Reducing fuel consumption: Biofuels and high efficiency engines are becoming a real solution to mitigate transport emissions

Reducir el consumo de combustibles: Los biocombustibles y los motores de gran eficiencia pueden ser una solución real para ayudar a mitigar las emisiones en el sector del transporte

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Resumen

Este documento ofrece una revisión exhaustiva de las estrategias y tecnologías actuales destinadas a descarbonizar el sector del transporte, con especial atención a los desafíos y oportunidades que plantean las nuevas regulaciones, los avances tecnológicos y los factores socioeconómicos. Examina las limitaciones de depender exclusivamente de la electrificación, y destaca la importancia continua de los vehículos híbridos y los combustibles alternativos como el biogás, el bioetanol y el biodiésel para lograr reducciones significativas en las emisiones de gases de efecto invernadero. El análisis subraya la necesidad de soluciones pragmáticas y multitecnológicas que consideren las limitaciones del mundo real, como la disponibilidad de infraestructura, el poder adquisitivo y la edad promedio de las flotas de vehículos. En el presente documento se destaca la importancia de la acción coordinada entre los responsables políticos, los fabricantes y los consumidores, y se aboga por marcos de políticas que incentiven la adopción de vehículos eficientes con base en su desempeño real en materia de emisiones. Conseguir un enfoque equilibrado y flexible, respaldado por la innovación, incentivos específicos y clasificaciones ambientales precisas es esencial para avanzar hacia la neutralidad climática, manteniendo al mismo tiempo la movilidad y la estabilidad económica.

Palabras clave

Descarbonización, biocombustibles, hibridación, motores y eficiencia.

Abstract

This document provides a comprehensive review of current strategies and technologies aimed at decarbonizing the transport sector, with a particular focus on the challenges and opportunities posed by new regulations, technological advancements, and socioeconomic factors. It examines the limitations of relying solely on electrification, highlighting the continued importance of hybrid vehicles and alternative fuels such as biogas, bioethanol, and biodiesel to achieve meaningful reductions in greenhouse gas emissions. The analysis underscores the need for pragmatic, multi-technology solutions that account for real-world constraints, including infrastructure availability, purchasing power, and the average age of vehicle fleets. In the present document it is stressed the importance of coordinated action among policymakers, manufacturers, and consumers, and calls for policy frameworks that incentivize the adoption of efficient vehicles based on actual emissions performance. A balanced, flexible approach —supported by innovation, targeted incentives, and accurate environmental classifications— is essential for advancing toward climate neutrality while maintaining mobility and economic stability.

Keywords

Decarbonization, biofuels, hybridization, engines, and efficiency.

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1. INTRODUCTION

The ongoing rise in greenhouse gases (GHG) and their negative impacts on the global climate exert substantial pressure on politicians and policy-makers to implement regulations to decrease fossil fuel consumption and increase energy efficiency. Different strategies can be implemented to reduce fossil fuel demand, such as promoting renewable energy sources, investing in advanced technologies, developing sustainable transportation options, encouraging the use of hybrid and electric vehicles, and enhancing public transportation systems. By fostering a conservation culture and supporting policies that prioritize environmental sustainability, a more sustainable energy future, one that decreases our reliance on fossil fuels, seems an achievable goal. However, the transition to a decarbonized economy presents numerous challenges, making the goal of achieving net-zero emissions increasingly difficult. The elimination of GHG emissions associated with the industrial sector, such as the cement industry, metal refining, and steel production, is not currently possible. The freight transport sector lacks a viable alternative to diesel fuel for trucks, and the electrification of heavy-duty vehicles over long distances is not currently feasible. Although some strategies, such as the attenuation of CO_2 emissions through reforestation and carbon capture and storage, help avoid the accumulation of CO_2 in the atmosphere, greater efforts are needed globally to achieve a significant impact on the climate. Recognizing the existing problem that some CO_2 emissions are difficult to abate, the goal of achieving climate neutrality appears to be an aspirational target rather than a realistic objective. Technologies such as carbon capture and storage, as well as carbon utilization, are required to offset atmospheric CO_2 from the carbon balance (Schenuit et al., 2023) but are linked to a higher energy demand and therefore an increase in the price of goods.

Data reported from Statista in 2024 (Statista, 2024) indicated that more than 80% of the global energy demand was covered by coal, oil, and gas, accounting for a total value of 301.1 MMboe daily, giving a clear idea of the challenge to be faced when considering the substitution by renewable sources if nuclear power is not brought into the scene. Real possibilities of attaining decarbonization may be blown off by reality. One of the most aggressive European measures established for reducing carbon emissions is the Fit for 55 package, which is a set of regulations intended to reduce greenhouse gas emissions by at least 55% by 2030, using as a base those produced in 1990, thus initiating a route towards climate neutrality by 2050 (Council of the European Union, n.d.). The goals of the package are ambitious and may be considered overly optimistic. In addition, a fact that should not be disregarded is the high cost associated with decarbonization technologies, and that many of them are not yet mature enough to assume that a fast and smooth transition will occur in the short term (González & Gómez, 2024). The package addresses restrictions in the transport sector by regulating CO_2 emissions for passenger cars and vans, implementing new rules for alternative fuel infrastructure, and introducing new legislation applicable to the maritime and aviation sectors (Erbach & Jensen, 2024).

Regulation (EU) 2019/631 (European Parliament & Council of the European Union, 2019) is an example of the strict measures implemented to limit CO_2 emissions in the transport sector. New passenger cars and vans must comply with new CO_2 emission performance standards, with targets being continuously strengthened until 2030, and a 100% reduction in emissions is expected to be reached by 2035. Target levels for the period 2020-2024 were set at 95 g CO_2/km for cars and 147 g CO_2/km for vans, as measured by the NEDC emission test procedure. For the following years, that is, between 2025 and 2034, it was expected that these targets (measured on the WLTP cycle [Worldwide Harmonized Light Vehicles Test Procedure]) reached a value of 93,6 g CO_2/km (2025-2029) and reduced to 49,5 g CO_2/km (2030-

2034) in the case of passenger cars (European commission, n.d.). The recent delay in applying this regulation to give a "breathing space" to car manufacturers is clear evidence of the intricate connections between the economy and GHG emissions (France24, 2025), demonstrating the need for careful assessment when implementing excessively aggressive targets that may risk one of the basic principles of the Fit for 55 package, which is based on a just transition. Efforts are being made by car manufacturers, as exemplified by the decrease in mean CO_2 emissions of passenger cars registered yearly in Spain, which has dropped from 173 g CO_2/km in 2009 to 116 g CO_2/km in 2024 (ANFAC, 2024a).

The electrification of the transport sector will unfold at a different pace in the global north, based on the availability of subsidies, public acceptance, and the mean income of citizens. Solutions for reducing fuel consumption must be global and consider all variables and parameters of the equations without focusing on regions with specific characteristics that are not easily extrapolated. Therefore, electric vehicles (EVs) may be an excellent mobility option, but they are far from being considered an adequate global solution (Morán et al., 2024). Car manufacturers are making significant efforts to reduce fuel consumption and increase security for drivers and pedestrians by introducing safety driving devices in new passenger cars. These efforts, along with the devices required for pollution control, result in an unavoidable increase in car prices. These higher prices are likely one of the primary reasons for the ongoing increase in the average age of vehicle fleets worldwide. In the case of Spain, this age has increased from 8 years in 2007 to 14.5 years in 2024, one of the oldest in the European Union (ANFAC, 2024a). But the Spanish fleet is just following the same trend experienced by other countries. The average age of the U.S. fleet has increased from 11.2 years in 2012 to 14 years in 2024 (Fitzgerald, 2024). Despite the different explanations behind this phenomenon, the evident conclusion is that any efforts to implement stricter regulations have the risk of being offset by the aging of the circulating fleet.

The adoption of electric vehicles in Spain is discouraging if compared with neighbouring countries, such as Portugal. In this latter country, the market shares of EVs sold in December 2024 reached an impressive value of 25.4% and the share of PHEV accounted for 12.3% (total of 37.7%) (European Alternative Fuels Observatory), whereas in Spain, the total share of EV + PHEV was 11.4% for the same month (ANFAC, 2024b). There are several causes for the low passenger car electrification rate of Spain, and many have been widely recognized and are common with those already reported by Boulanger et al. (2011), just right at the beginning of the introduction of the electric vehicle, such as range, charging access, and lack of public awareness about the availability and practicality of these vehicles. Back in 2016, Junquera et al. (2016) performed a study to analyse the purchasing intentions of the Spanish population regarding electric vehicles, reporting that price and charging times are the main adverse factors for the willingness to buy an EV, with these motives being replicated worldwide (Pamidimukkala et al., 2024). However, prices have been decreasing considerably since the date of this study. The charging infrastructure has been improved, and charging times have decreased significantly. In fact, depending on the type of EV, the sum of up-front costs, financial aids, and maintenance may currently result in a better economic balance, but EV adoption still experiences slow increments. Therefore, other reasons are behind this slow adoption and are fully complex. A possible explanation may be the aversion to financial risk and the influence exerted by the decisions made by others within the same social group (Cabeza-Ramírez et al., 2025). The rapid advances in technology may also incline the balance toward other propulsion systems, also characterized by low fuel demand. Another factor worth mentioning is the average age of the population and mean income, as reported in the study by Yang et al. (2023). The study found that younger people with higher incomes were more likely to be involved in EV purchase than the elderly population, who have lower needs for daily travel.

Given these complex challenges and the evolving landscape of decarbonization strategies in the transport sector, it is essential to assess practical solutions that can bridge the gap between current fossil fuel reliance and long-term electrification. The aim of the present document is to review current technologies capable of achieving a significant reduction in fuel consumption, which may serve as a transition towards electrification and facilitate easier extrapolation to emerging economies, thereby increasing the potential for a global decrease in transport CO_2-associated emissions.

2. EFFORTS PERFORMED BY CAR MANUFACTURERS TO REDUCE FUEL CONSUMPTION AND CO_2 EMISSIONS

Car manufacturers have made significant efforts and advances in developing new propulsion systems aimed at reducing fuel consumption. Probably one of the efforts having less awareness by the population is the difficulties associated with the loss of profitability when starting a new production plant for EVs. The transition towards an electrified vehicle fleet implies that the car manufacturer must dismantle a profitable combustion assembly line to start up an expensive EV assembly plant, which is full of uncertainties and initially operates at minimum capacity (Hancké & Mathei, 2024). Alternatives currently competing with electric vehicles include those capable of using dual fuels and hybridization, which incorporate batteries.

The development of systems based on the use of gaseous fuels such as natural gas, liquid petroleum gases and hydrogen aids in reducing fuel consumption. The use of compressed natural gas has the advantage that shares compatibility with biogas, which is derived from the anaerobic digestion of organics such as waste streams and fermentable biomass. Some examples of the technology are the Skoda Octavia model and the Skoda Scala model (Skoda, n.d.; Skoda-storyboard, n.d.), with CO_2 emissions being about 25% lower when running on natural gas. The additional advantage is the lower price of fuelling. Based on the information provided by the Ministerio para la Transición Ecológica y el Reto Demográfico, the price of fuelling with natural gas is about 4.53 € per 100 km; in contrast, this value goes up to 7.35 € for fast electric charging, and up to 9.26 € when using gasoline (Ministerio para la Transición Ecológica, n.d.).

Other fuels frequently used as alternatives in internal combustion engines include liquid petroleum gases (LPG). The acceptance of this option has been much wider than that of using compressed natural gas due to the high availability of recharging points and the ease of modification when the vehicle does not incorporate this feature directly from manufacturing. Dacia offers several models with this characteristic (Dacia, n.d.), reducing CO_2 emissions per kilometer by approximately 12-15%. H_2 is another alternative available in the market, and even though the price of vehicles has decreased in recent years, with models in the range of 75,000 and 82,000 €, such as the Toyota Mirai (Toyota.es, n.d.), the availability of recharging points is limited. However, this issue has not stopped other car manufacturers from designing and developing H_2-based models. Hyundai presented its Nexo model in 2023, which is based on a fuel cell and a powertrain using electric motors, with a price starting from approximately 73,500 € (Hyundai, n.d.). Honda is the third car manufacturer that incorporates this technology in its stock, initially with the Honda Clarity fuel cell and currently with the Honda CR-V e:FCEV, which is a plug-in vehicle (Automobiles Honda, n.d.). Despite the variety of options, the number of vehicles with hydrogen technology purchased in Spain increased to 21 units in 2023 and 62 units in 2024, with only 7 units of Hyundai Nexo purchased in 2024 (ANFAC, 2024a). The technology appears promising, but the amount of energy and water required to produce hydrogen through water electrolysis seems excessive for running a fleet based on this technology. Mansuri et al. (2020) estimated the need for a 4 MW capacity solar photovoltaic plant to serve a 100

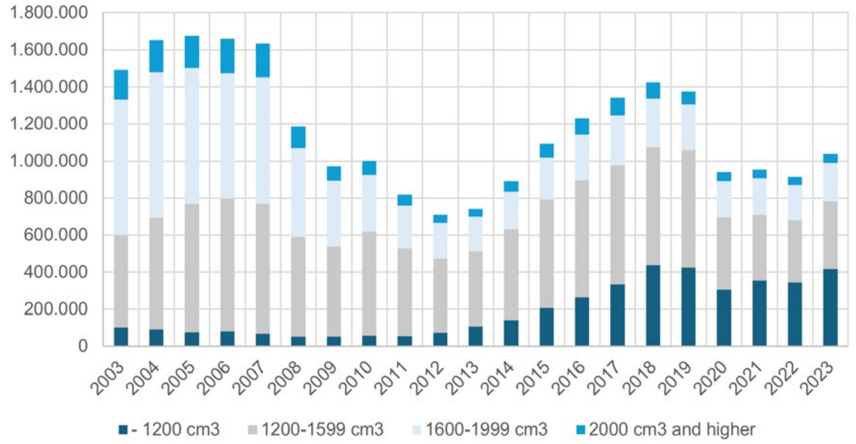

Figure 1. Distribution of engine cylinder volume in the Spanish fleet annually registered and CO_2 average emission of yearly registered vehicles.

vehicle fleet (50% being cars and the remaining being 2-wheel motorcycles) and a demand for water of 3.3 m3 water/day. The high costs of installing H_2 refuelling stations, along with the cost of producing hydrogen from electrolysers, restrict the deployment of the technology (installation costs for PEM electrolysers are about 1,812 $/kW updated to 2023) (Badgett et al., 2024).

Electrification will likely be the main key player in future mobility in the global north, but the global trend is for combustion vehicles to continue dominating the market due to the intrinsic difficulty for emerging economies to adopt a completely different charging infrastructure. Therefore, the development of high-efficiency engines will be a key driver for reducing global CO_2 emissions in the transport sector. This trend has also been observed in the Spanish fleet, where a general reduction in engine size has been accompanied by a significant decrease in average CO_2 emissions (Fig. 1). The reduction in fuel consumption is steeper than it may initially seem, because the decrease in emissions has been achieved with an increase in average vehicle weight and power (Hu et al., 2020). The car manufacturing sector has great influence in a country gross domestic product (GDP), thereby regulation regarding emission and transport limitation should carefully evaluate the real environmental benefits gained. For this reason, lacks any sense the intended Spanish future regulation banning publicity of cars having a diesel or a gasoline engine which do not count with any type of hybridization (Ministerio de Derechos Sociales, Consumo y Agenda 2030, n.d.) when the urgent aim to achieve is reducing fuel consumption and avoiding high levels of pollutant emissions.

Another striking issue is the population's commitment to the environment. A Eurobarometer survey conducted in 2010 indicated that consumers intended to purchase smaller vehicles to mitigate CO_2 emissions, but this intention was not realized, as sales of sport utility vehicles (SUVs) actually increased from 8.5% in 2009 to approximately 40% in 2020 (Vilchez et al., 2023). A similar behaviour may be observed in the population's intention to acquire an electric vehicle and the realization of the purchase. Intention may not be an adequate predictor of willingness to pay, because consumers may consider other issues to have more impact in their final decision when the purchasing moment finally arrives, thus making clear the inconsistency of what people say they will do and what they actually do (Cabeza-Ramírez et al., 2025; Bishop and Barber., 2014). Interestingly, the fuel consumption of SUVs is often comparable to, or even lower than, that of van-type family vehicles. As a result, car manufacturers are meeting consumer demand by offering vehicles that satisfy both versatile mobility requirements and personal aspirations. This approach

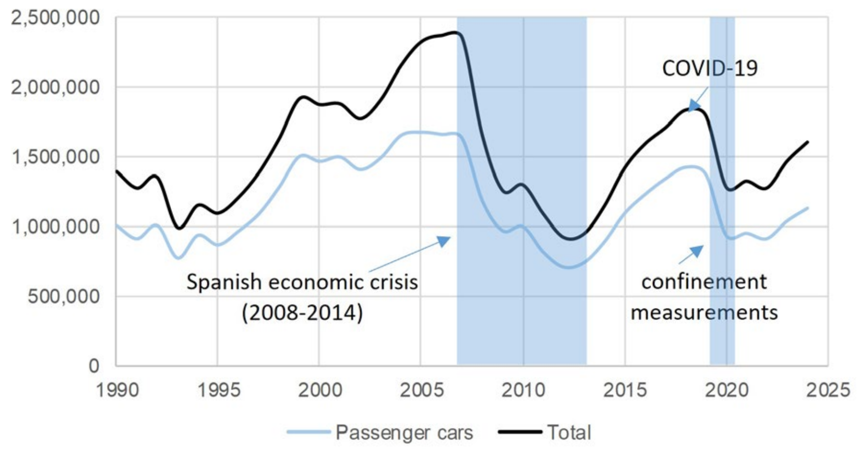

Figure 2. Evolution of car registration for the 1990-2024 period. Spanish economic crisis and confinement period are also represented.

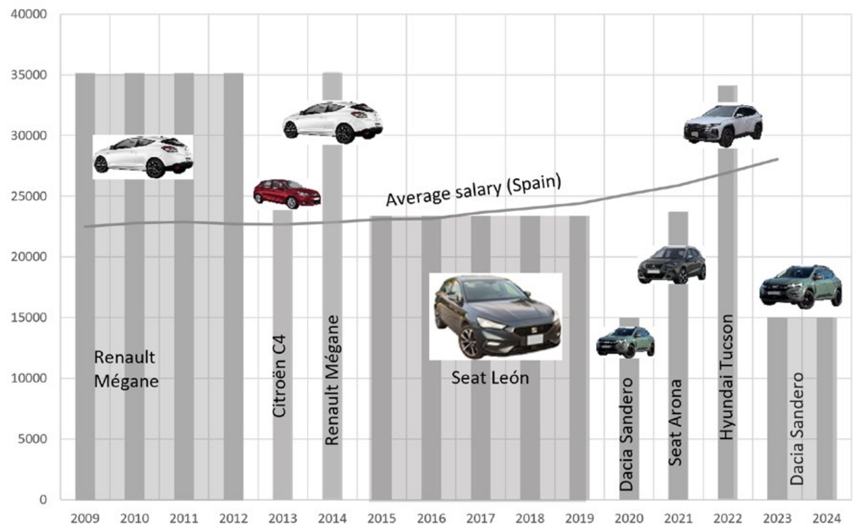

Figure 3. Most sold vehicles for the period 2009-2024 in Spain. The graph represents also the price of the vehicle (as of 2024) and average Spanish salary.

appeals to customers' preferences for vehicles that align with their lifestyle choices, rather than simply providing utilitarian family transportation.

One factor that should not be disregarded and has a significant influence on emissions is the evolution of the economy and the purchasing capacity of citizens for new vehicles. This issue is relevant since it affects the mean age of the passenger car fleet, with an increase in this value having an adverse impact on fuel consumption and pollutant emissions. The Spanish crisis period and the confinement measures associated with the pandemic are shown in figure 2, coincident with a significant decrease in the number of new vehicle transactions.

A noticeable increase in vehicle transactions occurred around 2012; however, pandemic-related restrictions later caused significant market disruption. From 2020 to 2024, vehicle registrations have once again trended upward, yet the most sold models during this period tend to be lower-priced vehicles. This trend is illustrated in figure 3, which presents both the average salary in Spain and the price (as of 2024) of the top-selling vehicle for each year from 2009 to 2024. Despite a nominal rise in average salaries, the data clearly suggest that families' purchasing power has declined, influencing the types of vehicles being bought.

3. BIOFUELS AS ALTERNATIVES FOR REDUCING CO_2 EMISSIONS FROM FOSSIL FUELS

The traditional biofuels market has been dominated by bioethanol and biodiesel. The first one is obtained from the fermentation of rich sugar-containing crops, such as sugar cane, and recently from maize crops and cereals, provided a saccharification stage is introduced, with the aim of releasing fermentable sugars. The United States and Brazil are the countries that dominate the ethanol production market (US Department of Energy, 2024), and therefore they also have a high presence in their vehicle fleets capable of using high ethanol content blends, reaching values close to 85% ethanol or even running on 100% ethanol. These vehicles are known as flex-fuel, and the preference for using either gasoline or ethanol highly depends on the user, based on the market prices of ethanol and gasoline. Despite the controversy surrounding ethanol production due to its impact on the food market, global ethanol production has maintained an upward trend over the last 18 years, with minor exceptions made during the pandemic period and the subsequent market distortions experienced worldwide (US Department of Energy, 2024).

The evolution of this technology towards processing lignocellulosic materials has not been an easy journey, with several challenges encountered when operating demonstration plants. Saad and Gonçalves (2024) examined the difficulties associated with producing ethanol from lignocellulosic materials and reported that the main issues were biomass handling and pre-treatment technologies, where high wear had been experienced by the equipment, thus excessively increasing operational costs. However, some exceptional stories of success are found, one in Norway with the case of the Borregaard biorefinery (Borregaard, n.d.) which produces ethanol from soft woods, and the companies Raízen and GranBio located in Brazil, which currently produce 2G ethanol at a commercial scale using as raw materials sugarcane bagasse and straw, this feature enables increasing ethanol productivity up to 50% per hectare of crop (Raízen, n.d.; GranBio, n.d.). The use of flex-fuel vehicles offers additional advantages over the simple substitution of a fraction of gasoline by ethanol. The higher oxygen content in ethanol improves flame propagation and reduces the trend of soot formation, reducing as well the emission of particles and volatile compounds in direct injection fuel engines, although emissions of oxygenated compounds (formaldehyde and acetaldehyde) are increased (Yang et al., 2019; Jin et al., 2017).

The use of biodiesel has shown a parallel trajectory to that of gasoline blends. This alternative fuel is compatible with conventional diesel, and unlike ethanol, the traditional fabrication process is based on a chemical process known as transesterification. In this case, diesel blends exhibit compatibility constraints, thus limiting the biodiesel content to up to 20% in many countries. Similar to the case of ethanol production, biodiesel fabrication has not been free of controversy because vegetable oils are also used for human and animal consumption. However, the development of new technologies has enabled the use of residual oils and animal fats through a technology based on the hydrotreatment of oils, where 100% compatibility is now achieved with this new biodiesel (Neste, n.d.; Repsol, n.d.; Moeve, n.d.). Therefore, the newly developed fuel meets all criteria related to sustainability and the circular economy, as it allows for the recycling of materials by valorising local waste streams and also achieves the goal of producing renewable fuels.

It is particularly striking that a fully compatible diesel fuel has emerged as one of the most effective alternatives for attaining decarbonization. The significant development of the diesel engine in passenger cars allows achieving substantial fuel efficiency and enjoyed excellent public acceptance in the European market, as well as in Spain, as observed in figure 4, with a notable introduction of this type of propulsion into the Spanish car fleet. The negative perception caused by the “Dieselgate” scandal, which garnered global attention in 2015, harmed the reputations of prestigious car manufacturers such as Volkswagen, Daimler, and BMW (Jong & van der Linde, 2022). The damage to reputation and the development of novel technologies, such as the hybridization of propulsion systems with batteries or LPG, have contributed to the decline in sales of diesel vehicles in recent years, promoting the resurgence of gasoline engines. However, the irruption of HVO fuels and electric hybridization in diesel engines has placed this type of propulsion system as the greenest alternative currently available in the passenger car segment. Mercedes offers GLC Plug-in Hybrid vehicle with a diesel engine, allowing a significant reduction in fuel consumption (Mercedes-benz.es, n.d.) and Kia offers a mild hybrid version of the Sportage also with diesel propulsion (Kia, n.d.), which reduces the consumption but it does not increase significantly the price of the vehicle due to the smaller size of the battery when compared with similar vehicles in the C segment.

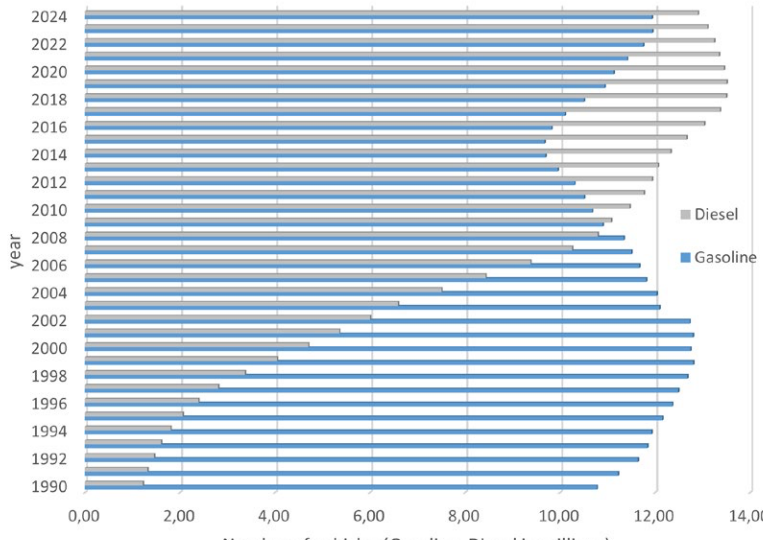

Figure 4. Data obtained from: Parque de vehículos-Series históricas 2024, data available on DGT, 2024.

Biogas is another fuel that can be used in the passenger car sector. Biogas is produced from the anaerobic digestion of easily degradable materials. Waste and energy crops can serve as raw materials for the process. Biogas is primarily composed of a mixture of methane (approximately 60%) and CO_2 (approximately 40%). Contrary to ethanol and biodiesel, which have been widely accepted by the general public, biogas faces two opposing conceptions: one is the public acceptance of being a renewable fuel considered environmentally friendly, and the other is the rejection caused when attempting to install biogas plants. Although it is recognized that biogas production from waste and biomass has a great potential (Bertasini et al., 2023), the widespread application of the technology is limited by the intrinsic constraints in scale increase due to the long distance involved in material transport (Bumharter et al., 2023) and the discomfort this may create to the local population. Another factor that has been clearly overlooked is the social rejection experienced by local communities that face the development of a biogas project. This phenomenon was studied by Bourdin and Chassy (2023), indicating that most homeowners prefer no changes to their status quo, with a limited willingness to endorse biogas plants. In contrast, young people showed a greater propensity to support environmental initiatives. The rejection effect encompasses not only changes in living conditions in nearby areas, but also uncertainty about environmental issues related to digestate management, which may raise public concerns regarding biogas plants. Digestate is a valuable by-product of the digestion process, and if land application of this material is not feasible, then other strategies need to be searched for valorising this organic product, as it may be thermal processes (Abdelfatah-Aldayyat et al., 2024; Abdelfatah-Aldayyat & Gómez, 2025).

One approach to circumvent this problem may be the adoption of hybrid approaches, whereby partial decentralization is implemented,

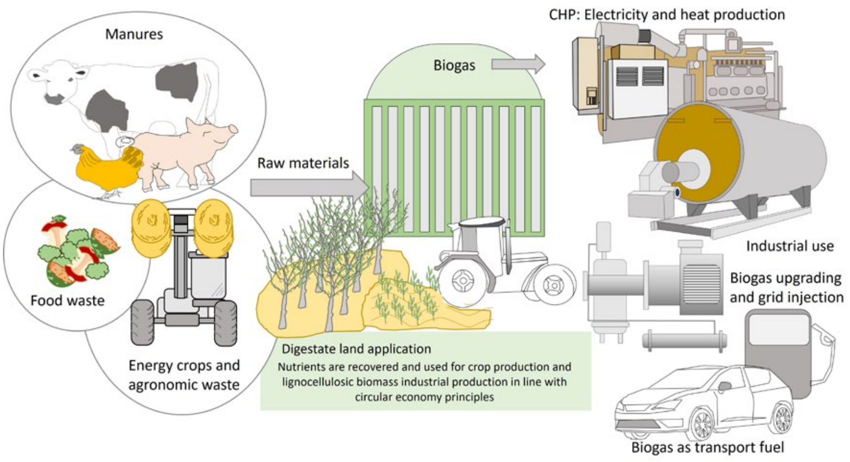

Figure 5. Schematization of raw materials used in anaerobic digestion and main technologies available for valorising biogas.

allowing for the local treatment of wastes in small digestion plants while centralizing the upgrading of biogas in large-scale systems (González et al., 2023), which may be less susceptible to social rejection. Even though the technology still needs to face the high installation cost associated with gas stations. The future implementation of biogas as a transportation fuel is closely linked to the further deployment of compressed natural gas (CNG) technology in vehicles and the installation of CNG stations, which currently face high financial investment, thereby hindering the wider adoption of these vehicles by the population. A similar situation to that experienced by electric vehicles, but in this case, it is less noticed by the national administration.

The high amount of CO_2 in biogas makes it imperative to apply upgrading technologies if this gas is to be used as a transport fuel or injected into the natural gas grid. Not only is CO_2 removed with this procedure, but other trace contaminants, such as water, hydrogen sulphide, trace amounts of oxygen, nitrogen, and hydrogen, are also eliminated (Ellacuriaga et al., 2021; Sevillano et al., 2021). The most common applications of biogas are the production of electricity from combined heat and power (CHP) engines or its use in industrial settings for heat production (Fig. 5).

Despite several years of experience, the widespread application of the technology has not been easy. Germany is the European country with the highest biogas production (87,100 GWh/year). Other countries, such as Denmark and Sweden, are recognized for having a significant share of biogas utilization in their energy mix; but the total amount of biogas produced is significantly lower than that produced by France (IEA Bioenergy, 2024). However, one particularity of the Swedish biogas sector is the high implementation of biogas in transport, although this feature is accompanied by a high dependence on policy incentives (IEA Bioenergy, 2024).

There is a recognized demand for increasing the share of renewable energy in the energy mix, and biogas should be one of the leading technologies. Therefore, the recent trend is to upgrade biogas to serve as a substitute for natural gas. The use of biogas has a substantial impact on rural economies by creating jobs, maintaining stable electrical infrastructure, and providing support to rural businesses (Barasa-Kabeyi et al., 2025). In addition to biogas, an organic slurry is also obtained as a by-product. The land application of this material enables the recycling of nutrients, primarily nitrogen and phosphorus, thereby reducing the demand for mineral fertilizers and increasing the circularity of the economy. Although digestion technology is considered environmentally friendly (Appels et al., 2011), one of the major objections to installing biogas plants is the risk of producing offensive odours associated with digestate management. However, this latter stream is the factor that ensures sustainability to the global process. Digestate contains recalcitrant material to the anaerobic microflora and concentrates nutrients and mineral components, thereby the application to land results in soil benefits as long as the organic quality of the digestate is high (digested material should be stable and matured) and application rates are controlled based on crop demands (Estrada et al., 2006; Panuccio et al., 2021). The biogas technology is not new. In fact, most biogas applications in the energy production sector and industry are related to the presence of digesters operating in wastewater treatment plants (WWTPs) and landfills. Recovering biogas from these facilities enables the conversion of waste into useful energy while also preventing uncontrolled emissions resulting from organic matter decomposition. The many years of large-scale application of digestion technology have built a strong foundation of operational experience, which should further strengthen public confidence in its reliability and benefits.

Other biofuels currently available but with less widespread applications are hydrogen and syngas. The first one can be categorized as a biofuel when produced through water electrolysis, with energy derived from renewable sources. However, the technology has high installation and operating costs. These factors along with the low acceptance of hydrogen vehicles and excessive increments in costs when intended as a replacement of some specific processes in industrial applications, relegates the use of hydrogen mainly to the industrial sector whereas in the case of transportation projects are at an experimental stage (Nikolamotor, n.d.; Sustainable Bus, 2025, Nordex Electrolizers, n.d.). Currently there is a low share of hydrogen passenger cars circulating. In the case of syngas, its direct use in transportation dates back to the gasoline shortage during World War II period (Inayat et al., 2024). Current efforts are focusing on the chemical conversion of syngas components into valuable fuels, mainly through Fischer-Tropsch synthesis or catalytic processes for producing methanol (Topsoe, n.d.; Technip Energies, n.d.). As long as syngas is derived from biomass, the fuels obtained may be catalogued as biofuels. The adoption of this technology may help revitalize regions by promoting the growth of lignocellulosic crops, thereby creating local job opportunities in low-income agricultural areas. However, the technological feasibility is limited by high energy demand and installation costs.

Ammonia can also be considered an alternative fuel, gaining biofuel connotations when produced using green hydrogen (González & Gómez, 2024). The main advantage of this gas is that the technology, storage, and transport infrastructure are already developed and mature, and several companies have successfully tested its use as a fuel or as a fuel supplement in combustion engines (including marine ship applications and gas turbines). Toyota is also improving its developed ammonia combustion engines for use in passenger cars, with the aid of GAC (Kable, 2023). Furthermore, technologies for controlling NOx emissions are well established, which further supports the practical deployment of ammonia as a fuel. While ammonia does present certain safety concerns, these are generally less significant than those associated with hydrogen, particularly regarding handling and flammability risks.

4. HYBRID VEHICLES ARE THE GLOBAL KEY PLAYERS IN EFFICIENT TRANSPORT SYSTEMS

Currently, the market offers different types of hybridizations ranging from the use of different fuels, that is, LPG or CNG, and conventional fuels, and those commonly recognized as battery hybrid vehicles where the energy stored in the battery can aid in vehicle propulsion at some specific moments or can provide full propulsion depending on the configuration of the system and size of the battery. These vehicles are categorized into mild hybrid vehicles where a small battery of usually 48 V aids (or even smaller, as that of Nissan Qashqai (12 V)) in reducing fuel consumption thanks to regenerative braking. Full hybridization, or simply hybrid electric vehicles, incorporates a larger battery size, allowing the vehicle to run on electric power alone, combustion, or in parallel propulsion using both engines. In this case, the combustion engine can recharge the battery in addition to regenerative braking. Plug-in hybrid vehicles allow for charging the battery directly from the electric grid (Fig. 6). The technology has evolved, so Honda currently offers the CR-V e: PHEV model with an electric autonomy of 80 km. However, the combustion engine can recharge the battery while driving, allowing the vehicle to run in electric mode after the "charge mode" is activated (Honda.es, 2024).

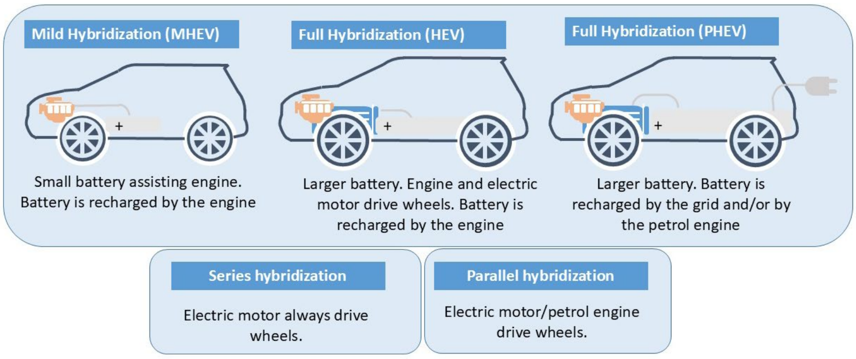

Figure 6. Description of hybridization types.

Hybridization configuration can be classified as series or parallel hybridization. In the first case, the electric motor drives the wheel, while the combustion engine is used for continuously recharging the battery; therefore, the engine power is provided by the electric motor. In the case of parallel hybridization both engines collaborate in vehicle propulsion. Therefore, the power of the vehicle is determined by an approximate summation of both engines, but the final output depends on different factors such as the point of maximum power of individual engines which is located at different RPM and smoothness and efficiency while driving which needs to be prioritized explaining the lower output of the parallel configuration, which does not come from the simple summation of engines individual power (Toyota, n.d.).

One significant advantage of hybrid vehicles is the feature of regenerative braking, which allows for a substantial reduction in particulate matter (PM 10 and PM 2.5 particles) during braking compared to conventional combustion vehicles. As a result, these vehicles offer threefold environmental benefits: they emit less CO_2 thanks to lower fuel consumption, generate fewer pollutants during braking, and use smaller batteries than fully electric vehicles—thus reducing the demand for raw material extraction. Hybrid and mild hybrid vehicles have a significant impact on lowering global CO_2 emissions. These vehicles are fully compatible with the existing transport infrastructure, enabling easy deployment in both developed and developing countries. Given these advantages, it is worth considering whether directing public funding toward incentives for hybrid vehicle adoption might be a more effective strategy for reducing global greenhouse gas emissions than current approaches.

Adding any type of battery to combustion vehicles increases manufacturing costs which is translated as an increase in the selling price of the vehicle. Therefore, causing a disincentive in the acquisition of a new vehicle and adversely affecting the fleet average age of any country. The aim of reducing fuel consumption, should consider not only the factor of electric hybridization but also the total fuel consumption of a vehicle, given that Euro 6d emission regulation is complied, there is no reason for assigning a lower environmental category to a vehicle adapted to Euro 6d regulation with a lower fuel consumption, that to another one with higher fuel consumption but having a battery in this case (Fig. 7). None should be penalized and both should

Figure 7. Example of combustion vehicles with C and ECO category.

be suitable candidates for receiving positive environmental categorizations.

5. CONCLUSIONS

This document highlights the multifaceted challenges and opportunities in decarbonizing the transport sector, emphasizing that a successful transition requires a combination of advanced technologies, pragmatic policy measures, and social acceptance. While regulatory frameworks such as the Fit for 55 package and ambitious emissions targets steer progress, their implementation must account for economic realities, technological maturity, and the risk of unintended consequences, such as the aging of vehicle fleets.

No single solution —whether electrification, alternative fuels, or hybridization— can independently achieve the required reductions in greenhouse gas emissions. Instead, progress will depend on a balanced approach that leverages the strengths of each technology. Hybrid vehicles, with their compatibility with existing infrastructure and significant reductions in emissions, emerge as a particularly effective bridge technology, especially for regions where full electrification is not immediately feasible.

Biofuels, including biogas, bioethanol, and biodiesel, offer viable alternatives for reducing fossil fuel dependence, especially when produced from waste streams. However, their wider adoption is constrained by infrastructure, cost, and social acceptance. Socioeconomic factors —such as purchasing power, consumer preferences — and the average age of vehicle fleets should be considered in policy design. Incentivizing the adoption of efficient vehicles, regardless of their propulsion system, and ensuring that environmental classifications accurately reflect their true emissions performance will be critical to achieving meaningful reductions. Decarbonizing transport demands coordinated action among policymakers, manufacturers, and consumers. A flexible, multi-technology strategy —supported by sound regulation, targeted incentives, and ongoing innovation— will be essential to advance toward climate neutrality while maintaining mobility, economic stability, and public acceptance.

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