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Pre-study Project Report

VINNOVA – FFI – 2023-02617

Circular Economy:
Retrofitting Fossil Fuel Passenger Vehicles to El-Hybrid

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Summary

This pre-study addresses the critical issue of global warming attributed to the long-term increase in Earth's average surface temperature, primarily fueled by the release of greenhouse gases, particularly from fossil fuel-powered vehicles. Urban traffic contributes significantly to global carbon dioxide (CO2) emissions, emphasizing the urgency for carbon-neutral mobility solutions.

Fossil fuel vehicles, reliant on non-renewable resources, adversely impact the environment through resource depletion, air pollution, and geopolitical challenges. This pre-study research deals with the environmental challenges posed by these existing and used vehicles, including noise pollution, oil leaks, and non-exhaust emissions.

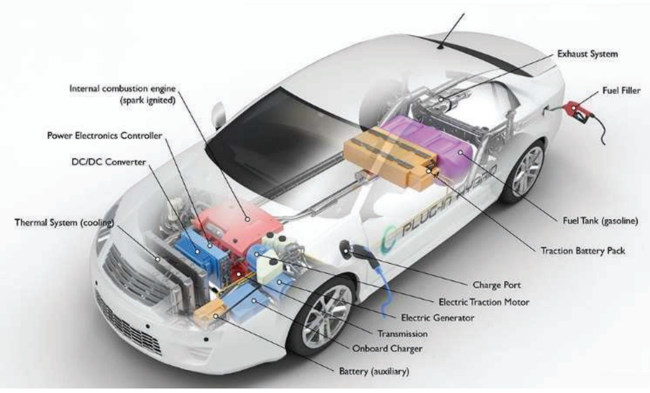
The focus then shifts to Hybrid Electric Vehicles (HEVs) as a promising alternative. HEVs, incorporating both internal combustion engines and electric propulsion systems, offer improved fuel efficiency and reduced emissions. The research categorizes HEVs into micro, mild, full, and plug-in hybrids, each with varying levels of electrification and fuel savings.

In addition, advantages of HEVs include enhanced fuel efficiency, regenerative braking systems, and lower emissions. The study details the different configurations of hybrid vehicles, such as parallel, series, and power split hybrids, highlighting their adaptability, improved efficiency, and driving range compared to traditional vehicles.

Despite their advantages, HEVs have certain disadvantages, including higher initial costs, increased weight, and reliance on fossil fuels too. The research acknowledges the challenges in the rapid transition to electric vehicles (EVs).

An interesting opportunity is explored regarding the technical feasibility of converting fossil fuel cars into electric hybrid vehicles. The research acknowledges the challenges and varying feasibility of such conversions but emphasizes the potential economic and environmental benefits, especially in specific applications like fleet vehicles.

The research concludes by presenting the growing market for hybrid electric vehicle conversion kits, with a forecasted substantial growth rate. Key players in this market, including XL Fleet, EDI, REV Electric Vehicle Systems, and others, offer solutions for commercial fleets and retrofitting classic vehicles. Overall, the research supports for the adoption of Hybrid Electric Vehicles as a transitional solution, addressing environmental concerns while acknowledging the challenges in the broader shift towards electric mobility. The exploration of conversion kits offers an additional avenue for sustainable transportation, contributing to an eco-friendlier automotive future.



1. Introductory Background

Transportation serves as a cornerstone of modern economies, enabling the vital movement of people and goods essential for economic progress and societal development. This mobility fosters access to employment, education, healthcare, and markets, thereby catalyzing socioeconomic activities worldwide. However, alongside its benefits, transportation imposes substantial environmental burdens. Among these challenges, the emission of greenhouse gases stands out as a pressing concern. Vehicles fueled by fossil fuels release carbon dioxide (CO_2) and other greenhouse gases, exacerbating global warming and its consequential effects, including heightened frequency and severity of extreme weather phenomena (Fig. 1) [1].

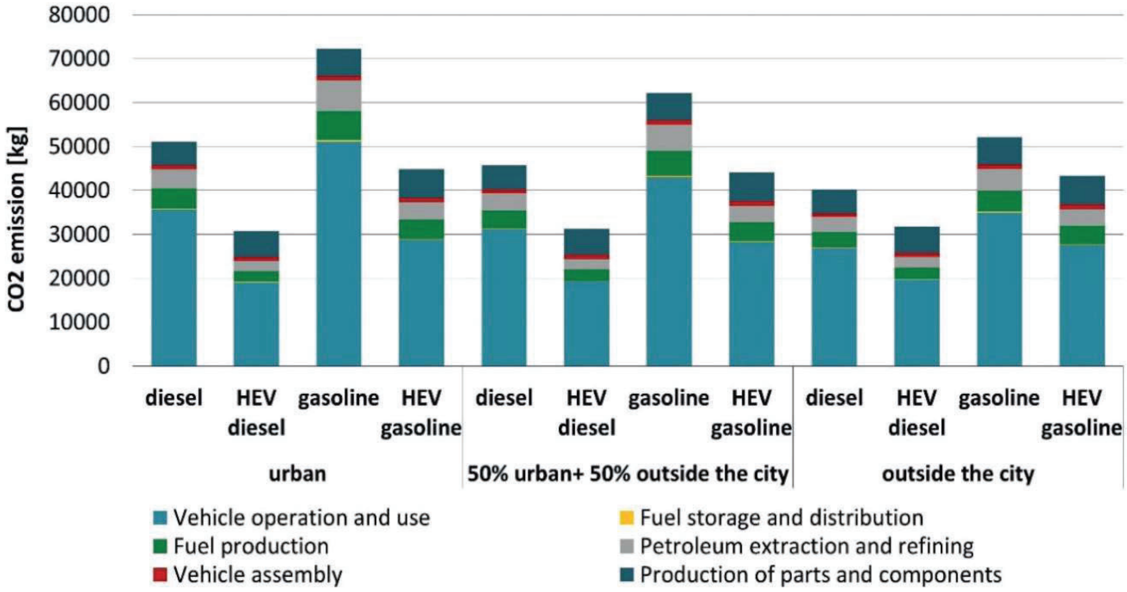


Fig. 1. CO2 emissions over the vehicle life cycle [8]

Urban areas face a disproportionate share of environmental consequences stemming from transportation activities. The density of vehicles within cities amplifies air pollution levels, characterized by elevated concentrations of nitrogen oxides (NOx), particulate matter (PM), and volatile organic compounds (VOCs) (Fig. 2) [2].

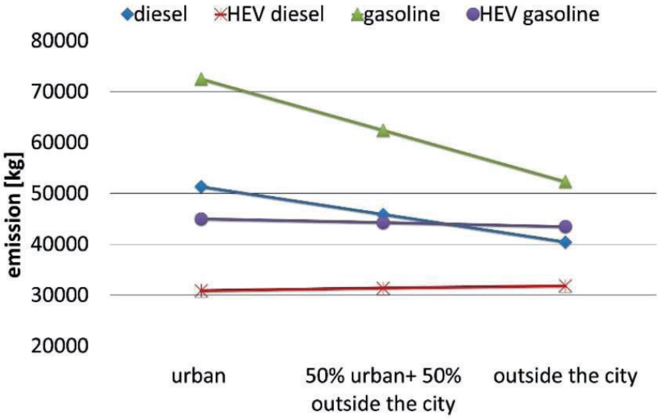


Fig. 2. Air pollutant emissions over the vehicle life cycle [8]

These pollutants not only degrade air quality but also pose substantial health risks to urban dwellers, contributing to respiratory illnesses, cardiovascular complications, and other health issues. Moreover, the expansion of transportation infrastructure, such as roads and highways, often triggers habitat fragmentation and loss, posing threats to biodiversity and ecosystems. Additionally, the construction and upkeep of transportation networks entail substantial resource consumption and energy expenditure [3-4].

In response to these pressing challenges, cities worldwide are increasingly embracing sustainable transportation policies and initiatives [5]. These efforts encompass various strategies, such as promoting public transit systems (like buses, trams, and trains) to discourage individual car usage, implementing carpooling and ride-sharing programs, fostering pedestrian-friendly environments, and expanding cycling infrastructure, including dedicated bike lanes and bike-sharing schemes. The aim of these endeavors is to alleviate traffic congestion, enhance air quality, and elevate overall urban livability.

Furthermore, automotive manufacturers are actively pursuing technological innovations to manufacture vehicles with reduced emissions and enhanced fuel efficiency. This includes the development and adoption of hybrid and electric vehicles, which rely on cleaner energy sources and emit fewer pollutants during operation compared to traditional internal combustion engine vehicles [6]. Moreover, advancements in engine design, the utilization of lightweight materials, improvements in aerodynamics, and the implementation of emission control technologies contribute to minimizing the environmental impact of vehicles throughout their life cycle.

This study focuses on the pressing environmental concern of global warming, mainly aggravated by widespread use of fossil fuel-based vehicles. Urban traffic, powered by fossil fuel combustion, notably adds to greenhouse gas emissions, worsening climate change. Acknowledging the multifaceted challenges posed by conventional fossil fuel vehicles – including resource depletion, air and noise pollution, and geopolitical concerns – the project aims to investigate and advocate for the uptake of Hybrid Electric Vehicles (HEVs) as a sustainable transition solution.

1.1 State-of-the-art

Global warming, marked by a sustained rise in the Earth's average surface temperature, stems largely from the release of greenhouse gases like carbon dioxide (CO_2) into the atmosphere. Human activities, notably the combustion of fossil fuels such as coal, oil, and natural gas, are primary contributors to these emissions [7, 8]. Research by the Intergovernmental Panel on Climate Change indicates that urban traffic, fuelled by vehicles reliant on fossil fuels, accounts for 35% of global CO_2 emissions, highlighting the critical need for carbon-neutral transportation (Fig. 3) [9].

Fossil fuel vehicles, characterized by their reliance on non-renewable resources such as oil, significantly impact the environment through various interconnected factors. First and foremost is the issue of resource consumption, as these vehicles heavily rely on finite fossil fuel reserves for energy. The extraction and processing of these resources not only contribute to environmental degradation but also pose geopolitical challenges. The Internal Combustion Engine in fossil fuel vehicles release a mix of air pollutants, such as carbon monoxide (CO), nitrogen oxides (NOx), volatile organic compounds (VOCs), and particulate matter (PM), posing threats to both air quality and human health. Notably, NOx plays a role in forming ground-level ozone and smog.

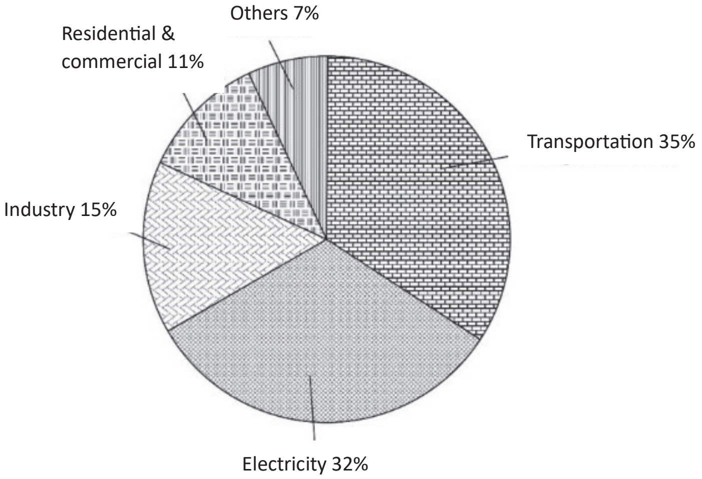


Fig. 3. Carbon dioxide emission by different sources (Verma, S. et al, 2021)

The combustion of fossil fuels generates PM, comprising tiny particles that can deeply penetrate the respiratory system upon inhalation, leading to associations with respiratory diseases and cardiovascular problems. Also, the accumulation of these gases traps heat in the atmosphere, leading to a gradual rise in global temperatures. This warming has far-reaching consequences, including more frequent and severe weather events, rising sea levels, and disruptions to ecosystems [10, 11].

On the other hand, considering the life-cycle cost of fossil fuel vehicles, it is essential to look beyond the initial purchase price. Fuel expenses, maintenance, and the societal costs associated with environmental damage constitute a significant portion of the overall expenditure [12]. As the world navigates towards sustainable transportation solutions, understanding the intricate relationship between fossil fuel vehicles, resource consumption, emissions, and life-cycle costs becomes imperative for informed decision-making and the search of more environmentally friendly alternatives [13, 14].

There are two well-known electric alternatives to the Fossil fuel cars including Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs). Hybrid Electric Vehicles (HEVs) represent a transformative evolution in automotive technology, offering a compelling alternative to traditional fossil fuel vehicles [15]. In 2019, the EU witnessed the registration of over a million new hybrid vehicles. However, data from Jato Dynamics, a service provider, reveals that this figure surged to over 1.4 million in 2020, marking a remarkable 47 percent increase from the previous year [16].

These innovative vehicles seamlessly integrate internal combustion engines with electric propulsion systems, providing a range of advantages that address environmental concerns and enhance overall driving efficiency. Hybrid vehicles derive power from both fossil fuel and electrical energy sources. As a result, these vehicles are equipped with a minimum of two energy storage systems including a fuel tank and a battery. Hence, feature at least two energy converters, namely the electric motor and the internal combustion (IC) engine. Essential components of a hybrid drive system also include an electronic control device responsible for determining the transition between the two drive systems and an inverter that converts direct current from the battery into alternating current while managing the electric motor [17].

The notable advantage of Hybrid EVs lies in their improved fuel efficiency. By combining the conventional engine with electric power, these vehicles optimize energy usage, particularly in stop-and-go traffic or during low-speed driving [18]. The result is a reduction in fuel consumption and lower emissions compared to their fossil fuel counterparts. This increased efficiency contributes to a more sustainable and eco-friendly mode of transportation, aligning with global efforts to mitigate climate change.

Furthermore, Hybrid EVs often boast a regenerative braking system that captures and stores energy during deceleration. This technology not only enhances energy efficiency but also extends the lifespan of braking components, reducing maintenance costs over the vehicle's life cycle [19]. The integration of intelligent energy management systems ensures optimal power distribution between the combustion engine and the electric motor, maximizing overall performance and minimizing environmental impact.

In terms of environmental impact, Hybrid EVs typically produce fewer emissions compared to their fossil fuel counterparts. The reduction in greenhouse gas emissions contributes to improved air quality and aligns with global initiatives to transition towards greener transportation [20].

According to the literature reviews Hybrid vehicles integrate two drive systems in various configurations, with the distribution of power between them varying. The three main categories are micro hybrid, mild hybrid, full hybrid, and plug-in hybrid, each offering different levels of electrification [19, 21, 22]. According to the German Automobile Association ADAC, these hybrids can achieve fuel savings ranging from 15% to 25% compared to traditional internal combustion engine (ICE) vehicles, and even more for plug-in hybrids. In following, different Hybrid EVs configuration are categorized:

1. **Micro Hybrid:**
    - Utilizes an automatic start-stop system to capture braking energy and store it in a 12V starter battery.
    - Primarily propelled by the internal combustion engine (ICE).
    - Not widely classified as a hybrid due to reliance on the ICE.
    - Limited fuel savings.
2. **Mild Hybrid:**
    - Features an electric motor supporting the ICE, operating during acceleration.
    - Equipped with a 48-volt battery for enhanced energy recuperation and more efficient start-stop system.
    - Consumes up to 15% less fuel than traditional ICE vehicles.
3. **Full Hybrid:**
    - Intelligent collaboration between an electric motor and an ICE.
    - Enables short trips in pure electric mode.
    - Utilizes a high-voltage traction battery with several hundred volts.
    - Fuel savings exceeding 20% compared to pure ICE vehicles, according to the German Federal Environment Agency.
4. **Plug-in Hybrid:**

  - Further evolution of full hybrids.
  - Features a larger, more efficient high-voltage battery.
  - Allows charging at a station or wall socket, offering electric-only ranges of up to 100 kilometers.
  - Standard fuel consumption is up to 35% less than comparable ICE vehicles.

In addition to electrification levels, hybrid vehicles are categorized based on their construction as:

- Parallel Hybrid: Utilizes both an electric motor and an ICE connected to the driving axle, allowing pure electric, ICE, or combined driving.
- Series Hybrid: Operates with a single drive system where the electric motor propels the vehicle, and the ICE generates electricity for the battery, with no mechanical connection between power sources.
- Power Split Hybrids: Combines elements of both series and parallel hybrid drives and allowing the driver to select the operation.

In comparison to vehicles equipped solely with an internal combustion engine, hybrid drive systems or pure electric motors offer numerous advantages such as:

- Hybrid vehicles can adapt to the driving situation, utilizing the optimal drive for city commuting and rural travel.
- Fuel consumption is notably lower, ranging from 15% to 35%, particularly beneficial in stop-and-go city traffic scenarios.
- Lower fuel consumption and, in some instances, pure electric mode contribute to reduced emissions.
- Enhanced efficiency in driving, with less energy loss compared to gasoline or diesel counterparts, thanks to energy recapture during braking and coasting.
- Longer driving range, making longer trips feasible compared to purely electric vehicles.
- Acceleration is improved by 10 to 20% compared to conventional drive systems, as electric motors provide high torque from the start.
- Except for plug-in hybrids, these vehicles do not require regular charging, eliminating the need for drivers to search for charging stations.

Besides, Hybrid Electric Vehicles emerge as a promising solution, bridging the gap between traditional fossil fuel vehicles and fully electric options. With advantages ranging from enhanced fuel efficiency and reduced emissions to improved overall performance, Hybrid EVs represent a pivotal step towards a more sustainable and environmentally conscious automotive future. In many instances, pure electric vehicles face challenges such as limited driving range, expensive batteries, and insufficient charging infrastructure. Hybrid vehicles offer a compelling solution by integrating an electric drive system with an internal combustion engine. This integration allows hybrid vehicles to achieve longer driving ranges compared to electric vehicles and consume less gasoline or diesel, striking a balance between the advantages of both technologies [23].

Despite the mentioned advantages, hybrid vehicles come with certain disadvantages when compared to internal combustion engine (ICE) vehicles or pure electric types:

- Higher initial purchase costs due to the complexity of dual-drive technology. This cost disadvantage is offset over time by lower fuel consumption.
- Increased weight due to the presence of two power sources and an additional battery, potentially leading to higher fuel consumption in specific situations where only the internal combustion engine is active.
- Limited trunk space in some models due to the presence of an additional battery.
- For plug-in hybrids, the overall carbon footprint depends on the source of electricity used for battery charging, with greener electricity yielding better environmental results.
- Unlike pure electric vehicles, hybrids are still reliant on fossil fuels and produce emissions.

One promising opportunity for promoting electric mobility involves exploring the technical feasibility of converting fossil fuel cars into electric hybrid vehicles [24, 25]. While this approach is acknowledged for its potential, it comes with its own set of challenges. Factors like cost implications, compatibility issues, and adherence to regulations must be carefully considered. The feasibility of such conversions varies depending on vehicle type, intended usage, and the willingness to invest in the retrofitting process. Notably, retrofitting may emerge as a practical and economical solution, particularly in specific applications such as fleet vehicles. The long-term savings and emissions reduction associated with retrofitting can potentially outweigh the initial investment, making it a compelling option for certain segments of the automotive market [26, 27].

The market size of hybrid electric vehicle conversion kits reached \$0.61 billion in 2022 and is anticipated to achieve \$1.85 billion by 2030, marking a notable Compound Annual Growth Rate (CAGR) of 17.2% during the forecast period spanning from 2023 to 2030. These kits consist of components and systems designed for installation in conventional gasoline-powered vehicles, transforming them into hybrid electric vehicles (HEVs). A standard conversion kit comprises elements such as an electric motor, a battery pack, a control unit, and other essential components [28, 29].

The electric motor collaborates with the existing internal combustion engine of the vehicle, enhancing fuel efficiency and mitigating emissions. The electric motor integrated into the conversion kit represents a peak of modern engineering [30]. Employing advanced technologies, such as permanent magnet motors or induction motors, these components are designed for optimal power delivery, efficiency, and endurance. The seamless collaboration between the electric motor and the internal combustion engine creates a synergistic powertrain that maximizes performance and responsiveness across diverse driving conditions.

The heart of the hybrid electric vehicle conversion lies in its cutting-edge battery pack. Utilizing state-of-the-art lithium-ion or solid-state battery technologies, these packs are engineered to deliver high energy density, rapid charging capabilities, and extended cycle life. The strategic placement within the vehicle ensures optimal weight distribution, contributing to improved handling and overall balance.

The control unit acts as the brain of the hybrid system, arranging the intricate dance between the electric motor and the traditional engine. Equipped with sophisticated algorithms, predictive analytics, and machine learning capabilities, this unit optimizes power distribution in real-time.

As a result, drivers experience seamless transitions between electric and conventional modes, achieving not only superior fuel efficiency but also an enhanced driving experience.

These cutting-edge conversion kits seamlessly integrate electric power with our existing combustion engine, offering us the best of both worlds. Experience enhanced fuel efficiency, reduced emissions, and the thrill of a smoother, quieter ride as the vehicle transitions effortlessly between electric and traditional modes. As a result of these compelling benefits, the global demand for hybrid electric vehicle conversion kits is experiencing significant growth.

Nowadays, there are many companies operate in the hybrid electric vehicle (EV) conversion kit market, offering solutions for commercial and municipal fleets. Notable companies include XL Fleet, Efficient Drivetrains, Inc. (EDI), REV Electric Vehicle Systems, Odyne Systems, A123 Systems, Bosch Automotive Service Solutions, and Hymotion (a subsidiary of A123 Systems). These companies provide various solutions, including hybrid powertrains, battery systems, and conversion tools, catering to different aspects of the hybrid EV market. Also, there are several companies offering conversion kits for retrofitting various classic and vintage vehicle models. Some of the companies include EV West, Zelectric Motors, Canadian Electric Vehicles (CEV), Electric GT, Green Shed Conversions, Zero EV, and Electric Classic Cars.

2. Introduction

Over the past two decades, the global energy crisis has sparked significant interest in the automotive industry due to the continuing rise in global warming. Transportation is a leading contributor to greenhouse gas (GHG) emissions worldwide. Conventional vehicles, powered by internal combustion engines (ICE) fuelled by fossil fuels, release gases such as carbon dioxide, hydrocarbons, carbon monoxide, and nitrogen oxides. According to the statistical database of the US Energy Information Administration, CO_2 emissions from the end-user sector are depicted in Fig. 4.

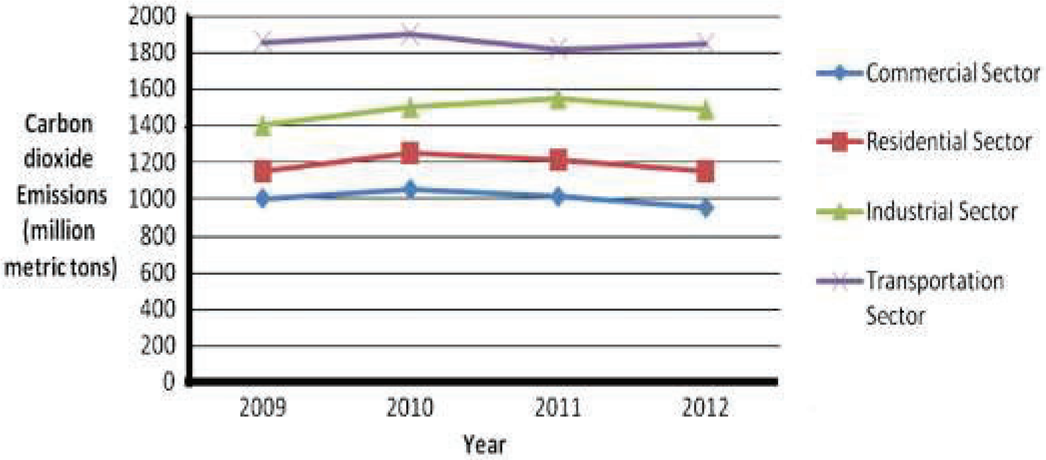


Fig. 4. The CO_2emissions based on different end-users (wileyonlinelibrary.com)

In 2012, the transportation sector accounted for 33.7% of greenhouse gas (GHG) emissions. Fig. 2, adapted from existing literature, illustrates the significance of hybrid electric vehicles (HEVs) and electric vehicles (EVs) in reducing global GHG emissions. However, both EVs and HEVs face challenges, for example in battery costs. Given the human impact on GHG emissions and their contribution to global warming, alternative powertrain vehicles are gaining attention. These include vehicles using compressed natural gas and advanced powertrain architectures combining different propulsion systems.

To enhance transportation performance, energy generators like fuel cells, solar panels, regenerative braking, and supplementary generators (e.g., flywheel, ultra-capacitors, wind energy) can be integrated into EVs. Researchers aim to address oil depletion, environmental pollution, and global warming through HEVs, which have entered the market with evolving technology.

To assist engineers and researchers in the automotive industry, software tools have been developed by the National Renewable Energy Laboratory with support from the US Department of Energy to design new HEVs. Despite technological advancements in automotive applications, there remains a significant need for optimizing consumption and reducing CO_2 emissions in hybrid vehicles. As fossil fuels are limited and access to new resources becomes increasingly challenging, the role of CO_2 emissions in climate change becomes more pronounced. Fig. 5 compares the sources of emissions in the EU-15 [31].

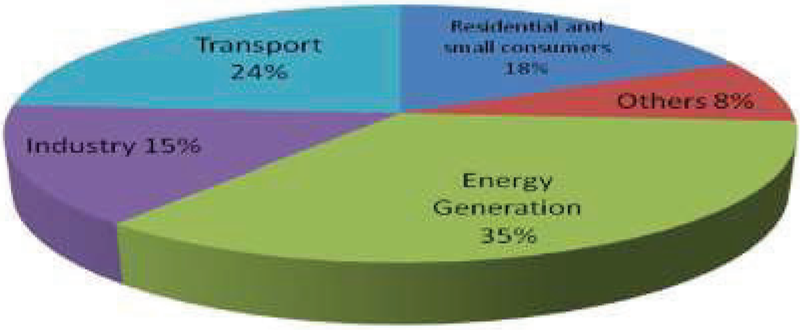


Fig. 5. Amount of CO_2emissions in percentage (wileyonlinelibrary.com)

Fig. 3 demonstrates that transportation contributes to approximately a quarter of total CO_2 emissions. As a solution to overcome the problem, this pre-study research aims to provide insights into hybrid vehicles. The hybrid vehicles is defined and explores various configurations, including integration with electric motors, power converters, internal combustion engines (ICE), and energy storage devices. It elaborates on different traction motors, power converters linked to traction motors and batteries, and energy management strategies for optimizing hybrid electric vehicles (HEVs).

Legal and regulatory pressures, particularly in Europe, to lower emissions and fuel consumption are driving the demand for hybrid and electric vehicles. This surge in demand is propelling advancements in electric powertrains and batteries. Virtually every car manufacturer is developing hybrid or electric vehicles to meet fleet consumption targets and avoid penalties. Manufacturers have devised multiple powertrain options to enhance fuel efficiency and reduce emissions, aligning with legal regulations. An overview of these options is depicted in the Fig. 6 [31].

To eliminate emissions from internal combustion engines, the most efficient approach is to replace the conventional powertrain with a fully electric one. However, this study outlines a cost-effective method to convert a vehicle from a conventional internal combustion engine (ICE) to an El-hybrid vehicle. The primary challenge involves integrating an existing engine into the vehicle's structure with minimal modifications to both systems, thereby reducing development time and costs. This research reveals how this integration is achieved through different methods and modifications to the existing systems.

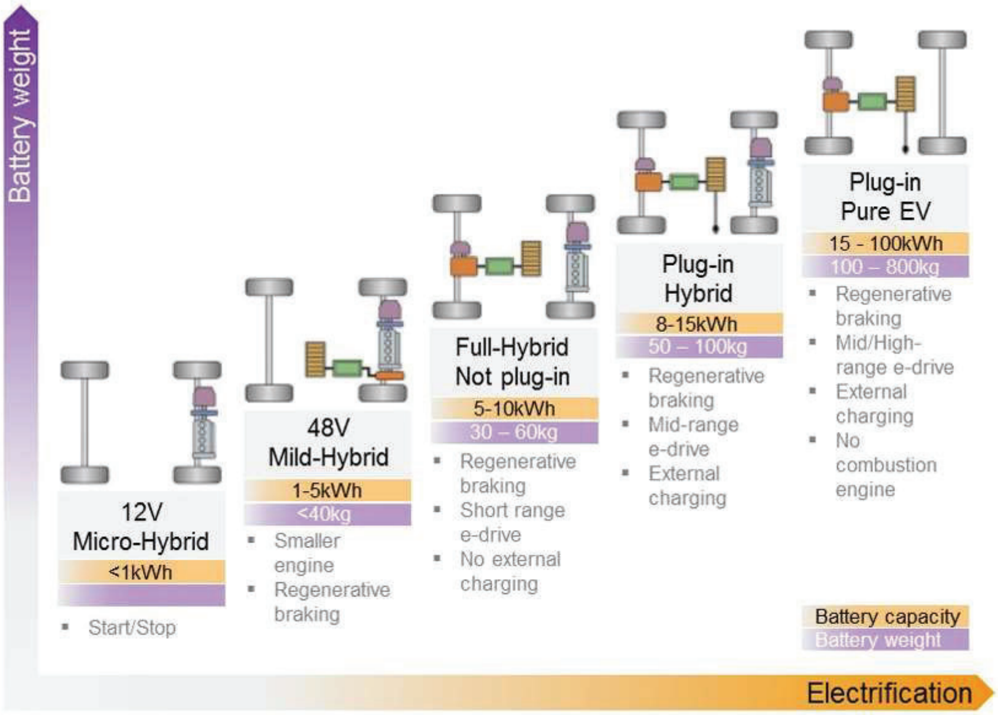


Fig. 6: Different Levels of Vehicle Electrification

3. Methodology

This study on converting personal fossil fuel cars into electric-hybrid vehicles employed a comprehensive methodology that integrated extensive literature review, industry consultation, and practical insights from private conversion kit manufacturers. This approach aimed to provide a comprehensive understanding of the existing landscape of electric-hybrid conversion technologies, addressing associated challenges and identifying potential opportunities.

3.1 Literature Review

Over 140 scholarly articles, industry reports, and technical documents were carefully reviewed. This extensive literature survey covered various domains, including automotive engineering, environmental impact assessment, and energy efficiency was to identify established methodologies for converting fossil fuel vehicles to electric-hybrid models, assess the environmental benefits of such conversions, and understand the technological and regulatory challenges involved.

3.2 Industry Consultation

Engagement with relevant industries was a critical component of our methodology. Representatives from leading automotive manufacturers, such as Volvo, and tech companies specializing in electric powertrains and battery technologies were contacted. These consultations aimed to gather expert opinions on the feasibility of conversions, the latest advancements in hybrid technology, and insights into consumer trends and regulatory considerations.

3.3 Collaboration with Conversion Kit Manufacturers

To bridge the gap between theory and practice, we contacted with several private conversion kit manufacturers. These builders possess hands-on experience in retrofitting fossil fuel vehicles with electric or hybrid systems. Discussions focused on the technical specifics of conversion kits, the process of retrofitting vehicles, cost implications, and the practical challenges faced during conversions. These discussions offered valuable practical perspectives that literature and industry consultations alone could not provide.

3.4 Data Synthesis and Analysis

The collected data from the literature review, industry consultations, and manufacturers insights were synthesized to identify common themes, innovations, and gaps in the current knowledge and practice of vehicle conversions. This analysis facilitated the development of a comprehensive understanding of the ecosystem surrounding electric-hybrid vehicle conversions and informed the recommendations for advancing this field.

This methodology provided a multi-faceted perspective on converting personal fossil fuel cars into electric-hybrid vehicles, ensuring that the study's findings and recommendations were well-grounded in both theory and practice.

4. Types of hybrid vehicle

A vehicle qualifies as a hybrid when it satisfies three criteria [32]:

1. Drive train configuration
2. Contribution of traction power from an electric motor
3. Characteristics of the non-electric power source

4.1 Drive train structure

A vehicle is considered a hybrid when it utilizes two or more distinct power sources to drive it. In a hybrid electric vehicle (HEV), internal combustion engines (ICE) and electric motors, one or more, work together. These configurations, along with the battery connections, are typically categorized as series, parallel, and series-parallel HEV [33].

4.2 Series HEV

In a series hybrid drivetrain, a vehicle is propelled by feeding power to a single electric motor from two sources. The key components in this drivetrain include the internal combustion engine (ICE), electric generator, converters, battery, and electric traction motor. The ICE is fuelled by a tank, which is connected to the electric generator. A converter with an inverter is placed between the generator and traction motor, with a battery also connected to the inverter. As a result, electrical power to the traction motor comes from either the ICE via the electric generator or directly from the battery [34].

Figures 7, 8, and 10 have been adapted from existing literature [35]:

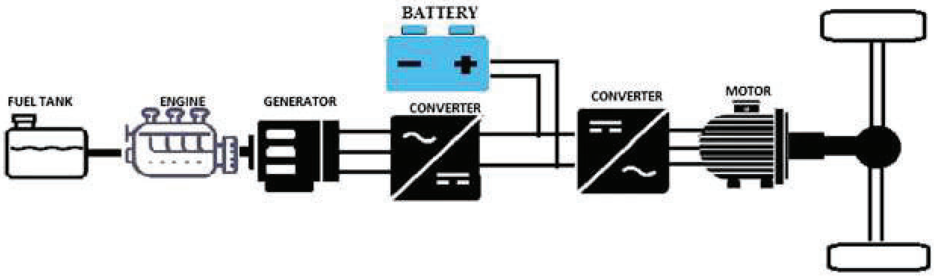


Fig. 7. Series drive train structure (wileyonlinelibrary.com)

The concept of hybrid electric vehicles (HEVs) was inspired by electric vehicles (EVs), which faced limitations such as short driving range due to battery charging issues. HEVs, particularly series HEVs, address this challenge by employing a series energy transformation process in the drivetrain during driving cycles. In a series HEV, the mechanical power generated by the internal combustion engine (ICE) drives an electric generator, producing electrical power. This electrical power, along with power from the traction battery, propels the electric traction motor, resulting in mechanical power for the wheels. This configuration is commercially available in vehicles such as Mitsubishi Outlander PHEV. During deceleration, the traction motor functions as a generator, charging the battery through a recuperation process that harnesses kinetic energy from braking.

Pros:

- High efficiency is achieved at high speeds since traction motors, not the internal combustion engine (ICE), drive the wheels, reducing emissions.
- Elimination of complex mechanical transmissions is facilitated by driving the wheels with traction motors.
- A simplified control strategy is employed due to the use of electrical transmission.

Cons:

- Increased component count results in higher losses as mechanical energy is converted to electrical energy and vice versa, reducing overall system efficiency.
- Additional cost and weight are incurred due to the presence of the generator.
- The electric traction motor must meet maximum requirements to drive the vehicle.

4.3 Parallel HEV

In parallel HEV drive train configuration, the vehicle is driven by either the ICE, the electric traction motor, or both simultaneously. Both the ICE and electric motor are connected in parallel to the same drive shaft, each providing separate drive power: PICE and PEM. This configuration is commercially available in vehicles such as the Honda Civic hybrid and Honda Insight, where the ICE is directly connected to the wheels [36].

In a parallel hybrid vehicle, the electric motor is also connected to the wheels. This type of hybrid is often referred to as a power-assist hybrid because the vehicle can be propelled solely by the electric motor and battery, resembling an electric vehicle (EV) for short distances. The battery is replenished through regenerative braking and cruising, during which the electric motor acts as a generator to recharge the battery. Proper coordination between the primary power source (ICE) and the secondary power source (battery) helps reduce the demand on the ICE, optimizing fuel efficiency.

Pros:

- Lower cost compared to series HEV.
- Fewer converters needed.
- Compact design relative to series HEV.
- Notable improvement in fuel economy.
- Simpler control circuitry.
- Considerably cost-effective.

Cons:

- Batteries in propulsion mode cannot be charged as in series drive trains.
- Placement of ICE is limited as it must be coupled with the propulsion system.

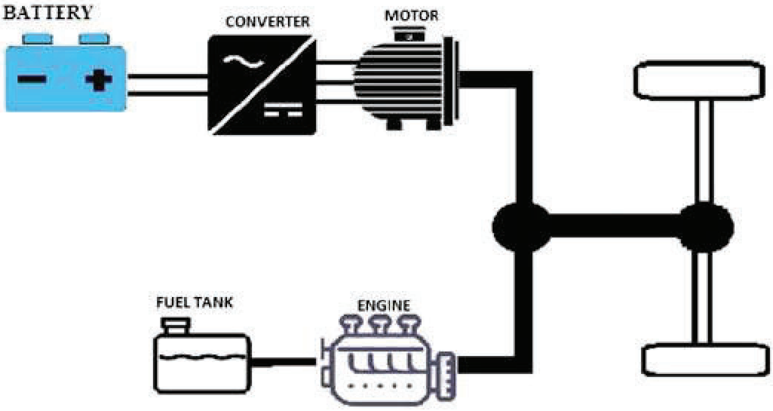


Fig. 8. Parallel drive train structure (wileyonlinelibrary.com)

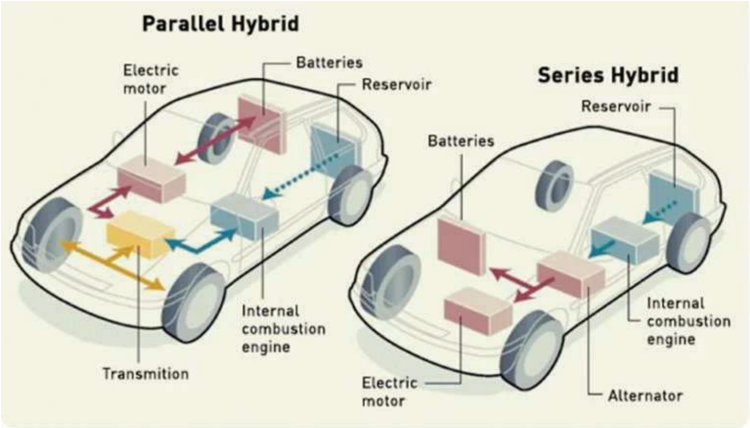


Fig. 9. Schematic view of Parallel and Series El-Hybrid cars

4.4 Series-parallel HEV

The power split, or combined hybrid, also known as series-parallel hybrids, amalgamates the attributes of series and parallel configurations. It incorporates two pathways for delivering power to the wheels: series and parallel. In the parallel path, power is transferred from the engine to the wheels, along with the motor power connected to the same shaft. Conversely, in the series pathway, there is a connection between the ICE and electric generator [37]. This pathway seems like the series hybrid drivetrain. Alongside battery power, power from the ICE through the generator is supplied to the electric motor of the wheels.

Pros:

- High flexibility characterizes this drivetrain.
- It offers a wide range of functions, a significant advantage.
- Batteries recharge during vehicle propulsion or when operating in electric mode.

Cons:

- Complex control circuits are needed.
- Increased complexity and vehicle size due to more components.
- An additional generator is necessary compared to parallel hybrids.

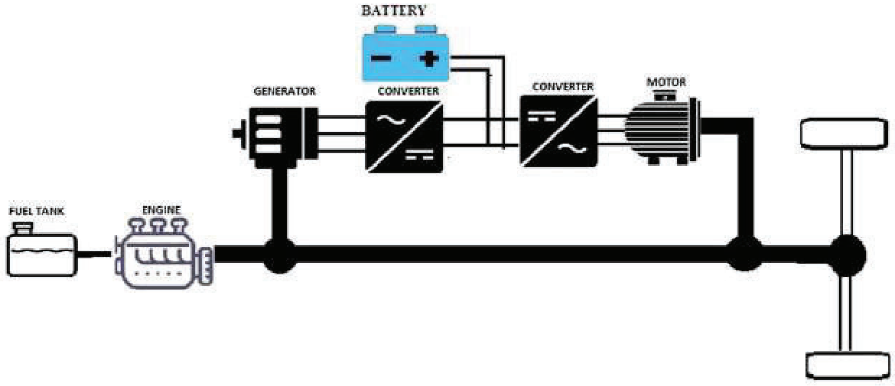


Fig. 10. Series-parallel drive train structure (wileyonlinelibrary.com)

Table 1 provides a brief comparison of the three HEV types [38].

Table 1. Comparison among 3 types of HEV

	Series HEV	Parallel HEV	Series/Parallel HEV
Fuel economy improvement:			
Idling stop	Superior	Superior	Excellent
Energy recovery	Superior	Superior	Excellent
High efficiency operation control	Superior	Somewhat unfavorable	Excellent
Total efficiency	Somewhat unfavorable	Superior	Excellent
Driving performance			
Acceleration	Somewhat unfavorable	Superior	Superior
Continuous high output	Somewhat unfavorable	Somewhat unfavorable	Superior

5. Modes of operation of HEV

The various operational modes of series, parallel, and series-parallel HEVs are delineated by Katrasnik [39].

The series hybrid electric drivetrain vehicle can operate in various modes:

1. Pure engine mode: Propelled solely by the engine, with power provided to the generator and motor. The battery remains inactive.
2. Pure electric mode: Driven exclusively by the battery's energy, with the engine turned off.
3. Hybrid mode: Power to the electric traction motor is supplied by both the engine generator and the batteries.
4. Battery charging mode (with propulsion): The engine drives the vehicle while also charging the batteries.
5. Battery charging mode (without propulsion): The engine and generator charge the batteries without supplying power to the electric motor.
6. Regenerative braking mode: Kinetic energy from braking charges the batteries, with the motor acting as a generator and the engine turned off.
7. Hybrid battery charging mode: The electric motor and engine generator both charge the batteries simultaneously.
8. Charge mode: In tandem with the engine-only mode, power to the wheels comes from the engine while the motor operates as a generator. The engine simultaneously charges the batteries while providing torque to the wheels.
9. Regenerative braking: When brakes are applied, the vehicle's kinetic energy is harnessed to charge the batteries via the generator, with the motor serving as a generator as well.

In parallel HEV drive trains, the following modes of operation are possible:

1. ICE only: The motor remains detached as power is solely supplied by the engine.
2. Electric mode: The engine is inactive, and power comes from the battery, allowing the motor to propel the vehicle independently.
3. Power assist mode: The motor (T_{em}) supplements the engine (T_{ice}) by providing additional torque (T_{req}) to the wheels. Here, the motor assists the engine in delivering extra power. ($T_{req} = T_{ice} + T_{em}$)

For series-parallel HEVs, the modes of operation are as follows:

1. Pure ICE mode: The wheels are solely propelled by the engine.
2. Pure electric traction mode: At low speeds, the vehicle is driven by the battery.
3. Hybrid mode: Both the engine and the electric traction motor jointly provide power to the wheels.
4. Engine traction and battery charging: The engine drives the vehicle while the electric motor charges the battery.
5. Regenerative braking: Kinetic energy from braking is used to recharge the battery, with the motor functioning as a generator during this process.

6. Types of degree of hybridization

Conventional vehicles rely solely on an internal combustion engine (ICE) for power and propulsion. However, if a vehicle incorporates any additional energy source besides the ICE, it qualifies as a hybrid vehicle. The level of hybridization reflects the vehicle's features and functionality, indicating whether the alternative source assists the ICE, drives the vehicle alone, or operates without fuel and the ICE for a specific duration. Based on these characteristics, vehicles are categorized as mild or micro hybrids, medium hybrids, full hybrids, and plug-in hybrid vehicles (Fig. 11).

6.1 Micro hybrid

The micro hybrid system represents the lowest level of vehicle hybridization in the automotive sector. It incorporates features such as regenerative braking for energy recovery and automatic engine start-stop functionality. While micro hybrids exhibit minimal energy recovery during regenerative braking, they can still reduce CO_2 emissions and fuel consumption by up to 4%, depending on the vehicle's drivetrain and driving conditions.

6.2 Mild hybrid

A conventional vehicle equipped with limited hybridization features is known as a mild hybrid. The parallel system can exhibit mild hybrid features under certain conditions. Mild hybrids may include start-stop functionality, either alone or combined with automatic engine shutdown when idling. Essentially, an oversized starter motor enables the ICE to shut off during coasting, braking, or when stopped, restarting as needed. For instance, the BMW 3-series (M340i) shuts off its engine when idle, with the electric motor also capturing energy during braking for regenerative braking. However, mild hybrids lack motor assist and EV modes, where the electric motor either doesn't assist the ICE for a period or doesn't propel the vehicle alone with the ICE off. Mild hybrids are sometimes referred to as micro hybrids, based on their features and performance. BMW has successfully combined regenerative braking and start-stop system features in their models.

6.3 Medium hybrid or motor assist hybrid

The medium hybrid vehicle integrates two power sources: the primary source from the engine and the secondary power, also known as engine assist power, from a torque-boosting electric motor. This setup places the ICE and electric motor in parallel. Unlike mild hybrids, medium hybrids can operate in electric mode for a limited period. The electric motor, typically larger, is positioned between the ICE and transmission. It serves to start the ICE when needed and provides additional power when required. During regenerative braking, the electric motor acts as a generator to charge the battery. The battery powers accessories during idle, and the electric motor restarts the engine. The battery size is optimized for the required electrical power. In models like the Honda Civic hybrid, the vehicle can cruise at medium speeds exclusively on electric power.

6.4 Full hybrid

The batteries in full HEVs are larger compared to those in medium and mild hybrids. Full HEVs can operate solely on the engine, solely on batteries, or a combination of both. These vehicles utilize high-capacity battery packs to enable extended operation in battery-only mode (EV mode). Models like the Toyota Prius, Auris, and Lexus exemplify full HEVs, capable of running solely on battery power. Full hybrids, along with medium and mild hybrids, fall under the category of charge-sustaining mode. In charge-sustaining vehicles, the energy storage system (battery) is designed to maintain the system's energy or state of charge (SOC) within a moderate range.

6.5 Plug-in hybrid electric vehicle

A full hybrid vehicle, equipped with larger batteries, can operate in electric-only mode (EV). If these batteries can also be recharged from the electric power grid, the vehicle is classified as a plug-in hybrid vehicle (PHEV). One key advantage of PHEVs is their ability to rely less on fuel for daily commuting, as they can draw power from the grid. For longer journeys, extended-range batteries enable sustained travel [40].

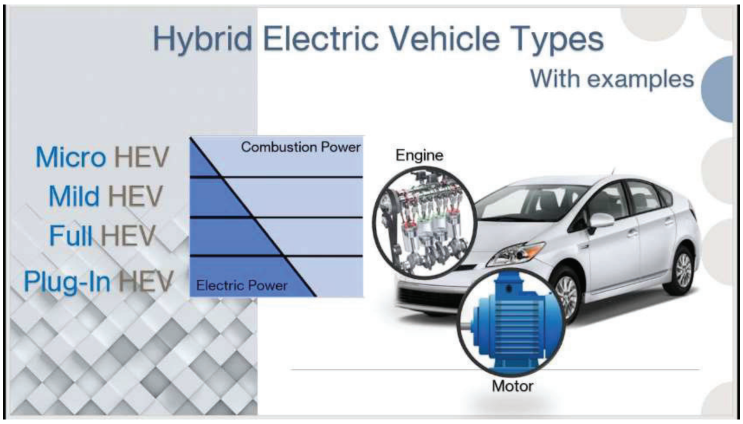


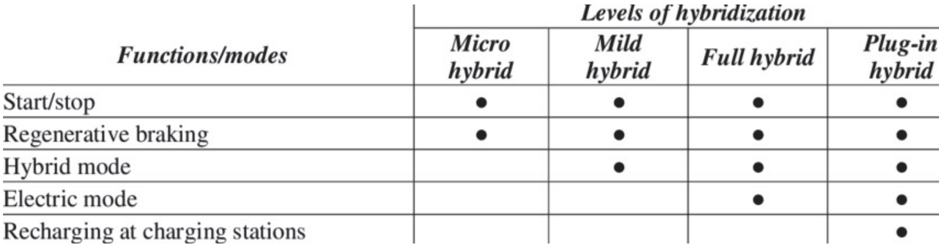
Fig. 11. Types of degree of hybridization

Tables 2 and 3 presents a brief comparison of the various types and functionalities of HEVs from different points of view.

Table 2. Types and functionalities of hybrid electric vehicle

Types of Hybrid System (Main Functions of Hybrids)	Engine Start-Stop	Regenerative Braking	Motor Assist	Electric Drive
Conventional vehicle	Feasible	Nominal	No	No
Micro HEV	Yes	Nominal	Nominal	No
Mild HEV	Yes	Meek	Meek	No
Medium HEV	Yes	Yes	Yes	Meek
Full HEV	Yes	Yes	Yes	Yes

Table 3. Types and functionalities/modes of hybrid electric vehicle



Functions/modes	***Levels of hybridization***			
	Micro hybrid	***Mild hybrid***	***Full hybrid***	***Plug-in hybrid***
Start/stop	●	●	●	●
Regenerative braking	●	●	●	●
Hybrid mode		●	●	●
Electric mode			●	●
Recharging at charging stations				●

7. Life Cycle Cost Assessment

The life cycle of vehicles is shaped by various factors, encompassing technical specifications, energy resources, the in-use phase, and production and recycling methods. A pivotal aspect of technical specifications is the propulsion system, which customers prioritize to strike a balance between resource consumption and energy efficiency. Conventional vehicles typically rely on internal combustion engines, predominantly consuming fossil fuels during their operational phase. Conversely, Electric Vehicles (EVs) mainly consume resources during manufacturing, particularly in the production of batteries, storage systems, and drivetrains.

The availability of resources and energy represents another significant factor influencing vehicle life cycles. Meanwhile, manufacturing technology and recycling methods define the third parameter, impacting the end-of-life phase of the product. The in-use phase considers lifecycle aspects such as transportation demand, individual driving profiles, and the consumption of energy and resources (such as fuel and electricity), ensuring a comprehensive balance [41].

To evaluate the environmental and economic impact of waste throughout the entire lifecycle, two assessment techniques are employed: life cycle assessment (LCA) and life cycle cost (LCC) analysis.

To estimate and evaluate environmental impacts at each stage of a vehicle's life cycle, the Life Cycle Assessment (LCA) serves as a robust methodology [42]. This approach encompasses the assessment of raw materials and energy usage, emissions of pollutants and greenhouse gases, starting from vehicle manufacturing, through material production and assembly, extending into vehicle operation including fuel or electricity generation, evaluating fuel consumption, and concluding with end-of-life considerations such as recycling and disposal costs. LCA serves as a standardized method to compare various vehicle technologies across their life cycles, providing insights into their environmental footprint at different stages. It's important to note that economic considerations are typically not included in LCA analyses. In general, LCA is described in four major phases:

1. Goal and Scope Definition: Clearly defining the objectives of the assessment and setting boundaries for what will be included (e.g., system boundaries, functional unit).
2. Life Cycle Inventory (LCI): Compiling an inventory of all relevant inputs (e.g., raw materials, energy) and outputs (e.g., emissions, waste) for each stage of the product’s life cycle.

3. Life Cycle Impact Assessment (LCIA): Assessing the potential environmental impacts of the identified inputs and outputs using impact categories such as global warming potential, acidification, eutrophication, etc.
4. Interpretation: Drawing conclusions and recommendations based on the findings of the LCA, interpreting the results to provide insights into the environmental performance of the assessed vehicle technologies.

On the contrary, the life cycle cost (LCC) of a system accounts for the total expenses incurred over its entire lifespan. This encompasses all costs from the initial design phase, through its operational use, to its eventual disposal. LCC analysis enables engineers to evaluate the comprehensive expenses associated with developing a system or product, rather than solely considering the initial costs of procurement, manufacturing, and transportation, which typically constitute only a portion of the overall expenditure. LCC can be divided into two primary components: the first includes ownership costs, such as procurement, depreciation, interest, inflation, and disposal costs; while the second encompasses operational expenses, including operational costs, maintenance, downtime, obsolescence, operator training, and inventory expenses [43].

As indicated by [41], the primary focus of life cycle cost (LCC) analysis for electric vehicles (EVs) often revolves around the considerable impact of battery costs, which make up a significant portion of the total price of current EVs. For example, the retail price of a lithium-ion battery averages around $300 per kilowatt-hour (kWh). In the case of a Nissan Leaf EV with a 24 kWh battery, this amounts to approximately $7,200, highlighting its crucial role in determining the overall cost of the EV. It's important to note that the comprehensive assessment of an EV's LCC is greatly influenced by the assumptions made during its life cycle modeling and the specific scope of the study.

The life-cycle study conducted by the International Council on Clean Transportation (ICCT) compares the greenhouse gas (GHG) emissions of battery electric vehicles (BEVs) and internal combustion engine vehicles (ICEVs) throughout their entire life cycle. This comprehensive comparison encompasses emissions from the production, operation, and disposal phases across major markets including Europe, the United States, China, and India [44].

The study's key findings underscore that battery electric vehicles (BEVs) registered in 2021 already exhibit lower life-cycle greenhouse gas (GHG) emissions compared to internal combustion engine vehicles (ICEVs) across all examined regions. This advantage is projected to significantly increase by 2030 as the energy grid continues to decarbonize. Notably, the study incorporates recent data on battery production and considers real-world fuel and electricity consumption, offering a comprehensive and realistic assessment of emissions. It highlights the imperative of transitioning to BEVs and renewable energy sources to achieve substantial GHG reductions and align with climate objectives, such as those articulated in the Paris Agreement. The research emphasizes that combustion-engine vehicles, including hybrids, cannot meet the stringent decarbonization targets necessary to address severe climate impacts. Regulatory policies that promote electrification and grid decarbonization are deemed essential for maximizing the environmental benefits of electric vehicles, according to the study's recommendations.

The paper [45], provides a detailed analysis of the economic aspects of various vehicle technologies, encompassing internal combustion engine vehicles (ICEVs), hybrid electric vehicles (HEVs), and electric vehicles (EVs). Its principal aim is to juxtapose the life cycle costs (LCC) linked with these vehicle categories, considering diverse stages of their life cycle, which include production, operation, maintenance, and end-of-life disposal.

According to this study, Electric Vehicles (EVs) typically entail higher initial purchase costs compared to Internal Combustion Engine Vehicles (ICEVs) and Hybrid Electric Vehicles (HEVs) due to the expensive battery technology. However, as battery technology advances and economies of scale come into play, the initial cost disparity between EVs and other vehicle types is anticipated to diminish. In terms of operational and maintenance costs, EVs exhibit significantly lower operational expenses than ICEVs, mainly attributable to cheaper electricity costs relative to fuel and fewer moving parts, which translates to reduced maintenance requirements. HEVs also enjoy reduced fuel consumption compared to ICEVs, albeit their maintenance expenses can be higher than EVs due to the intricacy of their dual powertrains. The research underscores that the cost of fuel for ICEVs represents a significant component of their overall life cycle expense, and EVs display less sensitivity to fluctuations in electricity prices compared to the sensitivity of ICEVs to fuel prices. Furthermore, EVs offer substantial environmental advantages by curbing greenhouse gas emissions, thus yielding long-term economic benefits through diminished health expenses and environmental harm. The economic merits of EVs are further bolstered by supportive policies like subsidies, tax incentives, and investments in charging infrastructure. Ultimately, to optimize the adoption and benefits of EVs, the study advocates for policies aimed at reducing the initial purchase cost barrier and fostering infrastructure development. Policies advocating for renewable energy in electricity generation also play a pivotal role in securing the environmental benefits of EVs.

In the study presented by [46], the economic ramifications of various vehicle technologies in China are thoroughly examined. It juxtaposes the life cycle costs of conventional vehicles against those of Battery Electric Vehicles (BEVs) and Fuel Cell Electric Vehicles (FCEVs), accounting for traffic and environmental policies. The research reveals that BEVs generally boast lower life cycle costs than conventional vehicles, owing to savings in fuel and maintenance expenses. Moreover, environmental and traffic policies exert a substantial influence on the comparative economics of vehicle technologies. Subsidies and incentives tailored for Electric Vehicles (EVs) have the potential to diminish their purchase and operational costs, rendering them more financially appealing. Conversely, FCEVs, despite their potential for zero-emission benefits, currently exhibit higher life cycle costs in comparison to both conventional vehicles and BEVs. This disparity is partly attributable to the elevated expenses linked with fuel cell technology and hydrogen infrastructure. Ultimately, the economic viability of EVs, particularly FCEVs, remains highly contingent on the level of policy support, with alterations in subsidies, fuel prices, and regulatory frameworks capable of reshaping the cost competitiveness among different vehicle types.

In another comparative study conducted by Lipman and Delucchi [47], the costs associated with manufacturing, retail pricing, and the lifecycle of five types of hybrid electric vehicles (HEVs) in high-volume production are thoroughly scrutinized. Utilizing an updated cost model alongside the ADVISOR vehicle simulation model, the research juxtaposes 25 hybrid vehicle cases against baseline gasoline vehicles. The study's findings suggest that mild hybridization, coupled with advanced vehicle enhancements, has the potential to achieve lifecycle costs akin to those of conventional vehicles, particularly amid higher gasoline prices, thus rendering HEVs cost-competitive over their lifespan.

Furthermore, another study [48] delves into the economic feasibility of Hybrid Electric Vehicles (HEVs) and Battery Electric Vehicles (BEVs) in comparison to conventional vehicles. This research spans from 1997 to 2015 across the UK, US, and Japan. By scrutinizing purchase costs, running expenses, and maintenance outlays, the study seeks to ascertain the total cost of ownership (TCO). The results indicate that despite their elevated upfront costs, HEVs and BEVs often boast lower TCOs owing to savings accrued from reduced fuel consumption and maintenance requirements. Additionally, the study explores how TCO influences market dynamics, revealing a robust correlation between decreased TCO and heightened adoption of hybrid and electric vehicles.

In conclusion, Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) analyses emerge as indispensable tools for holistically evaluating environmental impacts and economic considerations associated with vehicle manufacturing, utilization, and disposal. These analyses shed light on the environmental footprints and economic feasibility of various vehicle technologies from inception to end-of-life. The lifecycle of vehicles is intricately influenced by factors such as technical specifications, energy sources, production methodologies, and recycling technologies, all of which significantly shape their environmental sustainability and economic viability.

For instance, Electric Vehicles (EVs) exhibit promising potential in curbing greenhouse gas emissions throughout their lifecycle compared to conventional Internal Combustion Engine Vehicles (ICEVs), notwithstanding their higher initial costs primarily attributed to battery expenses. Consequently, policies aimed at bolstering EV adoption, fostering advancements in battery technology, and facilitating the decarbonization of energy grids play pivotal roles in maximizing the environmental benefits and economic competitiveness of EVs within the global automotive landscape.

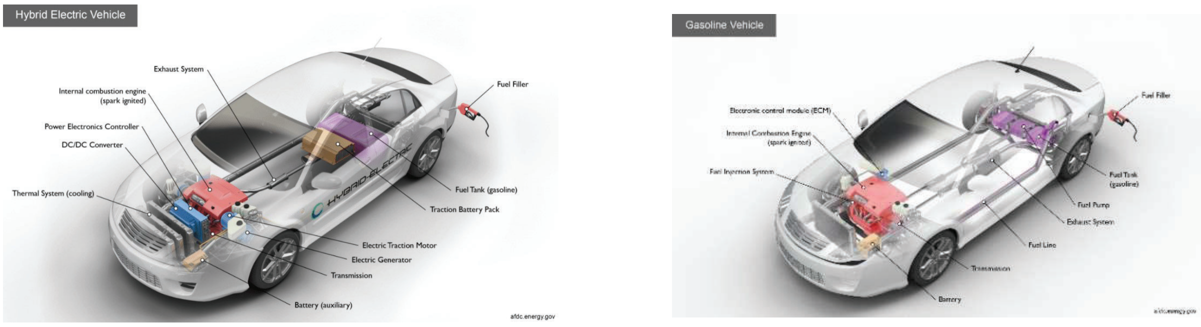


Fig. 12. Hybrid and Internal Combustion Engine cars

As mentioned before, transportation stands as a significant contributor to urban pollution and greenhouse gas emissions. In 2010, this sector accounted for roughly 22% of global carbon dioxide emissions, with projections indicating a potential doubling by 2050 [49]. Recognized as a primary driver of global warming, this trend has urged European regulations to prioritize the decarbonization of transportation [50], leading to increased production of electric, hybrid, and plug-in hybrid vehicles. Indeed, a viable strategy to substantially reduce tailpipe emissions, including local environmental impacts from conventional combustion pollutants, involves replacing conventional vehicles with electric counterparts [51]. Pure electric vehicles currently face limitations in terms of range, making hybrid electric vehicles – featuring a combination of an ICE and an electric powertrain – or other alternative powertrains like fuel cell vehicles, attractive short-term solutions for reducing GHG emissions [52]. However, while governments primarily focus on emissions during the driving phase, it's crucial to recognize that comparing vehicles solely based on tailpipe emissions is inadequate. Despite pure and hybrid electric vehicles having minimal or zero local emissions, the energy-intensive nature of electricity production for battery charging means it's far from emission-free. Additionally, it's recognized that both the manufacturing and disposal processes of batteries and fuel cells have significant environmental drawbacks [53, 54, 55, 56]. Hence, evaluating the environmental sustainability of alternative mobility solely based on the driving phase is inadequate. Consideration must also be given to the environmental impacts associated with electricity production and the lifecycle processes of vehicle construction, dismantling, and material disposal. Taking a broader perspective, it's essential to consider all stages of a vehicle's lifecycle, employing a life cycle assessment (LCA) approach [57]. Numerous studies have already adopted this approach, emphasizing the environmental advantages of introducing electric and hybrid vehicles into the market [58, 59, 60, 61, 62, 63]. Typically, these studies compare the life cycle impacts of various powertrain types, evaluating the overall environmental sustainability of the entire vehicle. In [64, 65] different technologies are compared using representative vehicles from each category – conventional, electric, and hybrid electric vehicles – based on market relevance and utilizing the best available technology as per published specifications. Casals et al. [66] conduct a Monte Carlo analysis to address parameter variability in the energy use phase, without considering production and end-of-life (EoL) phases. Boureima et al. [67] analyze vehicle technologies within the same family car segment, utilizing ranges of weights, emissions, and fuel consumptions extracted from the Ecoscore database [68]. Bartolozzi et al. [69] use experimental data for the on-board fuel cell inventory and literature data for other vehicle components. Kudoh et al. [70] incorporate vehicle manufacturing and maintenance stages using a hybrid method that employs a Japanese input-output table. The utilization of Input-Output Life Cycle Assessment (LCA) models can offer a promising approach for handling large-scale systems like manufacturing or transportation [71]. Nonetheless, it's crucial to acknowledge that these models are built upon numerous assumptions.

One of the primary challenges lies in compiling a comprehensive list detailing the specifications of all vehicle components, including materials and weights, in order to assess each production process [72]. Moreover, the literature referenced for filling in missing data is often outdated [73]. Furthermore, vehicles are typically manufactured by various companies, each employing potentially distinct processes, making it difficult to integrate all relevant aspects into the assessment. Additionally, various components of the same vehicle might originate from countries other than the manufacturer's, characterized by diverse energy compositions. Often overlooked is the energy demand associated with transportation. Access to such information is rather limited, necessitating reliance on assumptions. Consequently, this reliance could lead to a somewhat rudimentary analysis.

Due to these factors, studies employing a life cycle approach can hold greater significance when they utilize less data but with higher reliability. A robust comparison of different products should hinge on a uniform foundational model, ensuring consistency across all scenarios in terms of assumptions and system boundaries. This approach ensures severe methodological consistency in comparisons and facilitates drawing meaningful conclusions [74].

A literature review conducted by the Argonne National Laboratory [75] brought to light the significant variability in estimating the energy consumption during the vehicle manufacturing and assembly (VMA) stage across the studies analyzed. This variability is not unexpected, given that vehicles consist of numerous parts, each typically composed of various materials. Additionally, while some parts are produced in-house by the vehicle manufacturer, others are sourced from external suppliers. This review underscored a limitation of LCA results regarding absolute values. By excluding the contributions of body, chassis, and other non-powertrain components from the construction and end-of-life inventory analysis, a consistent additional contribution is overlooked for each system. Consequently, since LCA lack absolute significance, this assumption doesn't impact the analysis when comparing the two cases. Hence, this research suggests applying a life cycle approach specifically to the powertrains rather than to the entire vehicles. However, during the use phase, the total vehicle weight must be considered as it significantly influences powertrain performance. The review by Nordelöf et al. [76] indicates a common approach in studies focusing on the LCA of batteries, where the impact contribution during the use phase is typically assessed by considering the electricity consumption of the entire pure electric vehicle. Meanwhile, the construction and recycling/disposal phases are often evaluated solely for the battery pack.

8. Conversions kits

Electric conversion kits come in two varieties: custom kits designed for specific vehicle models, and universal kits suitable for installation in a range of vehicles. Universal kits comprise essential drive-system components, with the builder tasked with creating custom elements such as battery racks or boxes. On the other hand, custom kits encompass the entire drive system, along with tailored battery racks and boxes, crafted to fit a particular model (Fig. 13).

Fig. 13. Sample of electric conversion kits

8.1 Hybrid EV Conversion Kit Market

In 2022, the Hybrid EV Conversion Kit Market was valued at USD 420.10 Million. It is anticipated to witness significant growth, with the market size projected to expand at a compounded annual growth rate (CAGR) of 16.5% from 2023 to 2029, reaching nearly USD 1425.48 Million (Fig. 14).

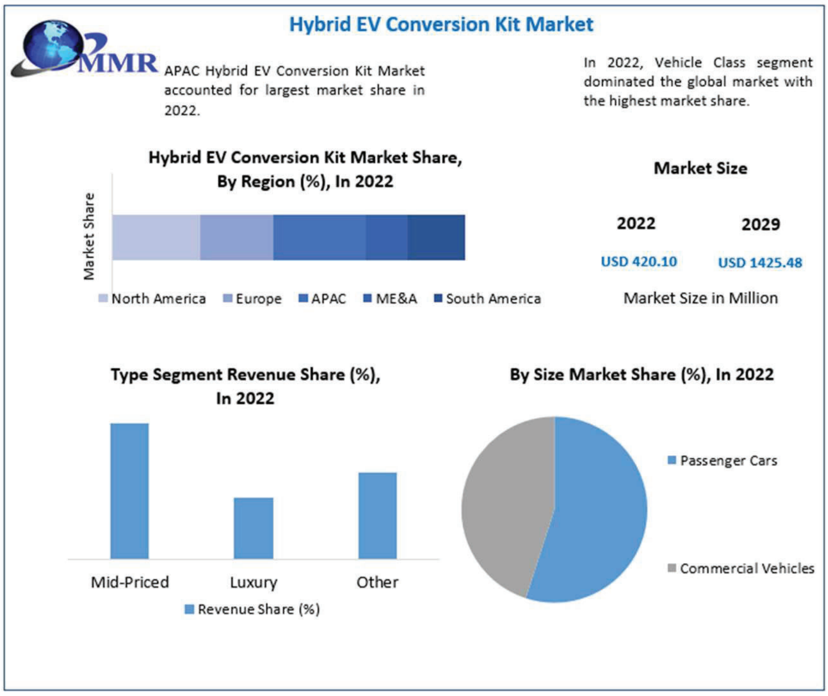


Fig. 14. Hybrid EV conversion kit market [77]

As it's known the Hybrid Electric Vehicle (HEV) conversion kit refers to a system installed in a traditional vehicle to convert it into a hybrid electric vehicle, utilizing both an internal combustion engine and an electric motor for propulsion. This conversion kit commonly consists of an electric motor, battery pack, power electronics, and control systems. The electric motor aids the engine during acceleration and facilitates regenerative braking to replenish the battery pack.

HEV conversion kits are available from several providers. XL Fleet is a prominent supplier of vehicle electrification solutions tailored for commercial and municipal fleets. Their XL Hybrid system is compatible with a diverse array of Class 2-6 commercial vehicles, spanning vans, trucks, and buses. EV West specializes in transforming vintage and classic cars into electric vehicles, offering an assortment of conversion kits, including HEV conversion kits suitable for various vehicle models. Additionally, Hymotion, a Canadian company, specializes in converting Toyota Prius hybrid vehicles into plug-in hybrid electric vehicles (PHEVs).

Their conversion kit incorporates a larger battery pack and a charging system, enabling the vehicle to operate in electric-only mode for extended distances. A123 Systems is a top provider of cutting-edge lithium-ion batteries and energy storage systems. They offer a variety of HEV conversion kits that can be tailored to fulfill the unique requirements of diverse applications. The report extensively covered micro-level analyses of key market players, along with their strategies and recent developments.

While the HEV conversion kit market remains relatively small, this is primarily due to most automakers now manufacturing hybrid and electric vehicles directly from the factory. Nevertheless, there remains a notable demand for conversion kits, especially among fleets and individual vehicle owners aiming to minimize their environmental footprint and enhance fuel efficiency. These factors are anticipated to propel the hybrid EV conversion kit market forward during the forecast period.

8.2 Plug-in hybrid electric vehicle (PHEV) conversion kits

The emergence of plug-in hybrid electric vehicle (PHEV) conversion kits marks a notable trend in the HEV conversion kit market. These kits typically encompass a larger battery pack, a charging system, and supplementary control systems, enabling the vehicle to operate in electric-only mode for extended distances. A key advantage of PHEV conversion kits is their compatibility with existing hybrid vehicles, offering owners the opportunity to upgrade their vehicles without the need for a new purchase. S mentioned earlier, the demand for Hybrid EV conversion kits is on the rise, largely driven by the availability of PHEV conversion kits. Additionally, these conversion kits can prove to be more cost-effective than purchasing new plug-in hybrid or all-electric vehicles, particularly advantageous for fleet operators seeking to upgrade multiple vehicles.

Numerous companies in the Hybrid EV Conversion Kit sector are currently focusing on the development of PHEV conversion kits. For instance, **Enginer**, headquartered in California, specializes in offering PHEV conversion kits tailored for vehicles like the Toyota Prius and other hybrid models. Their conversion kit comprises a larger battery pack, a charging system, and a control unit, enabling the vehicle to run solely on electric power for approximately 65 km. Similarly, Plug-In Supply, situated in Michigan, provides PHEV conversion kits designed for various hybrid vehicles such as the Ford Escape, Toyota Highlander, and Lexus RX400h. Their conversion package allowing the vehicle to operate in electric-only mode for about 55 km.

8.3 REVOLT company solution

The aforementioned company provides PHEV conversion kits suitable for a range of vehicles, both hybrid and non-hybrid, such as the BMW 3 Series, Mercedes-Benz E-Class, and Audi A4. Their conversion package enabling the vehicle to operate solely on electric power for approximately 50 miles. The emergence of PHEV conversion kits within the Hybrid EV conversion kit industry represents an exciting trend with the potential to notably decrease emissions and enhance fuel efficiency. This is particularly beneficial for fleet operators and individual vehicle owners seeking vehicle upgrades without the necessity of purchasing a new car.

At present, the market for converting gasoline cars into electric-hybrid configurations using retrofit kits remains relatively niche, though there are a few noteworthy options accessible to consumers (Fig. 15). It's crucial to acknowledge that the availability of such kits and services may differ depending on location and could evolve over time alongside technological advancements. Here's a summary of some recognized kits and companies engaged in these conversion endeavors:

1. XL Hybrids (now XL Fleet)

- **Product**: XLH Hybrid Electric Drive System
- **Description**: XL Fleet provides systems tailored mainly for commercial fleets, including vans, pickup trucks, and shuttle buses. Their technology integrates an electric motor and a lithium-ion battery into pre-existing vehicles, enhancing fuel efficiency and diminishing emissions with minimal alterations to the engine or transmission.

2. Engineer

- **Product**: Plug-in Hybrid Retrofit Kit
- **Description**: Enginer previously provided kits designed for installation in conventional non-hybrid vehicles, effectively converting them into plug-in hybrids with augmented battery capacity. These kits were available in different sizes, enabling the vehicle to operate on electric power for brief distances before reverting to gasoline.

Enginer's availability and operational status may vary, so it's recommended to directly verify their current situation.

3. EV West

- **Product**: Electric Conversion Kits (primarily full electric, but hybrid components can be sourced)
- **Description**: Although EV West is primarily recognized for their expertise in converting cars to full electric, they also offer components that could be beneficial for hybrid conversions, such as electric motors and battery management systems. Their specialization predominantly revolves around classic car conversions.

4. OEM Solutions

- **Description**: Certain car manufacturers have considered the possibility of providing hybrid conversion kits for their older models or for select markets. However, these kits are relatively uncommon and would generally be restricted to newer models and specific markets.

Fig. 15. An El-Hybrid car engine

9. Technical challenges

Converting fossil fuel cars into hybrid vehicles involves several technical challenges. These challenges include:

1. **Powertrain Modification:** Incorporating the electric motor and its associated components into the vehicle's existing powertrain system, often necessitating adjustments to the transmission to accommodate both electric power and the internal combustion engine.

2. **Battery Integration:** Fitting and integrating a high-voltage battery pack into the vehicle, locating suitable space for it, and ensuring it doesn't compromise the vehicle's structural integrity.
3. **Software and Control Systems:** Creating advanced control systems to manage power distribution between the internal combustion engine and the electric motor, guaranteeing optimal performance and efficiency.
4. **Charging and Energy Management:** Deploying an efficient and dependable charging system for the hybrid battery, potentially incorporating regenerative braking systems to recapture energy during braking.
5. **Weight and Space Constraints:** Managing the increased weight and size of the battery pack and electric components, which could impact available space, vehicle balance, and overall performance.
6. **Mechanical Modifications:** Modifying the braking, suspension, and steering systems to accommodate the additional weight and alterations in the vehicle's dynamic behavior.
7. **Engine Control and Tuning:** Fine-tuning the engine's settings and control mechanisms to synchronize with the electric motor, ensuring smooth operation between the two power sources.
8. **Compliance and Safety Standards:** Guaranteeing that all modifications and installations hold to pertinent safety regulations, standards, and certifications, particularly those concerning high-voltage electrical systems.

Effectively overcoming these technical challenges necessitates extensive engineering knowledge, integration proficiency, and thorough testing to deliver a hybrid vehicle conversion that is safe, dependable, and efficient.

10. Findings and Discussion

With sustainability and environmental awareness gaining momentum in the automobile industry, there's an increasing demand for greener mobility solutions to reduce vehicle emissions, particularly at the tailpipe level. While the government is considering promoting alternative fuels like CNG and ethanol, there's also a growing focus on innovations such as electrification solutions to meet the needs of long-distance vehicle users, for whom traditional petrol-driven vehicles may not be cost-effective.

The current electric vehicle technology, as well as anticipated advancements in the near future, presents challenges that require significant resolution efforts. Issues such as limited vehicle range, insufficient widespread recharging infrastructure, and the relatively slow recharge process impose significant constraints on electric vehicle usage. Moreover, for electric vehicles to be truly sustainable, the electricity used for recharging must primarily come from renewable or low-carbon emission energy sources. Additionally, electric vehicles still carry high costs, and concerns regarding the lifespan of batteries remain prominent. Consequently, a swift transition to fully electric mobility is not imminent, and there is limited time available before irreversible damage to the climate occurs.

A study conducted by researchers from the University of Salerno [78] proposes that one of the most sustainable solutions is to convert existing vehicles into environmentally friendly ones demonstrated that transforming a traditional vehicle into a plug-in-hybrid car represents one of the most sustainable options in the short term.

10.1 Aftermarket hybrid-electric retrofit solution

In response to this emerging demand and segment of car users, several innovative ideas have been proposed and introduced. Below is a brief overview of these ideas.

10.1.1 Folks Motor kit

Folks Motor, based in Delhi, has introduced an aftermarket hybrid-electric (xEV) retrofit solution for passenger vehicles, targeting cost-effectiveness for urban users with long commutes.

The Retrofit xEV platform from Folks Motor has been collaboratively developed with Automotive Research Association of India (ARAI), focusing on design, engineering, and validation (Fig. 16). This platform features a twin-regeneration xEV setup, intended for installation on conventional ICE vehicles, thereby converting them into hybrid-electric (xEVs) and enabling full-BEV (battery-powered electric vehicle) functionality within city limits. The retrofit kit comprises a motor, controller, and battery, seamlessly integrated into the existing driveline of manual-transmission cars, also providing automatic driving capability up to speeds of 30km/h.

Christened HyB Car Kit, this retrofit hybrid-electric (xEV) solution offers integration in a range of configurations, including series, parallel, or plug-in-hybrid layouts. Its objective is to reduce the current losses in a manual transmission (MT) car, which can amount to as much as 70 percent.

Folks Motor's retrofit hybrid-electric (xEV) platform is founded on a patented technology called 'Hybrid ReGeN Drive'. This platform encompasses 10 EV subsystems, featuring a traction motor, motor controller, electric vacuum pump, battery pack (8-10 kWh), retrofit gearbox, hybrid control unit, and a DC-DC converter.

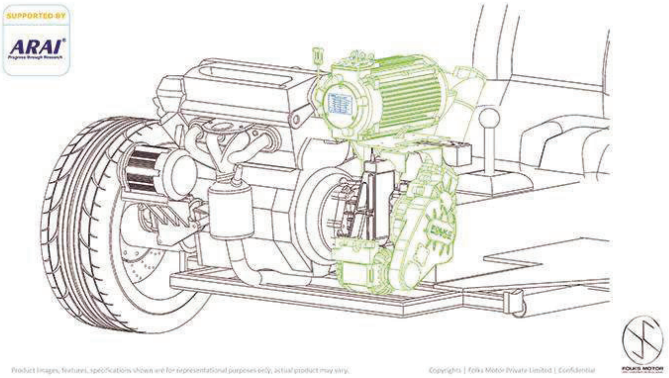


Fig. 16. ARAI developed solution

During the retrofit process, the new electric drivetrain is seamlessly integrated into the existing drivetrain of the vehicle, establishing hybrid mode as the default driving function. This eliminates the need to shift gears in traffic conditions, as the car can accelerate up to 30kph in a gearless driving fashion. The system operates as a series hybrid up to speeds of 30kph, transitioning to a parallel-hybrid arrangement thereafter.

Folks Motor claims that users can unlock a full-electric range of up to 50 km after approximately 70 km of hybrid driving, provided the battery pack is adequately replenished. Additionally, users have the option to charge the battery by connecting it to a wall socket, thus extending the range for driving in pure-EV mode.

The hybrid-electric system generates a power output of 30kW, equivalent to 40bhp (40 brake horsepower), with the electric charge sourced from a lithium-ion battery pack housed in the trunk. The battery capacity ranges from 8 to 10 kWh, depending on the size of the vehicle.

10.1.2 French firm solution

While not inexpensive, this technology will enable older vehicles to avoid emission regulations in French cities. It is anticipated that garages throughout France will soon be equipped to convert diesel and petrol cars into hybrid rechargeable vehicles, thereby lowering both fuel expenses and emissions.

A French company has developed a kit designed to be installed in various older vehicles, converting their internal combustion engines into plug-in hybrid cars (Fig. 17).

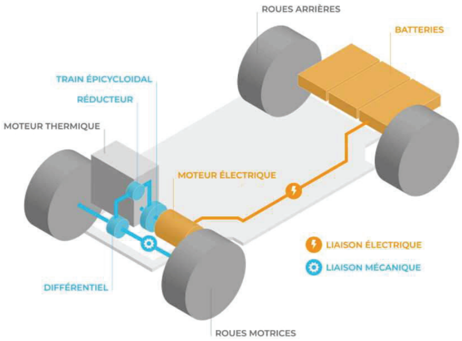


Fig. 17. French developed kit

10.1.3 REVR conversion kit

Once installed, the battery will provide cars with a range of 70 km before requiring a recharge, allowing them to access low-emission zones (ZFEs) in cities where they might otherwise be prohibited.

Initially targeted at city car drivers, such as hatchback owners, the kits will be available for installation in Renault Clio 3, Kangoo, Scenic, and Megane models, as well as Dacia Logan and Sandero cars in 2024. Peugeot, Citroën, and Ford cars will follow in 2025.

In 2023, the Australian national Dyson Award was won by RMIT University design student Alexander Burton for his creation, the bolt-on REVR retrofit kit. This kit aims to transform internal combustion engine (ICE) cars into practical and efficient hybrid vehicles. Burton is currently advancing the prototyping phase, focusing on the most mechanically intricate component of the system: a flat, power-dense, liquid-cooled 50-kW motor designed to fit snugly between the wheel and brake disc (Fig. 18).

Fig. 18. REVR conversion kit

The motor is a pancake-style axial flux design, featuring a flat stator plate bolted to stationary points on the rear of the wheel hub. The rotor, another flat plate, transmits torque via the wheel bolts. While adapter plates tailored to each car model will be necessary, their construction is expected to be straightforward, and motor installation should be a quick 10-minute task, requiring no specialized expertise. The battery pack, along with the motor controllers, will be housed in the trunk well, typically reserved for the spare tire (Fig. 19).

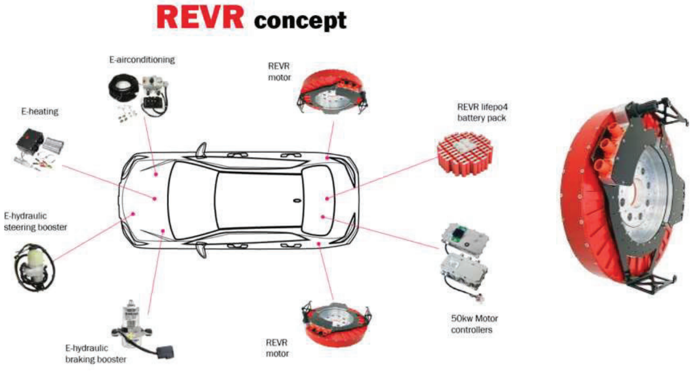


Fig. 19. REVR concept

Burton estimates that the circular area can accommodate approximately a 15-kWh battery pack, sufficient for over 100 km (62 miles) of all-electric range during stop-and-go city driving, aided by regenerative braking. This range would cover the majority of daily driving needs for most individuals.

The REVR (Rapid Electric Vehicle Retrofits) kit preserves the majority of the original car's components; it's engineered to operate either in parallel with the combustion engine or independently. To activate the electric drive, you'll turn the ignition key to the "on" position and toggle a separate switch. If you wish to start the combustion engine simultaneously, you'll turn the key slightly further.

When the internal combustion engine (ICE) is inactive, the large battery pack will maintain the charge of your standard 12-V battery, ensuring that your headlights and other 12-V electrical systems remain operational. Additionally, the kit will provide electric alternatives or enhancements for components such as air conditioning, heating, power steering, and brake boosters, which typically rely on belts driven by the engine (Fig. 20).

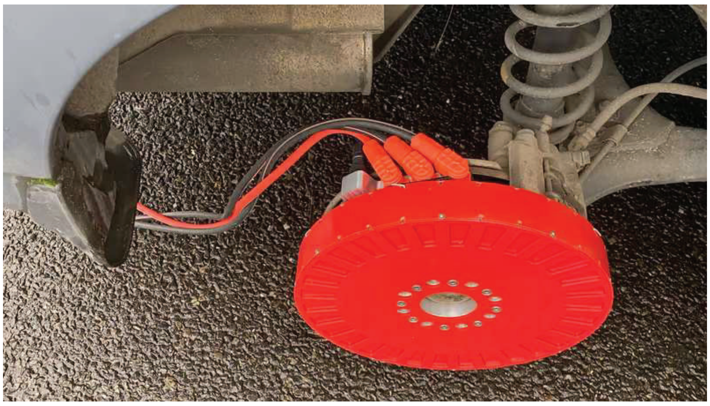


Fig. 20. REVR kit installed on car wheel

10.2 Automotive research

Numerous renowned automotive research institutions and organizations worldwide are dedicated to advancing research, development, and innovation within the automotive sector. These entities typically focus on diverse areas of automotive technology, encompassing electric and hybrid vehicles. Here are some notable automotive research institutions:

1. **The Center for Automotive Research (CAR):** CAR, situated in the United States, is an independent, non-profit organization specializing in research across various automotive and mobility domains, with a particular emphasis on alternative propulsion systems. (https://www.cargroup.org/)

2. **The International Council on Clean Transportation (ICCT):** ICCT is a global research organization with a focus on mitigating the environmental footprint of transportation. Their research primarily centers on clean vehicle technologies, encompassing electric and hybrid vehicles. (https://theicct.org/)

3. **The Fraunhofer Society for the Advancement of Applied Research:** Fraunhofer, a prominent research institution in Germany, is renowned for its work across diverse domains, including automotive technology. They specialize in developing innovative solutions for sustainable and efficient transportation. (https://www.fraunhofer.de/en.html)

4. **The Electric Power Research Institute (EPRI):** EPRI, headquartered in the United States, is an organization dedicated to researching electricity generation, distribution, and utilization. Additionally, they focus on researching electric vehicle technologies and infrastructure. (www.epri.com)

5. **The Automotive Research Association of India (ARAI):** ARAI stands as one of India's foremost automotive research organizations. They specialize in researching automotive technologies, encompassing electric and hybrid vehicles, and offer certification services. (https://www.araiindia.com/)

6. **The Institute for Automotive Engineering (ika):** Situated in Germany, ika is affiliated with RWTH Aachen University and is engaged in researching diverse automotive technologies, with a focus on electric mobility and advanced vehicle concepts. (www.ika.rwth-aachen.de)
7. **The European Commission's Joint Research Centre (JRC):** The JRC undertakes research across a broad spectrum of subjects, including sustainable mobility and transport, and produces reports and studies concerning electric and hybrid vehicles. (www.commission.europa.eu) - joint-research-centre
8. **The National Renewable Energy Laboratory (NREL):** NREL, situated in the United States, specializes in renewable energy research, with a particular emphasis on electric vehicle technology and charging infrastructure. (www.nrel.gov)
9. **The Automotive Research & Testing Center (ARTC):** ARTC, headquartered in Taiwan, provides research and testing services tailored to the automotive industry, with a specific focus on electric and hybrid vehicle technologies. (www.artc.org.tw/en)
10. **The Centre for Connected and Autonomous Automotive Research (CCAAR):** CCAAR, situated in the UK, specializes in connected and autonomous vehicle technologies, although its research frequently intersects with electric and hybrid vehicle studies. (www.coventry.ac.uk)

These examples represent just a fraction of the numerous automotive research institutions globally. Each of these organizations plays a vital role in driving forward automotive technology, including research pertaining to electric and hybrid vehicles.

10.3 Challenges with conversion

Transforming gasoline cars into electric-hybrid vehicles poses various challenges, encompassing both technical and practical aspects. Below are some of the primary challenges linked to these conversions:

1. **Integration of Electric Components:** Incorporating electric components such as an electric motor, battery pack, power electronics, and control systems into a vehicle through retrofitting demands detailed integration with the existing vehicle structure. Addressing challenges related to space limitations, weight distribution, and compatibility is crucial in this process.
2. **Drivetrain Compatibility:** Aligning the electric motor with the vehicle's drivetrain can be complicated. This may demand adjusting the transmission or substituting drivetrain components to ensure compatibility and optimize power transmission efficiency.
3. **Battery Placement:** Determining a suitable location for the battery pack can pose challenges. Batteries are both heavy and bulky, and their placement can impact vehicle balance, handling, and overall safety.
4. **Cooling and Thermal Management:** During operation, electric motors and battery packs produce heat. It is crucial to implement effective cooling and thermal

management systems to prevent overheating and uphold optimal performance and safety.

5. **High-Voltage Systems:** Operating at high voltages, electric and hybrid vehicles present safety challenges. To safeguard occupants and technicians from electrical hazards, it is essential to implement proper insulation, shielding, and comprehensive safety measures.
6. **Control Systems Integration:** The integration of control systems that manage the interaction between the internal combustion engine (if retained) and the electric components is complex. Calibrating these systems to achieve optimal performance and efficiency presents a significant challenge.
7. **Safety and Regulatory Compliance:** Retrofit conversions must comply with safety standards and emissions regulations. Ensuring that the converted vehicles meet these requirements can be technically demanding and may necessitate extensive testing and certification processes.
8. **Cost:** Equipping vehicles with electric components through retrofitting can incur high costs. Expenses related to electric components, labor, and system integration may serve as a substantial obstacle to widespread adoption.
9. **Warranty and Reliability:** Retrofit conversions could potentially void the original vehicle warranty, underscoring the importance of ensuring the long-term reliability of the hybrid system to maintain user satisfaction.
10. **Charging Infrastructure:** Adapting a vehicle to a plug-in hybrid typically involves installing a charging system and related components, a process that can be both challenging and costly. The feasibility and expense are often contingent on the accessibility of charging infrastructure.
11. **Space Constraints:** Securing sufficient space for installing electric components and batteries without encroaching on passenger or cargo room can pose a significant challenge, especially in smaller vehicles.
12. **Engineering Expertise:** Successfully retrofitting vehicles necessitates specialized engineering proficiency and access to suitable tools and equipment. Competent technicians and engineers are necessary for achieving effective conversions.
13. **Environmental Impact:** The environmental advantages of retrofitting can fluctuate. Factors such as the origin of electricity utilized for charging can influence the overall environmental footprint, potentially resulting in different outcomes compared to new electric vehicles.
14. **Regulatory Approval:** Depending on the jurisdiction, retrofitting a vehicle with electric components may necessitate regulatory approval or certification, adding complexity to the process.

Considering these challenges, retrofitting gasoline cars to electric-hybrid configurations is typically most suitable for specialized projects conducted by seasoned professionals or organizations possessing the requisite expertise in automotive engineering and electric vehicle technology.

10.4 Fossil fuel cars Vs. Electric hybrid cars

Contrasting fossil fuel cars (gasoline or diesel) with electric hybrid cars unveils numerous notable distinctions regarding their power sources, efficiency, environmental footprint, and performance. Here's a breakdown comparing the two vehicle types (Fig. 21):

Fig. 21. Internal combustion car Vs. El-Hybrid car

1. **Power Source:**
    - Fossil Fuel Cars: Fossil fuel cars operate exclusively on internal combustion engines fueled by gasoline or diesel.
    - Electric Hybrid Cars: Electric hybrid cars integrate two power sources – an internal combustion engine (typically gasoline) and an electric motor driven by a battery.
2. **Fuel Efficiency:**
    - Fossil Fuel Cars: Typically exhibit lower fuel efficiency when contrasted with electric hybrids. Their reliance solely on the combustion of fossil fuels tends to be less efficient.
    - Electric Hybrid Cars: Enjoy enhanced fuel efficiency thanks to the support of the electric motor. Hybrid systems optimize power distribution, resulting in improved fuel economy.
3. **Emissions:**
    - Fossil Fuel Cars: Release greenhouse gases such as carbon dioxide (CO_2), nitrogen oxides (NOx), carbon monoxide (CO), volatile organic compounds (VOCs), and particulate matter (PM), thereby exacerbating air pollution and climate change.
    - Electric Hybrid Cars: Emit fewer pollutants in comparison to pure gasoline or diesel vehicles. Hybrid systems facilitate regenerative braking, minimizing emissions during urban driving. Plug-in hybrid variants have the capability to operate solely on electric power, resulting in zero tailpipe emissions.
4. **Environmental Impact:**
    - Fossil Fuel Cars: Pose a substantial environmental burden attributable to their role in intensifying air pollution and greenhouse gas emissions.

    - Electric Hybrid Cars: Generally, exhibit a reduced environmental footprint, particularly when operating in electric mode. Plug-in hybrids can further mitigate their impact when powered by renewable energy sources.

5. **Fuel Costs:**
    - Fossil Fuel Cars: Rely on gasoline or diesel fuel, which can incur significant costs and are susceptible to price fluctuations.
    - Electric Hybrid Cars: Present opportunities for fuel savings owing to their enhanced efficiency. Plug-in hybrids may enjoy reduced electricity expenses when charging during off-peak periods.
6. **Maintenance:**
    - Fossil Fuel Cars: Generally, entail higher maintenance needs due to the difficulties of internal combustion engines, encompassing tasks such as oil changes, exhaust system repairs, and more.
    - Electric Hybrid Cars: Often incur lower maintenance expenses, attributed to features like regenerative braking (which minimizes wear on brake components) and the reduced number of moving parts in the electric motor.
7. **Performance:**
    - Fossil Fuel Cars: Typically provide a diverse array of engine choices, encompassing high-performance variations. Acceleration and top speeds can be notably impressive.
    - Electric Hybrid Cars: Combine electric and gasoline power, delivering commendable acceleration and responsiveness while potentially limiting fuel consumption.
8. **Range:**
    - Fossil Fuel Cars: Generally, boast longer driving ranges on a full tank of gasoline or diesel fuel.
    - Electric Hybrid Cars: Present constrained electric-only ranges, which may fluctuate based on the model. Plug-in hybrids may feature extended electric-only ranges when the battery is fully charged.
9. **Charging vs. Refueling:**
    - Fossil Fuel Cars: Refueling at gas stations is swift and widely accessible.
    - Electric Hybrid Cars: Charging requirements vary depending on the hybrid type. Conventional hybrids do not necessitate external charging, whereas plug-in hybrids rely on access to electric charging infrastructure.

In the end, the decision between a fossil fuel car and an electric hybrid car hinge on personal preferences, driving habits, environmental considerations, and access to charging facilities. Electric hybrid vehicles represent a middle ground, blending the advantages of electric vehicles (reduced emissions and enhanced efficiency) with the convenience associated with traditional fossil fuel cars (extended driving ranges and rapid refueling).

10.5 Pros and cons of electric hybrid cars

Electric hybrid cars present a fusion of electric and internal combustion engine (ICE) power sources, resulting in a distinct array of benefits and drawbacks. Below is an overview of the advantages and disadvantages of electric hybrid cars:

10.5.1 Advantages of Electric Hybrid Cars

1. **Improved Fuel Efficiency:**
    - Hybrid systems optimize power delivery, enhancing fuel economy compared to traditional ICE-only vehicles. This optimization can translate into notable fuel savings, particularly during city driving.
2. **Reduced Emissions:**
    - Hybrid cars emit fewer greenhouse gas emissions and air pollutants than conventional ICE vehicles. Features such as regenerative braking and electric-only driving modes contribute to reduced emissions, especially in urban traffic conditions.
3. **Lower Operating Costs:**
    - Decreased fuel consumption and reduced frequency of brake and engine maintenance can result in lower overall operating expenses.
4. **Enhanced Performance:**
    - Electric motors deliver instantaneous torque, enhancing acceleration and overall vehicle performance.
5. **Quiet Operation:**
    - Hybrid cars frequently operate quietly in electric-only mode, thereby diminishing noise pollution in urban environments.
6. **Regenerative Braking:**
    - Regenerative braking captures energy during deceleration, storing it in the battery and thereby enhancing efficiency.
7. **Reduced Dependence on Fossil Fuels:**
    - Hybrid cars consume less gasoline, diminishing reliance on fossil fuels and potentially reducing the carbon footprint.
8. **Potential Tax Incentives:**
    - In certain regions, hybrid vehicles may qualify for tax incentives or rebates intended to encourage the use of fuel-efficient and low-emission vehicles.

9. **Plug-In Hybrid Option:**
    - Plug-in hybrid versions provide extended electric-only driving ranges when charged, further diminishing emissions and fuel consumption.

10.5.2 Disadvantages of Electric Hybrid Cars

1. **Higher Initial Cost:**
    - Electric hybrid cars typically entail higher upfront costs compared to traditional gasoline or diesel vehicles, although this price gap is diminishing.
2. **Limited Electric-Only Range:**
    - Non-plug-in hybrid models have limited electric-only ranges, primarily assisting the internal combustion engine (ICE). Pure electric vehicles (EVs) provide longer electric ranges.
3. **Complexity:**
    - Hybrid systems can be intricate, involving multiple components and systems that may necessitate specialized maintenance.
4. **Reduced Trunk Space:**
    - The incorporation of battery packs and hybrid components can diminish trunk space in certain hybrid models.
5. **Charging Infrastructure (for Plug-Ins):**
    - Plug-in hybrid models necessitate access to electric charging infrastructure for prolonged electric-only driving, which may not be widely available in all areas.
6. **Battery Degradation:**
    - Over time, the battery's capacity may degrade, resulting in a diminished electric-only driving range. Battery replacement can be costly.
7. **Environmental Impact (Manufacturing):**
    - The production of hybrid batteries can have an environmental impact due to resource extraction and manufacturing processes.
8. **Dependency on Electricity Grid (for Plug-Ins):**
    - The environmental benefits of plug-in hybrids depend on the availability of a stable and clean electricity grid, as well as the source of electricity used for charging.
9. **Complex Transmission:**
    - Maintenance or replacement of specialized transmissions, such as CVTs, may be necessary for some hybrid vehicles.

Choosing between an electric hybrid car and other vehicle types depends on individual priorities, driving habits, and access to charging facilities. Electric hybrids are ideal for those seeking to lower fuel consumption and emissions without fully transitioning to electric vehicles (EVs).

10.6 Cost analysis

Analyzing the cost of converting a fossil fuel car to a hybrid entail evaluating various expenses such as part costs, labor, and potential alterations in operational expenses. Below is a comprehensive breakdown, accompanied by a numerical illustration.

10.6.1 Cost Analysis Components

1. **Parts**
    - **Electric Motor**: Needed to provide additional power.
    - **Battery Pack**: Essential for storing electrical energy.
    - **Power Electronics**: Includes inverters and controllers to manage the power flow between the engine, motor, and battery.
    - **Adapters and Mounting Kits**: Necessary for fitting new components into the existing vehicle framework.
2. **Labor**
    - **Installation**: Significant labor costs are involved in retrofitting a vehicle, which requires skilled technicians.
    - **Engineering and Design**: Costs incurred in planning and designing the retrofit system for different car brands and specifications to ensure compatibility and safety.
3. **Operational Cost Changes**
    - **Fuel Savings**: Hybrids typically use less fuel, so this should be accounted for in the long-term savings.
    - **Maintenance**: May decrease due to less wear on the internal combustion engine, but this could be offset by the need to maintain new electrical components.

10.6.2 Numerical Illustration

Suppose we consider the following prices and costs for converting a mid-sized sedan car (e.g. BMW 5-serie and Mazda 3) based on global average cost values:

<u>Parts Costs</u>

- **Electric Motor**: 15,000 SEK
- **Battery Pack**: 40,000 SEK (for adequate range and durability)

- **Power Electronics**: 15,000 SEK
- **Adapters and Mounting Kits**: 5000 SEK

Labor Costs

- **Installation Labor**: 10,000 SEK (complex integration work)
- **Engineering and Design**: 5000 SEK (pre-installation work)

Total Retrofit Cost

Total Retrofit Cost=Parts Costs + Labor

Parts Costs=15,000+40,000+15,000+5000=75,000 SEK

Labor Costs=10,000+5000=15,000 SEK

Total Retrofit Cost=75,000+15,000=90,000 SEK

Operational Savings

Suppose the vehicle drives 20,000 km a year and achieves an improvement from 9.5 l/100km to 7,2 l/100km with the hybrid system.

Original Fuel Costs (per year): Fuel Cost= (20,000 km × 9.5 l/100km) × 19 SEK/l = 36,100 SEK

New Fuel Costs (per year): New Fuel Cost= (20,000 km × 7.2 l/100km) × 19 SEK/l =27,360 SEK

Annual Fuel Savings: Annual Savings=36,100 – 27.360 = 8740 SEK

Payback Period

Payback Period=Total Retrofit Cost/Annual Savings

Payback Period=90,000/8,740≈11 years

Converting a fossil fuel car to a hybrid entails significant initial expenses, with a comparatively extended period for recovering the investment solely through fuel savings. While environmental advantages and potential longevity enhancements due to reduced engine strain could convince the decision, the financial appeal might be limited, particularly if more affordable or efficient new hybrids exist.

Evaluating the financial dynamics between fossil fuel cars and electric hybrid cars entails analyzing their acquisition expenses, operational outlays, upkeep costs, and possible tax advantages or encouragements. Below is a comprehensive breakdown of these aspects, followed by an illustrative numerical scenario.

10.6.3 Economic Factors to Consider

1. **Purchase Price**
    - **Fossil Fuel Cars**: Generally cheaper than hybrids in terms of upfront cost.

    - **Hybrid Cars**: More expensive due to additional components like batteries and electric motors.

2. **Fuel Costs**
    - **Fossil Fuel Cars**: Depend on gas prices, which can be unpredictable.
    - **Hybrid Cars**: Use less fuel and partly rely on electricity, potentially offering significant savings if fuel prices are high.
3. **Maintenance Costs**
    - **Fossil Fuel Cars**: Maintenance revolves around engine and related components.
    - **Hybrid Cars**: While hybrid vehicles may demand less frequent maintenance owing to decreased engine wear, the expenses associated with servicing or substituting batteries and other electronic parts can be higher.
4. **Tax Incentives and Rebates**
    - Authorities might provide motivations for acquiring hybrid automobiles, mitigating the elevated buying cost.
5. **Resale Value**
    - **Hybrid Cars**: Could maintain a superior resale worth because of their perceived economic advantages and attractiveness, particularly as fuel costs increase.

10.6.4 Numerical Illustration

Let's contrast the expenses over a five-year span for a standard mid-sized fossil fuel vehicle and an equivalent hybrid.

Assumptions:

- **Annual Mileage**: 20,000 miles
- **Fuel Cost (Gasoline)**: 19 SEK/l
- **Fuel Cost (Electricity for Hybrid)**: Equivalent to 5 SEK per liter of gasoline in energy terms.
- **Fuel Economy (Fossil Fuel Car)**: 9.5 l/100 km
- **Fuel Economy (Hybrid Car)**: 4.5 l/100km (combined fuel and electric)

Initial Purchase Price:

- **Fossil Fuel Car**: 250,000 SEK
- **Hybrid Car**: 500,000 SEK

Annual Fuel Costs:

- **Fossil Fuel Car**: 200 × 9.5 × 19 = 36,100 SEK per year

- **Hybrid Car**: 200 × 4.5 × 5 = 4,500 SEK per year

Total Fuel Costs Over 8 Years:

- **Fossil Fuel Car**: 36,100×8 = 288,800 SEK
- **Hybrid Car**: 4,500×5 = 36,000 SEK

Total Costs Over 5 Years (Excluding Maintenance and Tax Incentives):

- **Fossil Fuel Car**: 250,000+288,800 = 538,800 SEK
- **Hybrid Car**: 500,000+36,000 = 536,000 SEK

Over a eight-year period, the total cost of ownership for both the fossil fuel car and the hybrid car becomes comparable, with the hybrid slightly cheaper by 2000 SEK, assuming no major maintenance costs or battery replacements are required. However, this straightforward analysis does not take into account potential savings from maintenance, differences in resale value, or tax incentives, all of which could further favor the hybrid. The break-even point may vary depending on actual fuel prices, mileage, and specific vehicle models.

This example demonstrates the potential long-term economic viability of hybrid cars, especially when factoring in increasing fuel costs and potential environmental regulations affecting the operational expenses of fossil fuel vehicles.

11 Conclusions

Environmental sustainability was marked years ago by the adoption of the three Rs: Reduce, Recycle, and Reuse. These principles are applicable across all industrial sectors and, indeed, in the broader scope of human development. A recent study, commissioned by the United Nations and published by the Intergovernmental Panel on Climate Change, has underscored the urgency of our situation. Humanity now has limited time to safeguard the environment and limit global warming to a maximum of 1.5 degrees Celsius. Consequently, we are compelled to implement immediate solutions to preserve the environment and secure the survival of all species on Earth.

The transportation besides Industry and Power sectors stands out as one of the most significant contributors to CO2 emissions, accounting for almost 30% of emissions in Europe alone. While CO_2 emissions have a worldwide impact, vehicles also release pollutants like CO, NOx, and particulate matter, which directly harm human health and have localized effects. As new, stricter limits are imposed on CO_2 emissions and pollutants for new vehicles, including hybrid models, there's a growing momentum toward the shift to fully electric mobility, promising cleaner and more sustainable transportation solutions.

In addition, the current state of electric vehicle technology, as well as foreseeable advancements, presents complex challenges requiring thoughtful solutions. Issues such as limited range, sparse recharging infrastructure, and relatively slow recharge times significantly constrain electric vehicle usability. Moreover, for electric vehicles to truly offer a sustainable alternative, the electricity they consume must predominantly stem from renewable or low-carbon energy sources. High upfront costs and concerns regarding battery lifespan further complicate widespread adoption. Given these hurdles, a prompt transition to purely electric mobility isn't imminent, and the window to avert irreversible climate damage is narrowing. One promising avenue toward sustainability involves retrofitting existing vehicles to be more environmentally friendly called El-Hybrid cars.

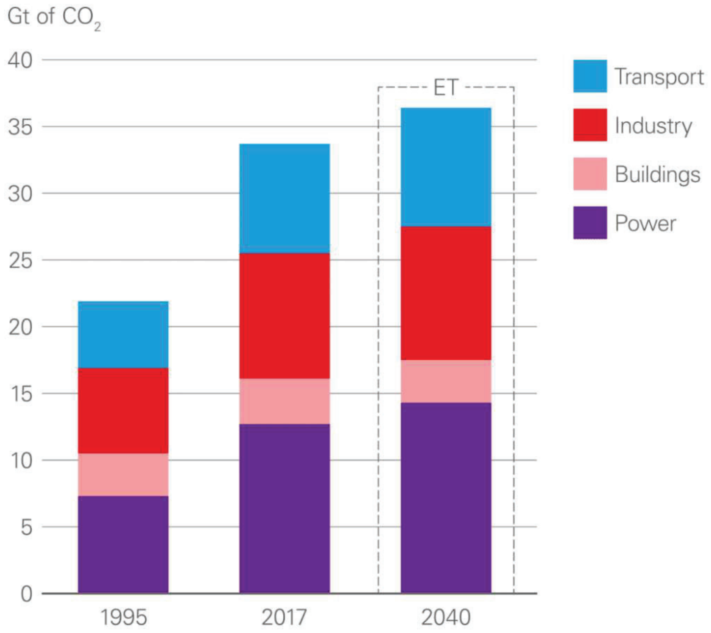


Fig. 22. Main sources of CO_2 emissions [78]

11.1 Considerations

- **Legality and Compliance**: Any conversion kit must adhere to local vehicular regulations, encompassing safety, emissions, and roadworthiness standards.
- **Technical Support and Warranty**: Access to technical support for installation and maintenance is essential, as is understanding how such a conversion might impact the vehicle’s existing warranty.
- **Cost vs. Benefit**: The cost of the kit and installation should be compared with the anticipated fuel savings and environmental advantages. Sometimes, it may be more cost-effective or feasible to buy a new hybrid or electric vehicle instead of converting an older gasoline model.

Before undertaking a conversion, it's wise to seek advice from a professional to assess your vehicle's suitability, estimate the total cost, and anticipate the performance post-conversion. Also, staying updated on the latest kits and solutions available in the market can offer more current options, as the technology and availability of these kits are continuously advancing.

11.2 Challenges of converting a conventional vehicle to a hybrid vehicle

Converting a vehicle from a conventional internal combustion engine to an El-hybrid one offers a significant advantage in terms of time-to-market compared to new developments. This approach entails minimal modifications to the major systems, such as the body in white and battery, resulting in a shortened development period. For vehicles with a limited range, separate battery packs can be installed in the trunk and original engine bay. Alternatively, for greater range, a common method involves placing a battery pack under the floor, necessitating the lifting of the body to maintain the original ground clearance. The primary objective of the new chassis system is to ensure consistent vehicle dynamics between the hybrid and original vehicles [79].

11.3 Insights from Case Studies and numerical illustrations

The studied case studies underscore several key insights:

- Technical Feasibility: Converting gasoline cars into hybrids is technically feasible and offers substantial advantages in fuel efficiency and emission reduction.
- Cost and Complexity: Initial expenses and technical complexities associated with conversions may restrict their suitability to scenarios where benefits outweigh costs.
- Tailored Solutions: Each conversion necessitates customization to suit the vehicle and its intended use, demanding substantial engineering proficiency.
- Policy Influence: Supportive policies and encouragements are pivotal in enhancing the viability and attraction of such conversions.

Modular concept: Research and dialog with industrial partners and manufacturers is necessary and recommended that play a pivotal role in the development of a compatible and modular powertrain suitable for retrofitting vehicles in subsequent phases of their lifecycle. This collaborative effort involves a comprehensive exploration of existing vehicle architectures, component specifications, and integration requirements.

The process begins with in-depth research into the design and engineering specifications of various vehicle models, both current and legacy, to identify commonalities and areas for standardization. This includes studying the layout of drivetrains, engine compartments, chassis configurations, and electrical systems to devise a versatile powertrain that can seamlessly integrate into diverse vehicle platforms.

Engaging in dialogue with industrial partners and manufacturers is essential to leverage their expertise in component manufacturing, supply chain logistics, and production capabilities. By collaborating closely with these stakeholders, specific design parameters and standards can be established to ensure compatibility and scalability across different vehicle types and brands.

The goal is to create a powertrain solution that is not only technically feasible but also economically viable for retrofitting purposes. This involves evaluating the cost-effectiveness of components, considering factors such as production scalability, procurement costs, and maintenance requirements.

Furthermore, the emphasis on modularity ensures that the powertrain can be easily adapted and upgraded as technology advances, allowing for efficient lifecycle management and futureproofing against evolving market demands and regulatory requirements.

Through this collaborative research and dialog, a forward-thinking approach to powertrain design is fostered, promoting sustainable mobility solutions and extending the usability and environmental performance of vehicles throughout their lifecycle.

11.4 Suggestion for continuing and future work

Investigating with industrial partners and manufacturers to design a compatible and modular powertrain for retrofitting involves a strategic and collaborative approach. This effort encompasses several key aspects aimed at ensuring the successful integration of new components into existing vehicle platforms:

1. **Technical Compatibility Analysis**: The first step involves conducting a thorough analysis of the existing vehicle architectures and powertrain configurations. This includes examining engine compartments, drivetrain layouts, chassis designs, and electrical systems to identify areas for integration and potential challenges.
2. **Component Standardization**: Collaborating with industrial partners and manufacturers allows for the development of standardized components that can be universally applied across different vehicle models and brands. This approach streamlines the retrofitting process by reducing the need for customizations and modifications.
3. **Modular Design Principles**: Emphasizing modularity in powertrain design enables the creation of interchangeable components that can be easily adapted to various vehicle types. Modular design facilitates scalability, flexibility, and future upgrades, providing a versatile solution for retrofitting initiatives.
4. **Integration Feasibility Studies**: Working closely with manufacturers helps assess the feasibility of integrating new technologies, such as electric motors, battery packs, and control systems, into existing vehicle platforms. This involves evaluating performance metrics, safety standards, and regulatory requirements.
5. **Cost-Effectiveness Evaluation**: Collaborative investigations focus on optimizing the cost-effectiveness of retrofitting solutions. This includes analyzing production costs, supply chain logistics, and economies of scale to ensure competitive pricing and affordability for end-users.
6. **Lifecycle Assessment**: Understanding the lifecycle impacts of retrofitting efforts is essential. Through dialog with partners, considerations such as environmental sustainability, resource efficiency, and end-of-life disposal are addressed to promote responsible and eco-friendly practices.
7. **Market Readiness and Adoption**: Industrial partnerships contribute to assessing market readiness and consumer adoption of retrofitting technologies as well. Engaging manufacturers helps identify market trends, customer preferences, and regulatory landscapes to align retrofitting initiatives with market demands.

By leveraging collaborative investigations with industrial partners and manufacturers, the development of a compatible and modular powertrain for retrofitting becomes a comprehensive and inclusive process. This approach fosters innovation, efficiency, and sustainability in the evolution of automotive technology toward greener and more adaptable mobility solutions.

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Appendix

The following images depict the El-Hybrid version of Volvo XC60 cars. As shown, the most space-consuming component of the system is the battery pack, situated under the floor and in the middle of the car. In contrast, the electric drive train is positioned next to the engine and has been integrated with other components.