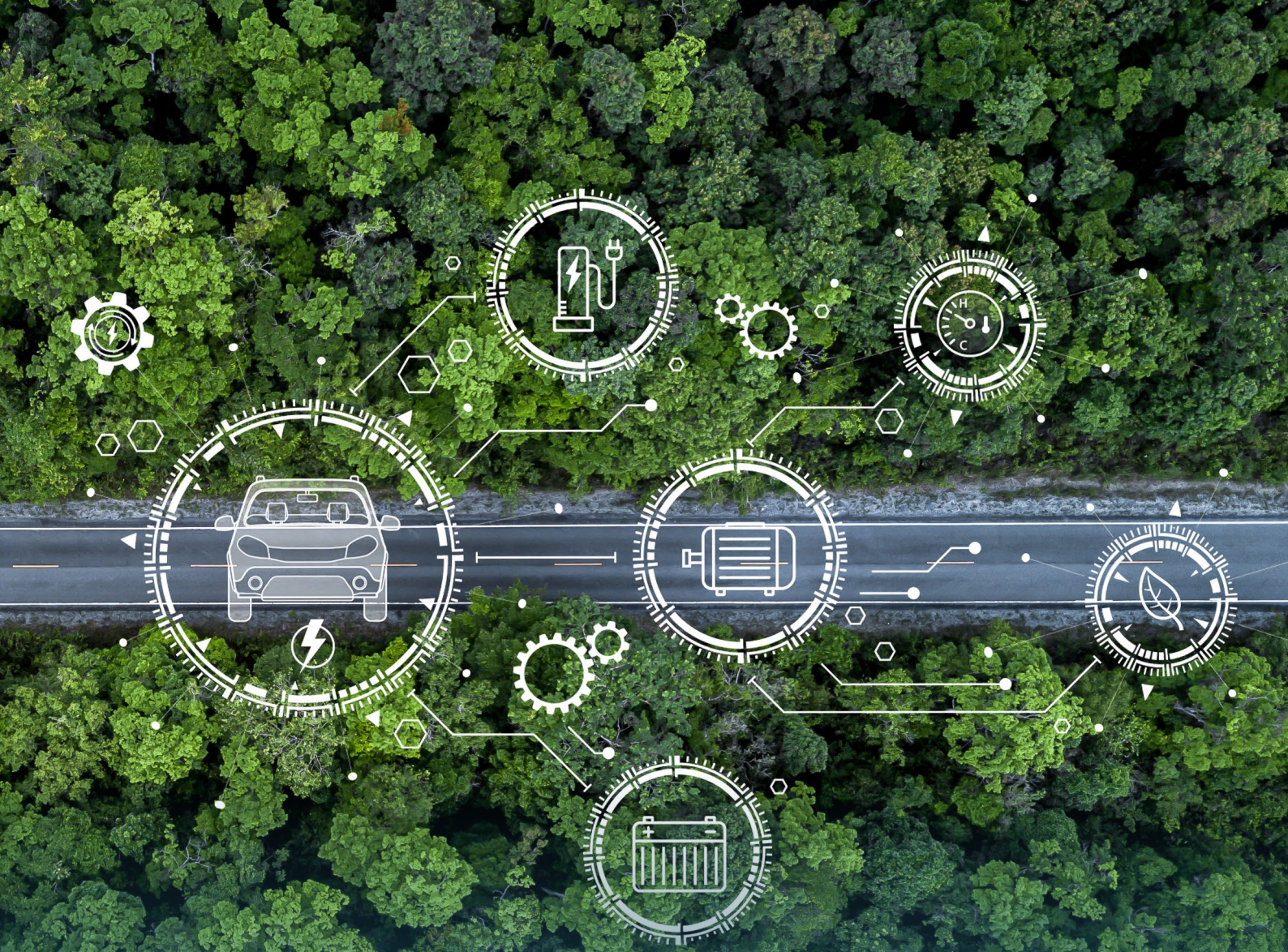

Vehicle Propulsion Systems: Technical and Regulatory Analysis

I-via
Israel Vehicle Importers Association

Introduction

In recent years, the global transportation sector has undergone a significant transformation, driven by rapid advancements in propulsion technologies, growing environmental awareness, and increasingly stringent regulatory standards. No longer limited to internal combustion engines alone, the industry now encompasses a broad spectrum of propulsion systems, from hybrid to electric and hydrogen technologies.

In light of these developments, we have found it appropriate to consolidate professional information into a single document presenting the full range of currently available alternatives, their advantages and disadvantages, while providing an in-depth presentation of their technical characteristics and implementation in the global automotive market.

The technological discourse has become increasingly complex, and vehicle propulsion systems, beyond being a technical matter, have become a cornerstone of transportation, energy, and environmental policy. A vehicle's propulsion system is a decisive factor in determining energy efficiency, emissions profile, and overall performance, and therefore lies at the heart of efforts to develop sustainable mobility.

Historically, internal combustion engines (ICEs) have dominated the market due to their high energy density, durability, and extensive availability of refuelling infrastructure. However, rising awareness of greenhouse gas emission impacts, dependence on fossil fuels, and urban air pollution has accelerated the development and implementation of alternative propulsion systems - electric vehicles (EVs)- including hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), fuel cell electric vehicles (FCEVs), and alternative fuel-based propulsion systems. These new technologies create both opportunities and engineering challenges, requiring innovation in energy storage, charging infrastructure, fuel production, and supply chain logistics.

This document is the result of extensive work, professional experience, and the belief that deep technical understanding is the foundation for understanding the future automotive market and our ability to forecast and prepare for future processes.

Propulsion systems are classified according to their application in various vehicle categories, including passenger cars, commercial trucks, public transportation buses, agricultural equipment, and civil engineering vehicles, each with unique performance and operational requirements.

In this work, we aimed to bridge the engineering and policy worlds, connecting scientific knowledge with field decision-makers, as well as individuals interested in the automotive market and its development trends.

We all hope that this document will serve as a resource for industry professionals, regulators, and stakeholders seeking reliable and up-to-date information that sheds light on the subject and provides a broader perspective on the present and future of vehicle propulsion systems.

Respectfully,

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Executive Summary

The global transportation industry is undergoing a technological and strategic transformation, driven by the urgent need to reduce greenhouse gas emissions, meet climate targets, improve air quality in urban areas, and address geopolitical crises in energy markets. In this era, vehicle propulsion systems have evolved from relatively simple mechanical mechanisms to critical components in environmental, engineering, and regulatory considerations of nations, manufacturers, and consumers alike.

This paper aims to provide a systematic mapping of all existing and emerging propulsion systems in modern vehicles. The paper presents a comprehensive engineering analysis of operating principles, advantages, disadvantages, performance, and environmental impacts of each technology, while addressing technology readiness levels (TRL), supporting infrastructure, and compliance with international standards.

The first chapter addresses classical propulsion, specifically internal combustion engines (ICEs), based on the Otto and Diesel cycles. We examine the effects of engine structure, compression ratio, injection systems, and valve management on thermal efficiency, pollutant emissions, and fuel consumption. Additionally, we discuss the challenges involved in meeting international emissions standards and the gradual transition from fossil fuels to alternative fuels.

Subsequently, the paper presents a review of alternative fuels from non-renewable sources, including compressed natural gas (CNG), liquefied petroleum gas (LPG), and synthetic fuels, which serve as a temporary transitional solution toward the use of renewable energy.

The central part of the paper is dedicated to hybrid and electric vehicles, including HEVs, PHEVs, BEVs, and hydrogen fuel cell vehicles (FCEVs). Each technology is examined in terms of its operating principles, propulsion systems, energy optimization, advanced control systems, efficiency, charging performance, and the lifespan of its battery or fuel cell.

Additionally, we discuss infrastructure challenges, including the deployment of public charging stations (AC/DC) and hydrogen refueling stations (HRS), as well as logistics and the integration of these systems in various countries. The paper presents current data segmented by application areas: private vehicles, commercial vehicles, public transportation, and engineering equipment, with representative case studies from Israel and worldwide.

The final part of the paper addresses regulatory trends and their integration into industrial strategies, implementation challenges related to material supply chains, and the need for multi-disciplinary coordination among regulators, manufacturers, and energy suppliers.

In summary, the paper positions propulsion systems at the heart of the 21st century's transportation and energy revolution. It presents a status report for those

involved in formulating transportation policy, vehicle engineering, sustainability, and technology. Through technical information, evaluation methodologies, and comparative analyses, the paper outlines practical directions for implementing advanced propulsion systems while maintaining a balance between engineering innovation, economic feasibility, and environmental contribution.

Internal Combustion Engine (ICE) - Propulsion Systems

Gasoline and Diesel Engines

1. Structure and Operating Principles

Internal combustion engines (ICEs) generate mechanical energy through combustion of a fuel-air mixture within a closed chamber, creating high-temperature gases that drive pistons connected to the crankshaft. This process involves converting the chemical energy stored in fuel into kinetic energy through controlled combustion, while maintaining an optimal balance between power output and energy efficiency. The basic operating cycle of an internal combustion engine is defined by the **Otto cycle** (for gasoline engines) or **Diesel cycle** (for diesel engines), each operating according to a unique thermodynamic sequence.

The **Otto cycle**, primarily implemented in spark-ignition gasoline engines, operates with a fixed compression ratio and controlled ignition timing via spark plugs. In contrast, the **Diesel cycle**, used in compression-ignition engines, is characterized by a higher compression ratio and relies on spontaneous fuel ignition under high-pressure conditions, leading to improved thermal efficiency. These operating cycles dictate the engine's performance characteristics, fuel consumption, and emissions profile, thereby influencing technological advancement and compliance with stringent regulatory standards.

Otto Cycle (Gasoline Engines)

Intake Stroke:

During the intake stroke, the intake valve opens, allowing a precisely measured mixture of air and fuel to enter the combustion chamber, as atmospheric pressure pushes the mix into the cylinder. In modern gasoline engines, this process is enhanced through Variable Valve Timing (VVT) systems that adjust valve operation to improve airflow and energy efficiency. Additionally, specific engines employ turbochargers or superchargers to increase intake pressure and improve volumetric efficiency. In Gasoline Direct Injection (GDI) engines, fuel is sprayed directly into the combustion chamber with high precision, enabling improved mixture formation, more efficient combustion, reduced emissions, and enhanced engine power.

Compression Stroke:

During the compression stroke, the mixture is compressed to a smaller volume, thereby increasing its pressure and temperature and raising its thermal potential energy. In gasoline engines, this process contributes to improved combustion efficiency when the spark plug ignites the mixture. Additionally, modern engines are equipped with **Variable Compression Ratio** (VCR) mechanisms that allow optimization of fuel consumption and performance according to varying loads.

Power Stroke:

During the power stroke, a spark plug ignites the compressed fuel-air mixture, resulting in rapid combustion and a sharp increase in pressure within the cylinder. As a result, the piston is forcefully pushed downward, converting chemical energy into mechanical energy. The piston's movement rotates the crankshaft, which ultimately drives the vehicle's wheels. The process efficiency is influenced by factors such as air-fuel ratio, ignition timing, and the design of the combustion chamber. In high-performance engines, technologies such as Gasoline Direct Injection (GDI) and Variable Valve Timing (VVT) optimize the combustion process, enhance power output, and reduce fuel consumption. Additionally, in turbocharged or supercharged engines, increased air intake pressure enhances the density of the fuel-air mixture, resulting in higher combustion efficiency and increased torque production.

Exhaust Stroke:

During the exhaust stroke, combustion gases are expelled in preparation for the following operating cycle. The exhaust valve opens, and high-pressure burnt gases are pushed out of the cylinder by the piston's upward movement. Efficient exhaust gas evacuation is crucial for maintaining engine performance, as residual gases can dilute the air-fuel mixture in the next cycle, thereby impairing combustion efficiency. Modern engines incorporate Variable Valve Timing (VVT) systems and Exhaust Gas Recirculation (EGR) to improve the process, helping control pollutant emissions and improve fuel efficiency. In high-performance engines, tuned exhaust manifolds and turbochargers are utilized to optimize the exhaust process, minimize backpressure, and improve engine responsiveness.

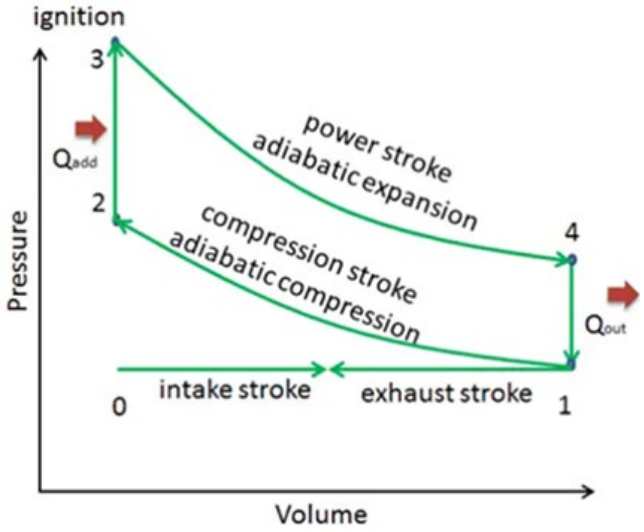
Figure 1

Intake Stroke (1 ⟶ 2): The air-fuel mixture is drawn into the cylinder.

Compression Stroke (2 ⟶ 3): The mixture is compressed, thereby increasing its pressure.

Power Stroke (3 ⟶ 4): Ignition occurs, and the subsequent expansion of gases drives the piston.

Exhaust Stroke (4 ⟶ 1): The combusted (or burnt) gases are expelled from the cylinder.



The P-V (Pressure-Volume) diagram for an ideal Otto cycle is illustrated. The area encompassed by the thermodynamic path represents the total work that can be performed during a single cycle.

Diesel Cycle (Compression Ignition Engines)

- Unlike gasoline engines, diesel engines do not rely on external spark ignition. Instead, they operate on the compression ignition principle, where the high compression ratio (typically ranging from 14:1 to 25:1) raises the air temperature within the cylinder to a level where fuel spontaneously ignites upon injection. This compression process leads to significantly higher thermal efficiency compared to gasoline engines, as the high pressures enable more complete fuel combustion. This design maximizes energy extraction from each unit of fuel, resulting in lower fuel consumption and substantial energy savings. To further improve efficiency and performance, modern diesel engines incorporate advanced fuel injection management systems, such as Injection Timing Control, Multi-Stage Fuel Injection, and Turbocharging. These technologies improve energy utilization, reduce pollutant emissions, and enable higher power output.
- Diesel engines offer higher thermal efficiency compared to gasoline engines, translating to more economical fuel consumption and lower CO_2 emissions per unit of energy produced. However, the high temperatures and pressures in the combustion process increase the formation of nitrogen oxides (NO_x) and particulate matter (PM). To meet stringent emission standards such as Euro 6 and future Euro 7 regulations, diesel engines are equipped with After-Treatment Systems, Diesel Particulate Filters (DPF) to reduce PM emissions, Selective Catalytic Reduction (SCR) systems for NO_x reduction, and Exhaust Gas Recirculation (EGR). Continuous improvements in fuel injection strategies, advanced turbocharging technologies, and combustion optimization enable further reduction of pollutants while maintaining the thermal efficiency and performance advantages of diesel engines.

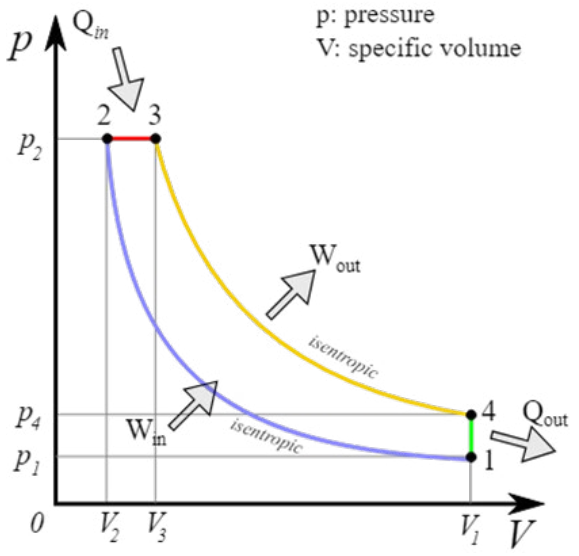
Figure 2

Adiabatic Compression (1 → 2): The piston moves upward, compressing the air as it does so. As this process is adiabatic (no heat is exchanged), the pressure and temperature of the air increase significantly.

Constant Pressure Heat Addition (2 → 3): As the piston reaches Top Dead Center (TDC), fuel is injected and ignites. Combustion occurs at a constant pressure while the volume expands.

Adiabatic Expansion (Power Stroke) (3 → 4): The hot, combusted gases expand, driving the piston downward and performing work.

Constant Volume Heat Rejection & Exhaust (4 → 1): The exhaust valve opens, causing a pressure drop at constant volume. The piston then moves upward to expel the remaining exhaust gases.



*An adiabatic process is one in which no heat is transferred between the system and its surroundings.

Key Components in Internal Combustion Engines

- Cylinder Block and Cylinder Head: The cylinder block forms the central structure of an internal combustion engine, housing the pistons, combustion chambers, and cooling channels. It is typically manufactured from aluminum alloys or cast iron to strike a balance between structural strength, thermal resistance, and optimal heat dissipation capability. The cylinder head, mounted on the block, contains the intake and exhaust valves, as well as spark plugs (in gasoline engines) or fuel injectors (in diesel engines). Additionally, the cylinder head features cooling and lubrication channels that help regulate operating temperature and reduce wear. Precise machining of the cylinder head is crucial for creating a complete seal during compression, enhancing combustion efficiency, and minimizing friction losses - all critical components for improving engine performance, reducing pollutant emissions, and extending the operational lifespan.

- Crankshaft and Connecting Rods: The crankshaft and connecting rods constitute the central interface between the pistons' linear motion and the engine's rotation, which drives the vehicle's drivetrain system. Connecting rods link the pistons to the crankshaft, converting linear motion into rotational motion. The crankshaft is typically constructed from forged steel or cast iron, which is adapted to withstand the high mechanical loads created during combustion. The structure includes bearings and precision balance shafts, whose function is to reduce vibrations and wear while improving engine operation. Integrated lubrication channels within the crankshaft provide optimal lubrication and minimize friction loss, thereby enhancing the engine's long-term durability. In high-performance engines, titanium alloys, advanced steels, or carbon composites are used for connecting rods to reduce rotating mass, improve the strength-to-weight ratio, and optimize energy efficiency.

- Camshaft and Valve Train: The camshaft and valve train are responsible for controlling airflow into and out of the cylinders, directly affecting combustion efficiency and engine power production. The camshaft opens and closes the intake and exhaust valves with precise timing in accordance with the engine's operating cycle. Advanced valve timing management systems, such as Variable Valve Timing (VVT) and Variable Valve Lift (VVL), enable dynamic adjustment of valve opening angle and timing. Advanced technologies, such as Dual Overhead Camshaft (DOHC) systems, Cam Phasing, and Cam Profile Switching, improve airflow, reduce pumping losses, and enhance throttle response. In high-performance and high-efficiency engines, there is a shift from mechanical camshaft mechanisms to advanced systems, such as electromagnetic or electro-hydraulic valve actuation, which allows for versatile control over valve cycles without unnecessary mechanical losses, thereby significantly improving energy efficiency and performance.

- Fuel Injection System: The fuel injection system is responsible for precise fuel delivery in carefully calculated quantities, ensuring optimal combustion efficiency, maximum power production, and pollutant emission control. Modern engines utilize high-pressure injection systems such as Common Rail Direct Injection (CRDI) in diesel engines and Gasoline Direct Injection (GDI) in gasoline engines. This technology enables superior engine performance by improving fuel atomization and providing precise injection control. By creating finer fuel droplets and optimizing the quantity, timing, and spray pattern of the fuel, it ensures more complete and efficient combustion. The result is higher energy efficiency, which simultaneously minimizes unburnt fuel losses and significantly reduces harmful emissions of carbon and nitrogen oxides.

- In diesel engines, CRDI systems operate at ultra-high pressures of up to 2,500 bar, enabling excellent fuel atomization and more homogeneous mixing with air, which improves combustion completeness and reduces particulate matter (PM) emissions. In gasoline engines, GDI systems inject fuel directly into the combustion chamber, rather than the intake manifold, enabling sharper throttle response and faster power transitions. This results in higher compression ratios without risk of knock, contributing to improved performance and fuel efficiency. Advanced technological innovations in injection systems include Multi-Stage Injection for improved combustion continuity and reduced pollution, Piezoelectric Injectors operating at high speed with micrometric injection precision, and Fuel Stratification strategies that further enhance efficiency and enable precise control over injection timing, fuel quantity, and spray patterns to optimize power delivery and emission reduction.

- Turbocharging and Supercharging: Air charging systems are designed to increase engine volumetric efficiency by increasing the air mass entering the combustion chambers, enabling combustion of more fuel and higher power production without increasing engine displacement. Turbochargers utilize exhaust gas energy to drive a turbine, which compresses the intake air before it flows into the combustion chambers.

- The benefits of turbocharging include: improved air density, allowing for more oxygen in the combustion process; optimized combustion and reduced pollutant emissions, achieved through an improved fuel-to-air ratio and lower CO_2 emissions; and improved fuel consumption, enabling more power from smaller engines (Downsizing).

Superchargers, in contrast, are mechanically driven by a direct connection to the engine's crankshaft, providing an immediate power boost without turbo lag. However, their disadvantage is the loss of efficiency due to increased mechanical load. To minimize operational disadvantages and improve performance, advanced engines incorporate advanced air charging technologies: Twin-Scroll Turbochargers for separating exhaust gases according to cylinder operating phase and improving turbo response, Variable Geometry Turbochargers (VGT) for changing exhaust gas flow according to engine load and improving performance across all RPM

ranges, and Electric Superchargers using electrical energy to provide immediate air compression and prevent turbo lag.

2. Energy Efficiency and Fuel Consumption in Internal Combustion Engines

Internal combustion engines experience significant energy losses due to heat dissipation, mechanical friction, and incomplete combustion. A substantial portion of the fuel's chemical energy is wasted as heat, rather than being converted into practical mechanical work, resulting in inefficiency. Heat dissipation occurs through the engine block, cooling system, and exhaust gases, with typical gasoline engines losing about 70-75% of fuel energy in these processes. Mechanical friction between moving components, such as pistons, bearings, and the valve system, also reduces energy efficiency. Incomplete combustion, particularly in older or poorly tuned engines, results in the emission of unburned hydrocarbons (HC) and carbon monoxide (CO). Advanced technologies such as high-pressure fuel injection, precise ignition timing, low-friction materials, and integrated hybrid assists are designed to minimize these losses and improve overall energy conversion efficiency.

In Gasoline Engines:

- Typical thermal efficiency ranges between 25% and 30%, with most losses caused by heat dissipation through the cooling system and exhaust.
- Technologies for improving efficiency in modern gasoline engines include Turbocharging, Gasoline Direct Injection (GDI), and Variable Valve Timing (VVT), which optimize airflow according to engine load.
- Additionally, Waste Heat Recovery Systems (WHRS) are used to recover wasted heat for reuse, increasing efficiency. The use of advanced piston coatings, such as Diamond-Like Carbon (DLC), and advanced oils helps reduce mechanical friction.
- Fuel consumption varies according to engine displacement, load conditions, and drivetrain optimization techniques such as:
- Cylinder Deactivation by shutting off cylinders under low load conditions to improve fuel consumption, Mild Hybridization systems incorporating a small electric motor to assist during acceleration and reduce demand on the thermal engine.
- Additionally, advanced engine control for real-time fuel-air mixture adjustment, Continuously Variable Valve Timing (CVVT), and Start-Stop systems reduce fuel consumption at idle.
- Reducing mechanical losses through innovations such as low-friction piston coatings, lightweight engine components, and optimal thermal management systems also plays a crucial role in minimizing fuel consumption.

In Diesel Engines:

- Higher thermal efficiency of 35-40% thanks to higher compression ratios, enabling greater energy extraction from fuel. High compression ratios result in increased cylinder pressures, leading to more complete combustion, lower fuel consumption, and reduced CO_2 emissions per unit of energy.
- Additionally, technologies for improving combustion and efficiency in diesel engines include Multi-Stage Injection systems for enhanced combustion continuity and pollutant reduction, Advanced Turbocharging, and Common Rail Direct Injection (CRDI) systems.
- These innovations contribute to performance improvement while maintaining strict compliance with pollutant emission requirements defined in international standards.
- Fuel injection pressures exceeding 2000 bar enhance the combustion process, resulting in more uniform and efficient combustion, which minimizes emissions of unburned hydrocarbons (HC) and carbon monoxide (CO). Additionally, precise fuel metering at these extreme pressures optimizes power delivery, reduces fuel consumption, and improves throttle response. Advanced systems, such as piezoelectric injectors and multiple injection events per combustion cycle, further refine this process by providing finer control over injection timing and spray patterns. This results in reduced noise, vibrations, and emissions, while maximizing fuel consumption and engine longevity.

3. Advantages and Disadvantages of Internal Combustion Engines (ICE) (Gasoline and Diesel)

✔ Advantages of ICE Propulsion Systems

- **Wide fuel availability:** Gasoline and diesel are available worldwide with established distribution infrastructure, making ICE-powered vehicles the most accessible.
- **Proven and mature technology:** ICE technology has been developed and refined for over a century, resulting in reliable, durable, and efficient engines.
- **Relatively low production costs:** Mass production of ICE vehicles is well-optimized, reducing per-unit manufacturing costs compared to newer propulsion technologies like electric or hydrogen engines.
- **High fuel energy density:** Gasoline and diesel have high energy density, enabling ICE vehicles to achieve long driving ranges without frequent refueling.
- **Fast refueling time:** Refueling an ICE vehicle takes only a few minutes, unlike battery electric vehicles (BEV) that require significantly longer charging times.
- **Developed maintenance and repair ecosystem:** With millions of ICE vehicles in operation, there exists an extensive network of mechanics, spare parts, and repair expertise.

- **Better performance in extreme cold:** ICE vehicles tend to perform better in cold weather compared to electric cars, which experience reduced battery efficiency at low temperatures.
- **Greater towing and heavy-duty capability (especially for diesel engines):** Diesel engines offer high torque at low RPM, making them ideal for heavy-duty applications such as trucks, buses, and industrial vehicles.
- **Flexibility in fuel options:** Certain ICE vehicles can operate on alternative fuels such as ethanol, biodiesel, or natural gas, potentially reducing dependence on fossil fuels.

✕ Disadvantages of ICE Propulsion Systems

- **Pollutant emissions (CO_2, NOx, PM, and HC):** ICE vehicles emit greenhouse gases (CO_2) and harmful pollutants like nitrogen oxides (NOx), particulate matter (PM), and hydrocarbons (HC), contributing to air pollution and climate change.
- **Lower efficiency compared to electric and hydrogen systems:** ICE vehicles typically have thermal efficiency ranging between 25-40%, meaning a significant portion of fuel energy is lost as heat. In contrast, electric motors have efficiency levels exceeding 90%.
- **Dependence on fossil fuels:** Reliance on gasoline and diesel contributes to energy security concerns and makes ICE vehicles vulnerable to fuel price fluctuations and geopolitical instability.
- **Higher operating costs due to fuel consumption and maintenance:** Frequent oil changes, engine maintenance, and fuel costs make ICE vehicles more expensive to operate over their lifetime compared to electric cars, which require less maintenance.
- **Noise and vibration:** ICE engines produce significant noise and vibrations, reducing ride comfort compared to the quiet operation of EVs.

4. Environmental and Regulatory Considerations

Internal combustion engines (ICEs) that rely on fossil fuels are a significant contributor to greenhouse gas (GHG) emissions and air pollution. The combustion process of gasoline and diesel fuels releases substantial amounts of carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter (PM), pollutants that contribute to global warming, respiratory diseases, and damage to ecological systems. To reduce their environmental impacts, stringent regulations have been formulated, including advanced emission standards and legislation for transitioning to cleaner fuels. Countries and international organizations are formulating policies to reduce the use of internal combustion engines while accelerating the adoption of electric and hydrogen propulsion systems as part of a long-term transition to sustainable transportation.

Euro 6, 7 Emission Standards of the European Union and EPA Standards of the USA

- European Union (EU) emission standards limit pollutant emissions by setting increasingly stringent limits for: nitrogen oxides (NO_x), carbon monoxide (CO), particulate matter (PM), and greenhouse gases (GHGs). The Euro 6 standard, which came into effect in the EU in 2014, mandated emission reductions from diesel and gasoline vehicles, leading to the widespread adoption of exhaust gas treatment technologies, including Selective Catalytic Reduction (SCR) and Diesel Particulate Filters (DPF). In the USA, the Environmental Protection Agency (EPA) regulates emission standards through Tier standards, focusing on reducing NOx and CO2 and improving fuel efficiency. The Worldwide Harmonized Light Vehicle Test Procedures (WLTP) have been adopted globally to replace outdated test cycles and provide a more accurate representation of fuel consumption and emissions under real-world driving conditions. These regulations play a critical role in shaping low-emission propulsion technologies and encouraging vehicle manufacturers to invest in hybrid and electric alternatives.

- Selective Catalytic Reduction (SCR) systems use a urea-based solution (AdBlue) to convert NOx emissions into harmless nitrogen and water vapor, significantly reducing the environmental impact of diesel engines. Complementarily, Diesel Particulate Filters (DPF) trap particles and periodically undergo regeneration to burn accumulated soot and maintain filter efficiency. Additional innovations, such as Exhaust Gas Recirculation (EGR) systems and oxidation catalysts, further enhance emission control, ensuring compliance with defined regulatory frameworks.

- Euro 7 Emission Regulations: Euro 7 standards, scheduled to be implemented on new vehicle models toward the end of 2026 and a year later on all new vehicles, represent the EU's most stringent regulations to date, aimed at significantly reducing nitrogen oxides (NOx), carbon dioxide (CO2), and particulate emissions from both gasoline and diesel engines. These new regulations will impose lower permitted emission thresholds and stricter Real Driving Emissions (RDE) testing requirements to ensure compliance throughout the vehicle's lifetime. Euro 7 will also introduce tighter controls on non-exhaust emissions from brake and tire wear, addressing broader environmental issues. Implementation of these regulations will push vehicle manufacturers to accelerate the adoption of cleaner technologies, including advanced catalytic converters, hybrid-electric propulsion systems, and EVs, to meet the stringent emission targets.

- **Corporate Average Fuel Economy (CAFE) Standards in the USA**

  Requires efficiency improvements across a manufacturer's entire fleet to curb fuel consumption and CO_2 emissions by setting increasingly stringent fuel consumption targets and emission reduction requirements for vehicle manufacturers. These regulations encourage the development of fuel-efficient technologies such as downsized turbo engines, advanced hybrid propulsion

systems, and lightweight vehicle materials. Vehicle manufacturers must meet Corporate Average Fuel Economy (CAFE) standards through a combination of engineering advancements, the adoption of alternative fuels, and improved aerodynamics. Additionally, significant penalties for non-compliance drive the transition to EVs and Low-Emission Vehicles (LEVs).

5. Alternative and Renewable Fuels - Regulatory Framework and Technological Implications

In an era where the energy and transportation sectors stand at the forefront of the climate change battle, the need has intensified for developing feasible interim solutions that will enable a gradual transition from traditional fossil fuel-based propulsion systems, such as gasoline and diesel, to clean propulsion technologies. The EU's Alternative Fuels Directive (AFD) and the United States' Renewable Fuel Standard (RFS) constitute key regulatory initiatives designed to accelerate the transition to renewable energy sources in transportation through mandatory regulations, economic incentives, and enforcement mechanisms. The transition phase is characterized by a combination of renewable and non-renewable alternative fuels, including biogas, liquid biofuels, biodiesel, natural gas, synthetic fuels, and shale oil. The role of alternative fuels in sustainable transportation is to serve as a technological bridge and interim stage, promoting gradual improvement in air quality, reducing the carbon footprint, and preparing the ground for a future complete transition to renewable energy sources. The interim stage faces challenges such as expanding production capabilities, ensuring economic viability, and achieving regulatory uniformity, which moderate their impact on the energy market.

- **Renewable Alternative Fuels**

  Renewable fuels derived from biomass (organic material originating from living organisms or organic waste) have emerged as a component in the transition to sustainable energy systems. These fuels are derived from organic materials such as: agricultural residues (prunings, corn husks, straw, crop waste), industrial residues (wood waste, sawdust, paper waste), municipal residues (organic waste from kitchens or landfills), dedicated energy crops (sugarcane, corn, or fast-growing trees), and animal waste (manure). Renewable fuels offer potential for a significant reduction in greenhouse gas emissions while maintaining compatibility with existing combustion-based infrastructure.

1. Biofuels (Ethanol and Biodiesel)

- **Ethanol (C_2H_5OH):** Produced from fermentation of organic material such as corn and sugarcane, widely blended with gasoline (e.g., E10 - 10% ethanol, or E85) to reduce net CO_2 emissions and improve combustion efficiency.

- **Biodiesel (Fatty Acid Methyl Esters - FAME):** Produced from vegetable oils, animal fats, or recycled oils, and typically blended with fossil diesel (e.g., B20 - 20% biodiesel blend). Biodiesel reduces sulfur oxide (SO_x) and particulate matter (PM) emissions while maintaining compatibility with existing diesel engines.

2. Synthetic Fuels (E-Fuels) - Carbon-Neutral Liquid Fuels

Fuels synthesized using Power-to-Liquid (PtL) technology are suitable for use as conventional fuel. These fuels are fully compatible with existing fuel infrastructure and internal combustion engine technologies, offering the advantage of net-zero CO_2 emissions.

3. Hydrogenated Vegetable Oils (HVO) - Advanced Diesel Alternatives

Hydrogenated Vegetable Oils (HVO) constitute an advanced biodiesel alternative that undergoes treatment to improve combustion efficiency and chemical stability. HVOs serve as a direct diesel replacement without the need for special engine adaptations, while also reducing NO_x and particulate matter (PM) emissions compared to conventional diesel.

Non-Renewable Alternative Fuels

Non-renewable alternative fuels are energy carriers not derived from renewable resources but differ from regular petroleum-based fuels in their composition, production process, or environmental performance. These fuels are typically developed to serve as cleaner or more efficient substitutes for traditional fossil fuels while leveraging existing infrastructure and engine technologies. Although sourced from finite natural resources (such as natural gas, coal, or petroleum byproducts), they are designed to reduce specific pollutants or improve operational efficiency. Examples of non-renewable fuels include: Compressed Natural Gas (CNG), Liquefied Natural Gas (LNG), and Liquefied Petroleum Gas (LPG).

Compressed Natural Gas (CNG) Propulsion Engines

Compressed Natural Gas (CNG) has emerged as a sustainable alternative fuel for vehicle propulsion, particularly in sectors such as public transportation, freight transport, and construction. Its application in buses, trucks, and construction vehicles offers both environmental and economic advantages.

1. Structure, Operating Principles, and Fuel Storage

CNG consists primarily of methane (CH_4), compressed to less than 1% of its volume and stored at pressures ranging from 20 to 25 MPa (2,900 to 3,600 psi). This high-pressure storage requires the use of substantial, cylindrical or spherical containers, typically manufactured from steel or composite materials, to ensure safety and durability.

Engine Modifications

Vehicles powered by CNG can use internal combustion engines that have been modified and adapted to operate on natural gas. These engines may be adapted for use with natural gas only or for dual-fuel use with other conventional fuels, such as gasoline or diesel. The main modifications include reinforced valve seats and special fuel injectors to accommodate the distinct combustion characteristics of methane.

Fuel Supply System

The fuel supply infrastructure in vehicles using natural gas includes high-pressure lines, pressure regulators, and injectors adapted for gaseous fuel. The system is designed to ensure precise fuel metering and maintain optimal pressure levels during the transition from storage tank to combustion chambers, facilitating efficient and clean combustion.

2. Advantages and Disadvantages of CNG Propulsion Systems

✔ Advantages

- **Environmental Benefits - Reduced Emissions:** Natural gas combustion produces lower emissions of carbon monoxide (CO), nitrogen oxides (NO_x), particulate matter (PM), and unburned hydrocarbons compared to gasoline or diesel engines. Additionally, natural gas emits approximately 20-29% less CO_2, contributing to greenhouse gas reduction.
- **Economic Benefits - Fuel Cost Savings:** Leading to reduced operating costs for CNG-powered fleets, and lower maintenance costs due to the clean combustion nature of CNG.

✘ Disadvantages

- **Energy Density and Storage Challenges:** CNG has lower volumetric energy density compared to diesel, requiring the use of larger or multiple storage containers to achieve a similar vehicle range.
- **Storage Volume Requirements:** The bulky nature of high-pressure CNG storage cylinders may compromise cargo or passenger space, posing design challenges, particularly in vehicles converted for CNG use.
- **Refueling Infrastructure - Limited Availability:** A shortage of natural gas refueling stations, particularly in certain regions, may limit the operational range and convenience of these vehicles. In Israel, despite past government plans and intentions to establish nationwide refueling stations, currently only one public refueling station operates at the Alon Tavor complex in the north. Bus companies such as Egged, Metropoline, Superbus, Dan, and others operating CNG-powered buses use Mobile Refueling Units (MRU) at their operational facilities.

3. Application in Buses, Trucks, and Heavy Mechanical Equipment

Buses

CNG-powered buses are utilized in urban public transportation due to their environmental benefits and lower operating costs. Municipalities worldwide have adopted these buses to improve air quality and meet emission regulations.

Trucks

In the transportation sector, CNG-powered trucks offer a cleaner alternative to diesel-powered vehicles. While the lower energy density of natural gas requires more frequent refueling or larger storage containers, advances in engine technology and fuel storage have reduced these challenges, making these trucks a viable option for short to medium-distance transport.

Heavy Mechanical Equipment

The application of CNG-powered engines in equipment such as forklifts and excavators serves as a strategy for reducing emissions at work sites. Manufacturers are developing compatible heavy machinery to meet stringent environmental regulations and satisfy the growing demand for sustainable construction methods.

4. Efficiency Calculations

Engine Efficiency

CNG engines can achieve thermal efficiencies similar to or slightly superior to those of gasoline engines. The high octane rating of methane (120 RON) allows the use of higher compression ratios without risk of early knock, which can contribute to improved thermal efficiency. However, the lower energy density of CNG may reduce vehicle range unless larger or multiple storage containers are used for energy compensation.

Emission Reduction

The use of CNG can lead to a significant reduction in particulate emissions (up to 50% in NOx) compared to diesel engines. These reductions are essential for meeting stringent emission standards and improving urban air quality.

5. Standards and Regulations

EU Standards and Regulations

Safety Standards: UNECE R115 regulation of the United Nations Economic Commission for Europe establishes uniform provisions for approval of CNG propulsion systems installed on vehicles.

Emission Standards: CNG vehicles in the EU must meet stringent emission standards designed to reduce pollutants. Euro VI standards, implemented in 2014 for heavy-duty vehicles, set limits on the amount of nitrogen oxides (NO_x), hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM) for each company. CNG engines typically produce lower NO_x and PM emissions compared to diesel engines, facilitating compliance with these standards.

United States Standards and Regulations

Safety Standards: The U.S. has established Federal Motor Vehicle Safety Standards (FMVSS) relevant to CNG vehicles:

- **FMVSS 303:** Addresses CNG vehicle fuel system integrity, ensuring the fuel system can withstand a crash without leaking.
- **FMVSS 304:** Concerns the integrity of CNG fuel containers, requiring them to meet specific criteria for pressure cycles and burst strength to prevent failures under normal and accident conditions.

Emission Standards: The U.S. Environmental Protection Agency (EPA) sets emission standards, including for CNG vehicles. The standards establish limits on NO_x, non-methane hydrocarbons, CO, and PM. The EPA's Tier III standards, phased in between 2017 and 2025, further tighten these limits to reduce air pollution and protect public health.

6. Summary

CNG presents an alternative to conventional fuels for vehicle propulsion, particularly in heavy-duty applications such as buses, trucks, and heavy machinery, and constitutes a step toward zero-emission vehicle propulsion.

Electric Vehicles (EV)

The growing need to address environmental challenges, primarily greenhouse gas emissions, air pollution, and global warming, serves as an accelerating factor in the search for sustainable alternatives to internal combustion engines. The transition to electric propulsion, which emits no pollutants during driving, contributes to air quality improvement, especially in urban areas, reduces transportation noise, and decreases dependence on fossil fuels, emerging as an achievable and preferable alternative for the coming years.

Significant advances in battery chemistry, energy storage, and the development of charging infrastructure have been essential for addressing technological and logistical barriers on the path to implementing sustainable transportation. Additionally, governments and industry stakeholders play a central role in promoting clean propulsion technologies through regulatory incentives, emission standards, and investments in supporting infrastructure. This chapter presents the operating principles and technologies that have entered use in EVs in recent years.

1. Structure and Operating Principles

EVs use electric motors that convert electrical energy into mechanical motion based on electromagnetic principles. Unlike internal combustion engines (ICEs) that operate on fuel combustion to create work, electric motors utilize the interaction between magnetic fields and electric currents to produce rotational motion. This process does not require complex mechanical components such as crankshafts, pistons, or exhaust systems, thereby reducing energy losses and mechanical wear. Electric motors can deliver instant torque, enabling sharp acceleration and higher responsiveness compared to traditional thermal engines.

Three Main Types of Electric Motors in EVs

- **AC Induction Motor / Asynchronous Motor**

  These motors operate based on electromagnetic induction, which enables the conversion of electrical energy stored in batteries into mechanical energy, translated into the rotation of the electric motor shaft and vehicle wheels.

  Induction motors are widely valued for their durability, independence from rare materials, and economy. Despite their relatively lower efficiency, their simple design, low maintenance requirements, and ability to operate across a wide speed range have led to their adoption in various EV models, including early Tesla vehicles and some commercial electric transportation solutions.

- **Permanent Magnet Synchronous Motor**

  These motors incorporate permanent magnets, ensuring efficiency and precise control. The motors operate with synchronized rotation, leading to minimal energy loss and an overall efficiency of approximately 95% under optimal conditions. Additionally, synchronous motors provide higher power outputs in a

compact size, making them ideal for modern EVs. However, the use of permanent magnets made from rare materials, such as neodymium and dysprosium, poses supply chain challenges and cost fluctuations. To reduce dependence on rare elements while maintaining performance, researchers are exploring alternatives, such as Ferrite Magnets based on iron oxides with additional materials like barium, and hybrid magnets that combine ferrite magnets with neodymium magnets.

- **Brushless DC Motors (BLDC)** These motors use an electronic controller whose function is to switch current direction in the coils according to rotor position, thereby creating a magnetic field for motor shaft rotation. These motors have improved efficiency compared to Brushed DC Motors, lower maintenance, and longer operational lifespan.

  Additionally, BLDC motors exhibit excellent torque control and power density, making them ideal for EVs requiring precise acceleration and energy efficiency. Their compact design and durability have led to widespread use in electric two-wheeled vehicles and auxiliary components such as cooling fans and power steering systems.

2. Range and Efficiency Calculations

- **Electric Motor Efficiency:** Electric motors typically exhibit efficiency rates between 85% and 95%, performing better than internal combustion engines operating at approximately 25%-40% efficiency. This higher efficiency results from eliminating mechanical losses associated with combustion, such as heat dissipation, friction in moving parts, and energy losses in exhaust. Unlike internal combustion engines, which require multiple conversion stages from chemical to mechanical energy, electric motors directly convert electrical energy to motion with minimal losses. Advanced control algorithms, electrical energy generation during vehicle braking or deceleration, and optimized electronics further enhance efficiency by dynamically managing the power supply, reducing energy waste, and improving overall system performance.

- **Range Considerations:** EV driving range depends on several factors, including battery capacity (measured in kWh), energy efficiency, regenerative braking systems, driving behavior, terrain conditions, aerodynamics, vehicle weight, and environmental conditions such as temperature and wind resistance. Higher battery energy density and efficient power management contribute to extended ranges, while advances in thermal management and battery chemistry, such as lithium-ion and solid-state batteries, play a crucial role in increasing total driving distance per charge. Additionally, vehicle software optimization, including intelligent energy distribution and predictive energy consumption algorithms, improves electric propulsion system efficiency, increasing range under varying driving conditions.

3. Charging Infrastructure and Energy

- **Home AC Charging versus DC Fast Charging:** Home chargers (AC) operate at lower power levels (3-22 kilowatts), are ideal for overnight charging, and provide a cost-effective and convenient solution for daily driving needs. However, they require several hours to fully charge a depleted battery, depending on the vehicle's battery capacity and the charger's power output. In contrast, DC fast chargers (50-350 kilowatts) enable rapid charging within minutes, significantly reducing downtime and making long-distance travel more feasible for vehicle owners. These quick chargers convert AC power from the grid to DC voltage, which is supplied directly to the vehicle's battery, thereby bypassing the onboard charger and accelerating the charging process. Despite their advantages, DC fast chargers are more expensive to install and operate, often requiring high-capacity grid connections and advanced thermal management to prevent battery overheating. Additionally, frequent use of rapid charging can lead to quicker battery degradation due to increased heat generation and higher charging currents, which can affect battery lifespan.

- **Public Charging Network Expansion:** Growing demand for EVs has led to significant investment in charging station deployment by both public and private entities. Governments worldwide offer subsidies and incentives to accelerate the development of fast charging networks, while companies compete to establish widespread charging infrastructure accessibility. However, infrastructure gaps remain between regions, with urban areas experiencing faster expansion due to higher EV adoption rates, while rural and underdeveloped regions lag. Factors such as electrical grid capacity, land availability, regulatory permits, and business viability play crucial roles in determining the pace of expansion. Additionally, interoperability issues between different charging networks and payment systems create additional challenges in achieving a seamless and universally accessible charging experience for users.

- **Grid Impact and Load Management:** Widespread adoption of EVs requires advances in innovative grid management, Vehicle-to-Grid (V2G) integration, and energy storage solutions. Increased electricity demand from millions of simultaneously charging EVs poses significant challenges to existing grid infrastructure, requiring real-time load balancing and dynamic energy distribution systems. Smart grids must incorporate advanced demand response technologies, leveraging AI-driven analytics to optimize charging schedules and reduce peak loads. V2G technology enables EVs to function as distributed energy storage units, feeding electricity back to the grid during periods of peak demand, thereby improving grid resilience. Additionally, distributed energy storage solutions such as stationary batteries and renewable energy integration can support the grid by providing backup power and stabilizing voltage fluctuations.

4. Summary

EVs represent a transformative shift in the automotive landscape, offering a cleaner, more efficient alternative with zero tailpipe emissions, reduced reliance on fossil fuels, and continuous improvement in battery technologies. EVs are at the forefront of sustainable mobility. As global infrastructure develops and policy frameworks continue to support electrification, EVs are poised not only to reduce environmental impact but also to redefine the future of personal and commercial transportation.

Hybrid Electric Propulsion and Plug-in Hybrid

Hybrid propulsion is a vehicle propulsion method combining two types of engines, typically an internal combustion engine (ICE) with one or more electric motors. The goal of combining engines is to achieve improved fuel efficiency, drive cost savings, and reduce pollutant emissions. Hybrid vehicles utilize regenerative braking and electric power assistance to reduce the workload on the internal combustion engine, thereby improving overall system efficiency. Regenerative braking captures the kinetic energy that would otherwise dissipate as heat during deceleration and converts it into electrical energy stored in the battery for later use. Electric power assistance improves fuel efficiency by supplementing engine output during acceleration and reducing dependence on the internal combustion engine in low-load scenarios such as stop-and-go traffic. This combination of electric and mechanical energy sources not only reduces emissions but also extends the lifespan of ICE components by reducing mechanical stress and wear.

Hybrid vehicles are commonly classified into two main groups: self-charging hybrid vehicles (Hybrid Electric Vehicles, or HEVs) and cars that incorporate external charging capability (Plug-in Hybrid Electric Vehicles, or PHEVs).

Plug-in Hybrid Vehicles (PHEVs): These vehicles feature a significantly larger battery than conventional hybrids (HEVs), allowing for extended electric-only operation before the internal combustion engine (ICE) engages. These vehicles are designed to maximize electric driving while providing the flexibility of a gasoline-powered range extender, making them suitable for drivers seeking reduced fuel dependence without range anxiety. The battery can be charged via external power sources such as home charging stations or public charging infrastructure, reducing overall fuel consumption and emissions. Like HEV vehicles, PHEVs also benefit from regenerative braking that recaptures kinetic energy during deceleration, further improving efficiency. The ability to operate in both all-electric and hybrid modes provides versatility, making PHEVs a transitional technology that leverages existing infrastructure on the path toward full electrification.

1. Electric Hybrid System (EHS): High-Performance Integrated Propulsion System

The Electric Hybrid System (EHS) is an advanced hybrid propulsion system that seamlessly combines dual high-speed motors, dual controllers, and advanced oil cooling technology to enhance power density, efficiency, and overall performance.

This innovative system is designed explicitly for HEVs and PHEVs, enabling optimal energy management between the ICE and electric propulsion components.

Key Technological Components of EHS

- Dual High-Speed Motors - Using two high-speed electric motors operating at speeds up to 15,000 RPM and serving as both primary propulsion units and regenerative braking systems, optimizing energy use and reducing dependence on fossil fuels. High-speed motors offer advantages in an improved power-to-weight ratio, a compact design that enables higher torque output per unit mass, increased energy conversion efficiency by reducing losses associated with motor windings, and a faster response time. This makes them ideal for hybrid vehicle applications, enabling a smooth transition between electric and internal combustion power.
- Dual Controllers for Intelligent Energy Management - The dual controllers play a crucial role in coordinating power distribution between the ICE, battery, and electric motors. The dual controller function includes real-time torque distribution according to driving conditions, optimal regenerative braking control for efficient energy capture, and battery charge and discharge management to ensure maximum efficiency and longevity. These advanced controllers optimize energy flow to provide the best balance between electric and combustion power.
- Advanced Oil Cooling Technology - Unlike traditional air-cooled or water-cooled systems, oil cooling technology offers superior heat dissipation while maintaining thermal stability in high-performance applications. Oil cooling advantages include improved engine efficiency, preventing overheating, and enabling the engine to maintain peak power output for extended periods. Additionally, it reduces component wear, extending the lifespan of electrical and mechanical components by minimizing thermal impact. Furthermore, it enhances system reliability, enabling operation in extreme temperature conditions, which is ideal for high-performance hybrid vehicles.
- The integration of high-speed motors, controllers, and oil cooling technology provides significant advantages - in improved driving experience, the integration offers smooth acceleration due to rapid torque delivery from electric motors, seamless transition between EV and hybrid modes, refined and comfortable driving with reduced noise and vibration levels, in improved regenerative braking and energy recovery, and in compatibility with hybrid and plug-in hybrid vehicles.

The EHS system is widely implemented in modern hybrid vehicles due to its ability to maximize performance while maintaining high fuel efficiency. Vehicle manufacturers utilize this technology to comply with stringent emission regulations. Future advances in battery energy density and motor efficiency will likely drive EHS systems to achieve even higher efficiency levels while reducing system weight and cost.

2. Types of Hybrid Propulsion Configurations

Parallel Hybrid: The ICE and electric motor operate in parallel to improve fuel efficiency, reduce emissions, and enhance vehicle performance. In this configuration, both the ICE and electric motor can supply power to the wheels simultaneously, independently, or cooperatively, depending on driving conditions. The electric motor assists the ICE during acceleration and high-load situations, reducing fuel consumption and engine load. Regenerative braking further contributes to efficiency by capturing and storing kinetic energy that would otherwise be lost as heat. This design is commonly used in hybrid vehicles to maximize fuel savings without requiring external charging, making it an attractive option for consumers seeking improved efficiency without fully transitioning to electric mobility.

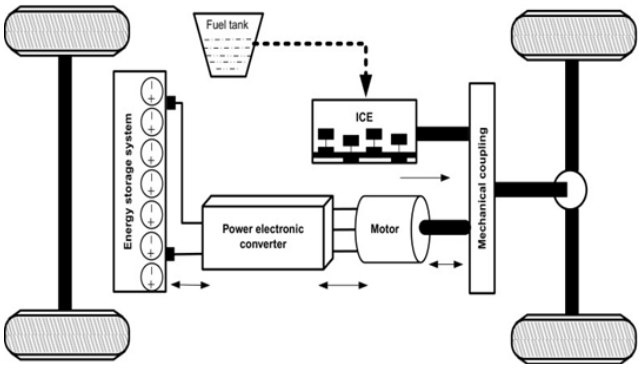


Figure 3: Parallel Hybrid configuration

Series Hybrid: In this configuration, the electric motor is solely responsible for driving the vehicle's wheels, while the internal combustion engine (ICE) functions only as a generator to charge the battery when needed. Unlike parallel hybrids, where the ICE can directly drive the drivetrain, the series hybrid configuration relies entirely on electric propulsion, improving overall efficiency and reducing emissions. This design enables optimal fuel consumption as the ICE can operate in its most efficient power range without a direct mechanical connection to the wheels. Additionally, this hybrid configuration can be integrated with plug-in charging capabilities to reduce dependence on fossil fuels further and extend the electric driving range before ICE activation.

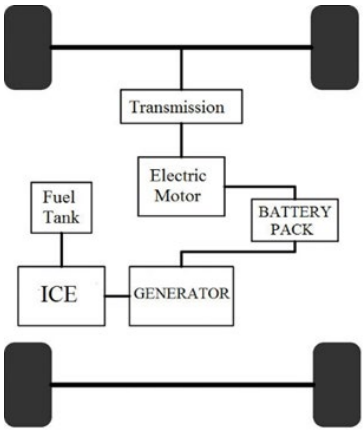


Figure 4: Series Hybrid Configuration

3. Advantages and Disadvantages of Hybrid Electric Propulsion

✔ Advantages

- **Improved Fuel Efficiency:** The electric motor assists the ICE during acceleration and low-speed driving, reducing fuel consumption. Regenerative braking recovers kinetic energy and charges the battery, increasing overall efficiency.
- **Reduced Emissions:** HEVs produce significantly fewer greenhouse gas (GHG) emissions than conventional ICE vehicles, especially in urban traffic, even when equipped with stop-start systems. Some hybrid cars meet Ultra Low Emission Vehicle (ULEV) or Super Ultra Low Emission Vehicle (SULEV) carbon emission standards.
- **Enhanced Performance:** Electric motors provide instant torque, improving acceleration responsiveness, enabling engine downsizing without sacrificing performance.
- **Extended Driving Range:** Combines the long range of ICE vehicles with the efficiency of electric motors, reducing range anxiety common with pure EVs.

✘ Disadvantages of Hybrid Electric Propulsion

- **Higher Initial Cost:** The dual propulsion system (ICE + electric motor + battery + control systems) increases complexity and manufacturing costs. May lead to higher retail prices compared to conventional vehicles.
- **Complex Maintenance Requirements:** A more complex propulsion system requires special diagnostic and repair skills. Components such as battery packs and inverters are expensive to replace.

Hydrogen and Fuel Cell Propulsion Systems (FCEV)

Fuel Cell Electric Vehicles (FCEVs) are a type of EV that uses a fuel cell to convert hydrogen into electricity. Unlike Battery Electric Vehicles (BEVs) that store electricity in a battery, FCEVs generate electricity on demand from a hydrogen fuel tank and fuel cell.

These vehicles are an example of zero-emission vehicles. This technology will help achieve the aspiration goal of electric mobility with zero pollutant emissions. These systems are particularly essential in situations where customers require longer driving ranges, where EVs would require significant and bulky battery volumes and charging durations that consume considerable time.

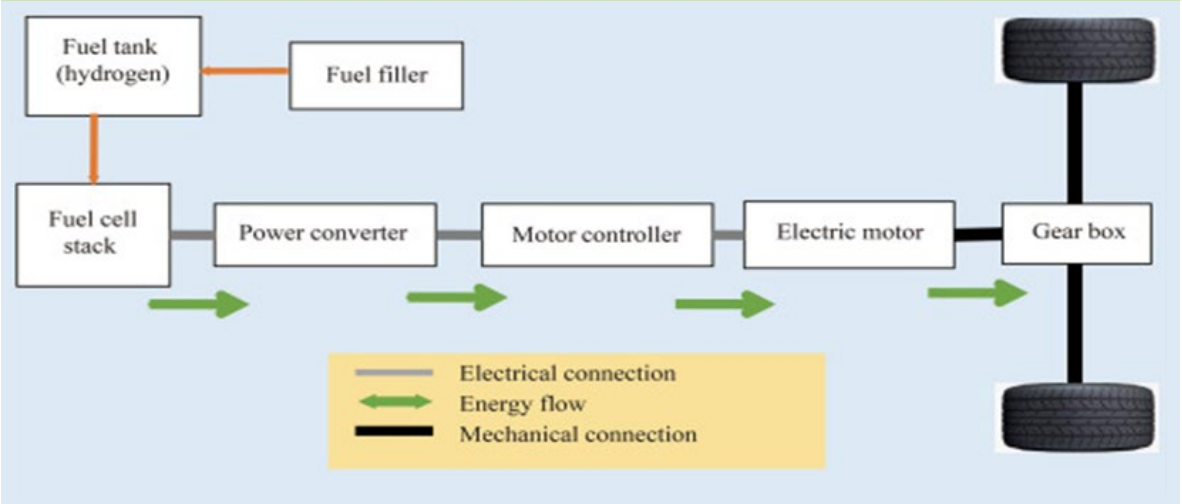
1. Operating Principles

- **Hydrogen Fuel Cell Technology:** FCEVs store compressed hydrogen gas in an onboard Hydrogen Tank. The hydrogen is fed to a Fuel Cell Stack, which converts the chemical energy of hydrogen into electricity through a process called reverse electrolysis. The electricity produced by the fuel cell powers an Electric Motor that drives the vehicle. The only byproduct of this process is water vapor, emitted through the exhaust pipe.

- **Refueling Process and Infrastructure:** Hydrogen refueling stations are essential for the adoption of hydrogen and fuel cell propulsion systems. They require significant investment in production, distribution, and storage technologies. The hydrogen refueling infrastructure includes multiple stages, including hydrogen production, transportation, and storage at refueling stations. Hydrogen can be produced through electrolysis using renewable energy sources (green hydrogen) or derived from natural gas (gray and blue hydrogen). Each method has different environmental implications and costs. Hydrogen transportation poses logistical challenges, as it requires high-pressure compression, cryogenic liquefaction, or chemical carriers to ensure safe and efficient distribution. Once delivered to refueling stations, hydrogen is stored in high-pressure containers and dispensed to vehicles at pressures typically ranging from 350 to 700 bar. The expansion of hydrogen refueling infrastructure depends largely on government incentives, private sector investments, and advancements in hydrogen storage and transportation technology. Additionally, standardizing refueling protocols and fostering international cooperation are essential to facilitate a global hydrogen economy for transportation applications.

- Key Components in Hydrogen and Fuel Cell Propulsion Systems (FCEV model):

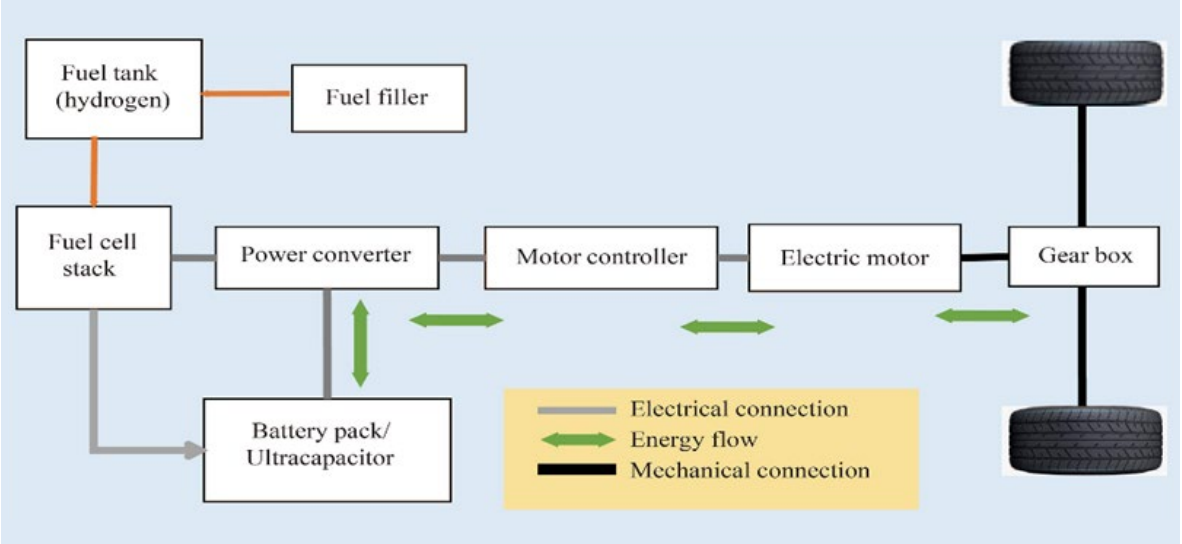
Figure 5:



fuel cell electric vehicle (FCEV)
(Green Energy and Intelligent Transportation journal)

- Additional Component in Fuel Cell Hybrid Electric Vehicle (FCHEV) Systems: The main difference between FCEV and FCHEV configurations is the addition of a Battery Pack. The battery serves a critical auxiliary role in the hydrogen fuel cell propulsion architecture. Unlike EVs, where the battery is the sole energy source, this propulsion form combines a hydrogen fuel cell stack for generating electricity through electrochemical reactions with a high-voltage lithium-ion battery. The battery in FCHEV functions primarily as a power buffer, providing supplementary energy under high-demand conditions, such as rapid acceleration or steep climbs, and absorbing regenerative braking energy during deceleration. This design enables downsizing of the fuel cell stack, thereby optimizing system cost, weight, and efficiency. Additionally, the battery's rapid response to changes in consumption, recovery capability, and fast energy delivery ensures a smooth power supply and improved overall propulsion system efficiency. Proper thermal management and battery charging are crucial for ensuring system longevity, safety, and optimal performance under varying operating conditions.

Figure 6:



fuel cell hybrid electric vehicle (FCHEV)
(Green Energy and Intelligent Transportation journal)

2. Advantages and Disadvantages

✔ Advantages:

- **Fast refueling times (3-5 minutes):** Significantly reducing vehicle downtime compared to battery charging, making hydrogen fuel cell vehicles more suitable for intercity travel and commercial applications where rapid refueling is critical.
- **Longer driving range than conventional EVs:** Making fuel cell vehicles particularly advantageous for applications requiring long-distance travel, such as freight transport, intercity buses, and emergency vehicles. The ability to travel such distances without frequent refueling improves operational efficiency. Additionally, it reduces downtime, making hydrogen and fuel cell propulsion a competitive alternative to battery EVs in sectors where continuous operation is critical.

✘ Disadvantages:

- **Limited hydrogen refueling infrastructure:** Constitutes a significant barrier to widespread adoption of FCEVs. The high costs associated with establishing hydrogen production facilities, safely transporting hydrogen, and installing refueling stations hinder the slow expansion of this technology. Unlike EV charging networks, which can leverage existing electrical grids, hydrogen infrastructure requires specialized high-pressure storage and dispensing systems, thereby increasing complexity. Additionally, regional gaps in hydrogen availability and the need for standardization across different markets further delay accessibility.
- **High production and storage costs:** Stem from reliance on rare and expensive materials such as platinum used in fuel cells, the complexity of hydrogen liquefaction, and high-pressure storage technologies. Additionally, limited

economies of scale in hydrogen production contribute to its high price per unit of energy compared to conventional fossil fuels and electric battery alternatives.

3. Safety Regulations for Hydrogen and Fuel Cell Propulsion Systems

Safety standards for hydrogen and fuel cell propulsion systems encompass strict guidelines for battery management, thermal efficiency enhancement, vehicle installation, hydrogen storage, and safety protocols in the event of accidents. Among the standards published by EU countries:

UNECE R134 - Safety-related performance of Hydrogen Fueled Cell Vehicles
Addresses the approval of compressed hydrogen storage systems, specific components in these systems, and the type approval of vehicles.

UNECE R100 - Specific requirements for the electric power train
Describes electrical safety measures for battery packs, including insulation resistance, thermal management, and fire protection.

Regulation (EC) No 79/2009 - type-approval of hydrogen-powered motor vehicles
Outlines safety requirements for vehicles powered by compressed natural gas, focusing on components such as fuel containers and fuel lines to ensure they withstand high pressures associated with compressed gases.

Regulation (EU) No 406/2010 - type-approval of hydrogen-powered motor vehicles
Specifies provisions for the approval of motor vehicles and their components regarding hydrogen propulsion.

International safety standards have also been published:

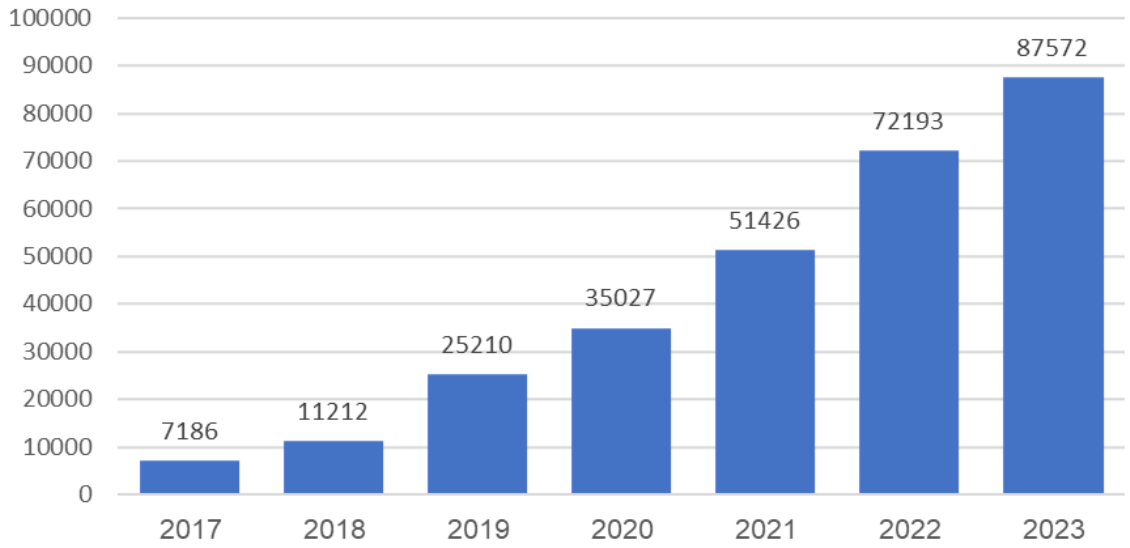
SAE-J2344 - Guidelines for EV Safety (including Fuel Cell Vehicles)
Includes safety procedures for handling vehicles containing high voltage.

ISO 19880 - Gaseous hydrogen - Fueling stations
Safe handling, storage, and refueling procedures reduce risks associated with high-pressure hydrogen containers.

4. Global Deployment of Hydrogen Vehicles

The number of FCEVs has been increasing over the years, although their proportion relative to vehicles powered by other propulsion methods remains very small. According to research data published by the Advanced Fuel Cells Technology Collaboration, here is the growth chart of FCEV vehicles worldwide by year:

Figure 7: FCEV vehicles worldwide by year



Regarding distribution by vehicle types according to the research as of 2023:

Passenger Cars

Global inventory: approximately 65,760 vehicles, constituting about 75% of the total fuel cell vehicle fleet. Of these, 33,591 vehicles are in South Korea, and 17,940 vehicles are in the USA.

Buses

Global inventory: approximately 8,043 buses, constituting about 9% of the total fuel cell vehicle fleet. Of these, 6,632 buses are in China and 651 buses are in South Korea.

Trucks (commercial, light, and heavy)

Global inventory: estimated at approximately 13,769 trucks, constituting about 15.7% of the total FCEV fleet. Of these, 13,181 trucks in China represent approximately 95.7% of the fuel cell truck fleet, reflecting its focus on decarbonizing heavy transportation.

This distribution highlights adoption rates and strategic focuses among countries, with Asia leading in both passenger and commercial vehicle deployment.

5. Global Deployment of Hydrogen Refueling Stations

According to data from the Interact Analysis research group, operating in Britain, the US, and Asia as of the end of 2024, the global deployment of Hydrogen Refueling Stations (HRS) has expanded significantly, with approximately 1,369 active stations in 44 countries. This growth reflects a concentrated effort by various governments to support the adoption of FCEV and develop the necessary infrastructure for a hydrogen-based transportation system.

Global Distribution of Hydrogen Refueling Stations

Refueling stations are primarily concentrated in a limited number of countries, with China, South Korea, Japan, France, and Germany together accounting for nearly 80% of the global total.

Asia-Pacific Region:

China: Leading globally with approximately 450 stations, continuing to invest heavily in hydrogen infrastructure to support its growing fleet of fuel cell vehicles.

South Korea: With approximately 200 stations, South Korea has rapidly expanded its network, including the deployment of liquid hydrogen stations.

Japan: Operating approximately 160 stations, maintaining a strong hydrogen infrastructure supporting both passenger and commercial vehicles.

Europe:

Germany: Leading Europe with approximately 115 stations, continuing to be a key player in developing the continent's hydrogen infrastructure.

France: With approximately 130 stations, France has actively expanded its network, recently surpassing Germany in the number of operating stations.

As of the end of 2024, Europe had a total of 412 hydrogen refueling stations across 27 countries.

North America:

United States: With 86 stations, 73 of which are located in California, the U.S. has experienced expansion and contraction in its hydrogen infrastructure, reflecting the dynamic nature of the market.

In summary, the global landscape of hydrogen refueling stations is evolving, with significant investments and policy support driving the expansion of infrastructure necessary for widespread adoption of hydrogen fuel cell vehicles.

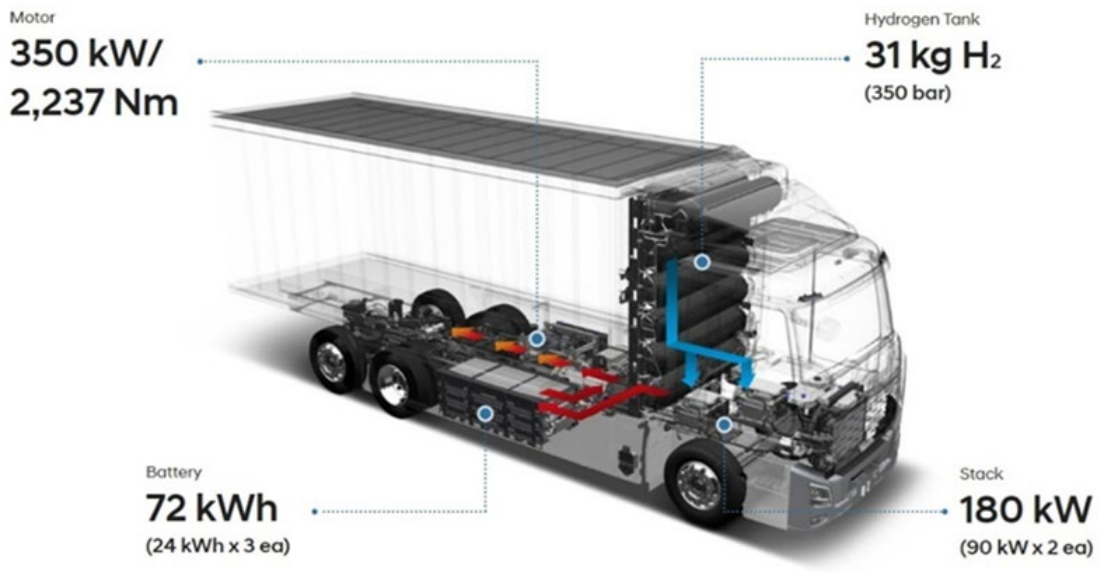
6. Hydrogen Truck Project in Israel

In 2022, three Hyundai hydrogen fuel cell trucks were imported to Israel by Colmobile, the Hyundai truck importer in Israel, with assistance from Bazan and Sonol companies, regulatory support from the Ministry of Transport, and financial support from the Ministry of Energy, for an operational pilot. The project's goal was to examine various operational aspects in Israel, including hydrogen supply, refueling stations, workshop maintenance methods, safety, suitability for transport zones, and other related factors.

The aspiration is that this pilot will lead to the penetration of hydrogen technology into the Israeli automotive market in the coming years, accelerate the

establishment of refueling stations, and subsequently expand the technology to private hydrogen-powered vehicles as well.

Figure 8: 2023 Hyundai XCIENT H2 FCEV/Truck



7. Challenges and Future Outlook

Despite progress in all areas related to hydrogen fuel cell vehicles, widespread adoption of these vehicles still faces challenges, including high production costs, limited refueling infrastructure, and competition from battery EVs. However, continued investments in research and development, along with supportive government policies and international collaborations, are expected to address these obstacles. Forecasts indicate an annual growth rate of approximately 95.4% between 2020 and 2030, with the global FCEV fleet potentially reaching approximately 13 million units by 2030.

Collaboration Between Policymakers, Engineers, and Industry Stakeholders

The transition to sustainable propulsion systems requires coordinated effort among multiple stakeholders, including policymakers, engineers, and industry leaders. Each group plays a crucial role in shaping the future of vehicle propulsion technologies.

- **Policymakers:** Governments and regulatory bodies must implement clear, science-based policies supporting the adoption of low-emission propulsion technologies. This includes setting ambitious emission reduction targets (such as the requirement to meet Euro 7 standards), enforcing stringent fuel economy standards, and incentivizing the development and adoption of alternative propulsion systems. Effective policy should strike a balance between regulation and market-driven innovation, ensuring that the transition to cleaner

transportation remains economically viable and sustainable. Policymakers have a crucial role in establishing research and development (R&D) funding programs, supporting pilot initiatives, and fostering collaboration between public and private entities. Additionally, infrastructure investments, such as expanding EV charging networks and hydrogen refueling stations, are critical for accelerating widespread adoption. Policy must also consider pollutant emissions throughout the vehicle's lifecycle and emissions created within the supply chain. Ultimately, collaboration among policymakers is necessary to establish global standards, facilitating a seamless transition to sustainable mobility solutions on an international scale.

- **Engineers and Researchers:** The automotive industry relies on engineers to develop next-generation propulsion systems that are energy-efficient, minimize environmental impacts, and improve cost-effectiveness. These professionals play a crucial role in designing advanced propulsion technologies, including high-efficiency electric propulsion systems, fuel cell systems, and internal combustion engines optimized for synthetic fuels. In particular, engineers focus on improving battery chemistry to enhance energy density, charging cycles, and safety, making EVs more practical and reliable. Hydrogen storage solutions are also a key area of innovation, addressing challenges related to fuel cell durability, hydrogen production efficiency, and the development of distribution infrastructure. Additionally, hybrid propulsion system optimization involves refining energy management algorithms, reducing drivetrain losses, and integrating regenerative braking systems to maximize efficiency. Engineers and researchers must work closely with policymakers and industry leaders to ensure that new technologies meet regulatory requirements and market demands, thereby advancing the automotive sector toward a sustainable future.

An example of collaboration between policymakers, engineers, and researchers can be seen in the Working Party on Pollution and Energy appointed by the World Forum for Harmonization of Vehicle Regulations (WP. 29), based in Geneva, whose role is to advance standards and requirements in the field of vehicle pollutant emissions.

- **Automotive and Energy Industries:** Vehicle manufacturers and energy suppliers must collaborate to create robust infrastructure for new propulsion technologies. This collaboration extends beyond vehicle production and includes establishing integrated energy solutions that support the long-term adoption of alternative propulsion systems. Investment in fast-charging networks is essential for EV adoption, requiring advances in grid management, smart charging stations, and ultra-fast charging capabilities to minimize downtime. Similarly, hydrogen refueling stations must be strategically deployed to support FCEVs, which require large-scale hydrogen production, efficient storage solutions, and adequate transportation. The synthetic fuel sector also plays a central role in decarbonizing existing internal combustion engines, necessitating innovation

in production methods, such as Power-to-Liquid (PtL) and Carbon Capture and Utilization (CCU). Cross-industry collaboration among vehicle manufacturers, energy suppliers, and infrastructure developers is essential to ensure new propulsion technologies can be efficiently scaled while maintaining grid stability, affordability, and accessibility to consumers worldwide.

- **Academia and Research Institutions:** Universities and independent research laboratories play a key role in advancing propulsion technology through fundamental research, prototype development, and testing of new materials and systems. These institutions conduct pioneering research on alternative fuel sources, next-generation battery technologies, fast electric charging, and hydrogen storage solutions, helping drive innovation in the transportation sector. Academic research also contributes to improving energy efficiency, reducing emissions, and optimizing propulsion system performance through the use of experimental models, simulations, and laboratory testing. Collaborative efforts between universities, industry leaders, and government agencies facilitate knowledge exchange, leading to advances that bridge the gap between theoretical concepts and real-world applications. Furthermore, academia plays a crucial role in training the next generation of engineers and scientists, equipping them with the skills necessary to develop advanced propulsion technologies and sustainable mobility solutions.

An example of academic involvement, the automotive industry, and government funding in advancing new technologies can be seen in research conducted by Purdue University, Indiana, USA, in collaboration with Cummins, Oak Ridge National Laboratory, and Walmart, to develop a high-power wireless charging system for heavy-duty electric trucks. The project aims to create a 750-kilowatt wireless charging solution, enabling trucks to charge efficiently without the need for physical connectors. This technology is being tested for real-world fleet operations, with potential for widespread commercial adoption.

https://www.purdue.edu/research/features/stories/purdue-researchers-collaborate-with-cummins-to-develop-wireless-charging-technology-for-heavy-duty-vehicles/

In summary, a collaborative approach by all parties, including government incentives, is essential for accelerating the development and adoption of new technologies and clean propulsion systems.

Adoption Rates of Different Propulsion Systems and Their Integration in the Global Market

Private Vehicles: The transition to electric and hybrid propulsion systems continues to dominate the passenger vehicle market, driven by advances in battery technology, growing environmental awareness, and supportive government policy. Vehicle manufacturers are expanding their EV and hybrid offerings to meet stringent pollutant emission regulations and changing consumer preferences. Development of higher-capacity batteries, improvements in charging infrastructure, and the emergence of affordable EV models are making electric propulsion more accessible to the general public. Additionally, vehicle manufacturers are investing in vehicle efficiency optimization, software integration, and aerodynamics to improve the range and performance of EVs further, ensuring that electrified mobility becomes the mainstream choice for private transportation.

Heavy-Duty Trucks: The commercial transportation sector is undergoing a significant transformation, integrating electric and hydrogen-based propulsion systems to improve efficiency and reduce emissions. Fleet operators are increasingly adopting electric trucks using batteries for short-range and urban delivery applications, benefiting from lower operating costs and zero emissions. Hydrogen fuel cell trucks are emerging as a sustainable alternative for long-distance transport and heavy cargo, offering fast refueling and extended range compared to equivalent electric trucks. Simultaneously, improvements in advanced biofuel and synthetic diesel technologies promise that traditional combustion engines will continue to play a role in the transition to sustainable freight transport. Widespread adoption of these technologies depends on expanding charging and refueling infrastructure, regulatory support, and continued advances in battery and fuel cell efficiency.

Public Transportation (Buses): Electrification of public transportation fleets is gaining momentum worldwide, driven by government initiatives, emission reduction targets, and advances in battery and charging technology. Cities around the world are investing in battery-electric buses and hydrogen fuel cell buses to replace traditional diesel-powered fleets, thereby reducing urban air pollution and operating costs. The transition to electric buses is supported by improvements in fast-charging infrastructure, energy-efficient battery systems, and policy incentives that promote sustainable public transportation. However, challenges such as high initial investment costs, grid capacity limitations, and the need for extensive charging infrastructure continue to be barriers to widespread adoption. Many countries are implementing pilot programs and phased rollouts to assess feasibility and optimize long-term integration strategies for zero-emission public transportation

solutions. An example of such a program can be seen in Chicago, USA, where the local transportation authority (CTA) unveiled a comprehensive plan in 2022 to transition its entire bus fleet, numbering over 1,800 buses, to electric buses by 2040, while investing in infrastructure.

https://www.transitchicago.com/cta-unveils-first-ever-roadmap-for-conversion-to-an-all-electric-bus-system-by-2040-/

In Israel, according to Ministry of Transport data, approximately 2,000 electric buses are already operating, as of early 2025. The Public Transportation Authority's target for 2035 is a complete transition to operating electric urban buses.

- **Agricultural Vehicles and Heavy Mechanical Equipment:** The transition to hybrid propulsion systems and alternative fuel in agricultural vehicles and heavy mechanical equipment is driven by the need to reduce emissions, improve fuel efficiency, and meet evolving environmental regulations. The electrification and hybridization of heavy machinery are being increasingly tested to reduce operating costs and minimize dependence on diesel. Advances in battery technology, hydrogen fuel cells, and biofuels are facilitating this transition, with many manufacturers investing in research and development to improve power output and durability in demanding work environments. The integration of intelligent energy management systems and automation further enhances efficiency, ensuring these industries can adapt to sustainable propulsion technologies while maintaining high productivity levels.

Israel - Vehicle Registration Trends

The share of gasoline vehicles in the Israeli automotive market is in decline, with a significant drop from 65% at the beginning of 2020 to 44.9% in the fourth quarter of 2024. This trend is also observed in diesel vehicles, with a decline from 14% in the last quarter of 2020 to approximately 7% of all vehicles registered in the fourth quarter of 2024.

In contrast, EVs have exhibited the most significant growth among all propulsion types, increasing from approximately 1% in the first quarter of 2021 to 24.8% in the fourth quarter of 2024. This rise highlights a notable shift toward electric mobility.

HEVs, after experiencing some fluctuations over the years, show a renewed increase in the fourth quarter of 2024, rising to 21.8% from 20.6% in the third quarter of 2024.

PHEVs experienced a decline in market share from approximately 6.5% in the last quarter of 2023 to approximately 2.6% in the previous quarter of 2024. This decline may have resulted from changes in taxation imposed on this vehicle type in Israel. However, in the first three months of 2025, a change in trend is observed, which is explained by the recent introduction of PHEV vehicles with improved electric driving ranges.

In the bus sector, the market share of diesel engines remains the highest at 91.8%, followed by electric buses with a market share of 5.4%, and CNG-powered buses with a market share of 2.8%.

Commercial vehicles with diesel propulsion constitute the largest share, at 96%, with the remaining 4% being electrically powered commercial vehicles.

As mentioned, for pilot purposes, three hydrogen fuel cell trucks were registered in Israel.

Figure 9: EV Registration in Israel, 2015-2024

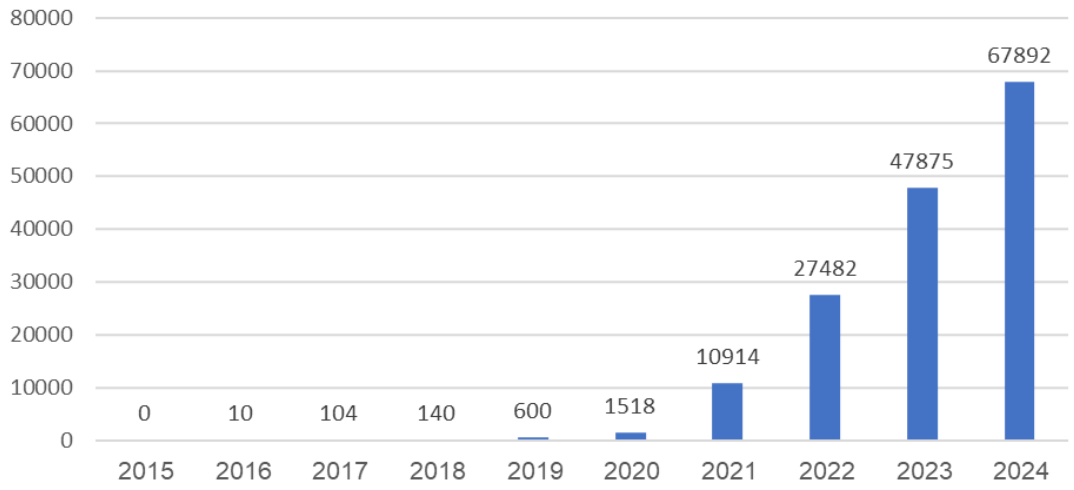
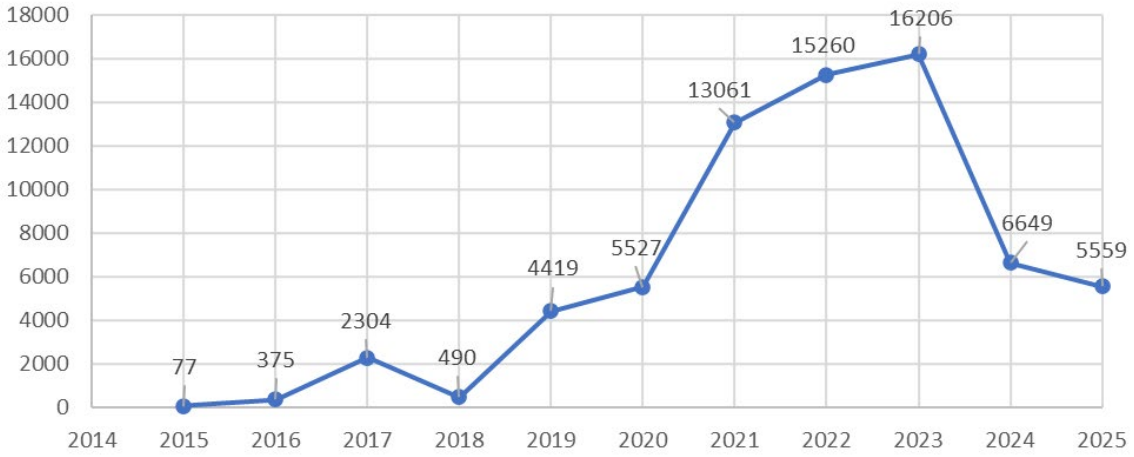


Figure 10: Number of PHEVs Registered in Israel, 2009-2025



The 2025 data refers to the total number of hybrid vehicles registered in the first quarter only.

Future Technologies and Innovations

- **Solid-State Batteries (SSB):** Solid-state battery technology represents a significant advancement in energy storage, offering significantly higher energy density, faster charging times, and improved safety compared to conventional lithium-ion batteries. Unlike traditional batteries that use liquid electrolytes, solid-state batteries utilize solid electrolytes, which enhances stability and increases thermal efficiency. The expected increase in energy density (up to 2.5 times) will enable a greater range in EVs without increasing battery size, while improved charging and discharging efficiency minimizes energy losses. From a lifecycle perspective, SSB batteries should be simpler to use and less polluting. Furthermore, the absence of flammable liquid components will improve overall safety, making SSB an attractive option for next-generation EVs. However, challenges such as high production costs, material availability, and scalability must still be addressed before widespread commercial adoption can occur.

- **Solar-Powered Vehicles:** Integration of photovoltaic (PV) panels in vehicles represents a promising advancement in sustainable transportation. Solar-powered vehicles harness energy from sunlight through high-efficiency solar cells, converting solar radiation into electrical power that can be used to support auxiliary functions or, in some cases, contribute directly to propulsion. While current technology limits the extent to which solar energy can replace traditional charging methods, advances in solar panel efficiency, lightweight materials, and energy storage solutions are expanding the feasibility of solar-assisted EVs. Research on flexible and high-output solar cells aims to maximize surface area utilization on the vehicle's exterior, thereby increasing energy capture and improving overall vehicle efficiency. Future developments in vehicle-integrated photovoltaics (VIPV) may enable partial or full solar-powered driving under specific conditions, reducing reliance on external charging infrastructure and improving vehicle autonomy.

- **Smart Energy Management (V2G, Smart Charging):** Smart energy management in EV ecosystems may leverage advanced grid interactions to improve energy efficiency, reduce operating costs, and enhance overall energy sustainability. Vehicle-to-Grid (V2G) technology will enable bidirectional energy flow between EVs and the grid, allowing vehicles to return electricity to the grid during peak demand periods and charge during low-demand periods, thereby stabilizing the electrical infrastructure. Smart charging, which incorporates AI-driven algorithms and real-time grid monitoring, optimizes charging schedules to prevent grid overload and maximize the utilization of renewable energy sources. These innovations will contribute to more flexible and efficient energy distribution, benefiting both vehicle owners and service providers by integrating energy storage solutions and dynamic load management systems.

Summary of Vehicle Propulsion Systems and Looking Ahead

The field of vehicle propulsion is at a critical turning point, balancing continued reliance on internal combustion engine (ICE) technology with the rapid advancement of electrification and fuel cell solutions. While ICE-powered vehicles are expected to remain in use for many years for specific applications such as long-distance transport and heavy machinery, the global transition toward low-carbon and zero-emission mobility is necessary and inevitable. The successful implementation of sustainable propulsion technologies requires an integrated approach that includes advances in propulsion efficiency, infrastructure development, and broad regulatory support.

Collaboration among policymakers, engineers, and industry stakeholders is crucial to accelerate the transition and ensure that regulatory frameworks, technological innovations, and energy infrastructure evolve in tandem. Governments must continually invest in advanced propulsion technologies. Policymakers must continue to enact and implement regulations that enable the adoption of clean energy. Additionally, vehicle manufacturers and energy suppliers must invest in scalable and cost-effective solutions. Additionally, ongoing research into energy storage methods, advances in hydrogen fuel cells, and the development of synthetic fuels will play a vital role in shaping the future of sustainable transportation. By fostering cross-sector collaboration, aligning international policy, and prioritizing investments in emerging technologies, the automotive industry can achieve a balance between performance, sustainability, and economic viability, paving the way for a clean and efficient global mobility ecosystem.

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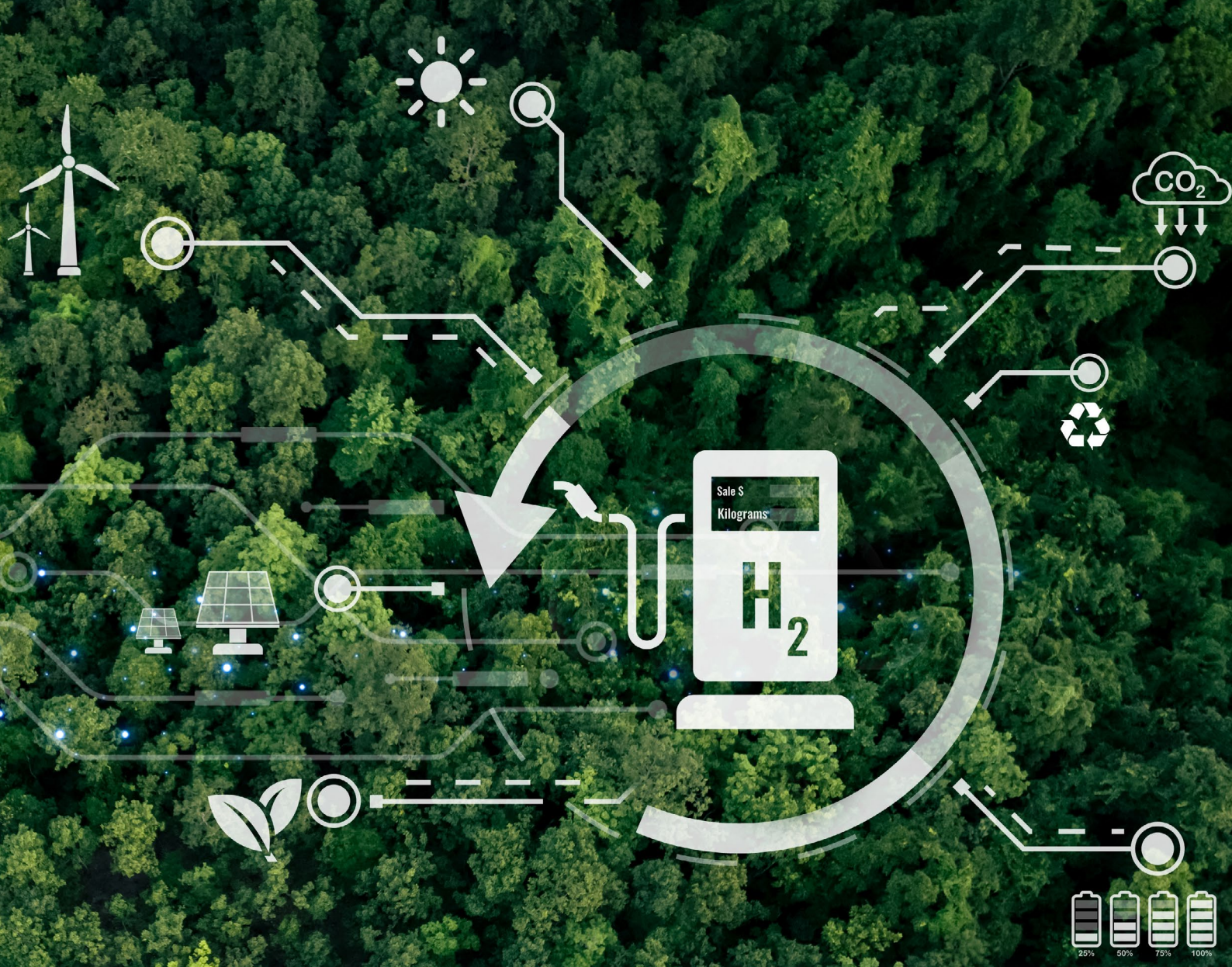

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