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Review

Renewable Energy Integration in Sustainable Transport: A Review of Emerging Propulsion Technologies and Energy Transition Mechanisms

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Abstract

Decarbonization of transport is a key element of the energy transition and of achieving the Sustainable Development Goals. Integration of renewable energy into transport systems is assessed together with the potential of electric, hybrid, hydrogen, and biofuel-based propulsion to enable low emission mobility. Literature published from 2019 to 2025 is synthesized using structured searches in Scopus, Web of Science, and Elsevier and evidence is integrated through a thematic comparative approach focused on energy efficiency, life cycle greenhouse gas emissions, and technology readiness. Quantitative findings indicate that battery electric vehicles typically require about 18 to 20 kWh per 100 km, compared with about 60 to 70 kWh per 100 km in energy equivalent terms for internal combustion cars. With higher renewable shares in electricity generation, life cycle CO_2 equivalent emissions are reduced by about 60 to 70 percent under average European grid conditions and up to about 80 percent when renewables exceed 50 percent. Energy storage and smart grid management, including vehicle to grid operation, are identified as enabling measures and are associated with peak demand reductions of about 5 to 10 percent. Hydrogen and advanced biofuels remain important for heavy duty, maritime, and aviation segments where full electrification is constrained.

Keywords: renewable energy integration; sustainable transport systems; low carbon mobility; propulsion technologies; electromobility; hydrogen energy; biofuels; smart energy management; energy transition

Academic Editor: Alan Brent

Received: 7 November 2025
Revised: 14 December 2025
Accepted: 16 December 2025
Published: 18 December 2025

Citation: Kochanek, A.; Zacłona, T.; Pietrucha, I.; Petryk, A.; Ziemiańczyk, U.; Basak, Z.; Guzdek, P.; Akbulut, L.; Atılgan, A.; Woźniak, A.D. Renewable Energy Integration in Sustainable Transport: A Review of Emerging Propulsion Technologies and Energy Transition Mechanisms. *Energies* **2025**, *18*, 6610. https://doi.org/10.3390/en18246610

1. Introduction

Transport is becoming one of the key challenges of the modern energy transition. This is primarily due to the fact that demand for mobility is growing faster than vehicle efficiency is improving [1]. It is true that the COVID-19 pandemic caused an unprecedented decline in transport activity in 2020, and thus in greenhouse gas emissions, which was associated with lockdowns and mobility restrictions, as well as the transition to remote working [2–4]. As researchers have shown, at the peak of the first wave of the pandemic, more than half of the population reduced their mobility by about 50% [5,6]. However, this was not a permanent [7] or uniform change [8], as mobility and emissions quickly returned to pre-pandemic levels. Every year, there are more and more cars on the road, traveling longer distances, which directly translates into growing energy consumption [9,10].

The transport sector also remains heavily dependent on oil [11–13]. It is still the most oil-dependent segment of the economy. It is particularly difficult to replace liquid fuels in heavy transport, aviation, and shipping, where rapid electrification faces both technological and economic barriers [14–16]. In terms of individual behavior, there is also a noticeable trend towards the popularity of SUVs, i.e., an increase in the weight and power of vehicles, which largely negates the effects of improved energy efficiency [17]. This phenomenon also has a social dimension, as cars are increasingly seen as a symbol of status and independence, rather than just a means of transport [18].

Other factors contributing to increased energy consumption in transport include urban sprawl and increased professional mobility [19]. This leads to longer daily commutes and weakens the competitiveness of public transport. As a result, despite the faster decarbonization of other sectors of the economy, such as energy and construction, the share of transport in national energy consumption is steadily increasing [20].

A similar trend applies to CO_2 emissions: in the EU, transport emissions are falling much more slowly than in energy and industry [21], which means that their relative share of total emissions is increasing [22,23]. This is due, among other things, to the lack of easy substitutes for liquid fuels in aviation [24], shipping [25], and heavy transport, the increase in transport activity (passenger and freight) [26], slow fleet replacement [27], and the rebound effect, whereby cheaper and more accessible transport leads to an increase in the number of trips and ton-kilometers, which in practice negates some of the benefits gained from improved energy efficiency [28].

It is worth noting that the narrative of transport sector development presented in this paper is largely rooted in the experiences of the EU and other highly developed countries, where the processes of fleet hybridization and electrification and the tightening of emission regulations are most advanced, which also coincides with the fact that the EU and other highly developed countries are the most advanced in terms of the development of electric vehicles and the introduction of new technologies [29–31]. The processes of fleet hybridization and electrification, as well as the tightening of emission regulations, are most advanced, which also coincides with the affluence of society, allowing for the purchase of new and less polluting car models [32–35]. However, it should be noted that developing countries, especially those in the tropics, where demand for mobility is growing faster than the pace of fleet modernization, are also responsible for global transport emissions. This is related to the growing import of used vehicles from wealthier countries [36–39]. A significant proportion of these cars do not meet basic environmental and safety requirements, which leads to the “import” of high emissions of air pollutants and greenhouse gases to developing countries and perpetuates the dependence of transport on fossil fuels [40,41].

In view of the presented trends of increasing energy consumption and the continuing dependence of transport on fossil fuels, it is necessary to seek and evaluate alternative technological solutions. New types of propulsion are becoming increasingly important, as they may reduce greenhouse gas emissions and make the transport sector independent of oil in the coming decades. Among them, electric [42], hybrid [43], hydrogen [44], and technologies based on the use of new-generation biofuels [45] deserve special attention.

The aim of this article is to analyze the role of these modern forms of propulsion in reducing fossil fuel consumption and supporting the energy transition of the transport sector. This study is a review based on an analysis of scientific literature from the last five years, including research results on energy efficiency, emission reduction, technological barriers, and the implementation potential of individual solutions.

2. Methodology

The aim of this article is to analyze the role of these modern forms of propulsion in reducing fossil fuel consumption and supporting the energy transition of the transport sector. The study is of a review nature and is based on an analysis of scientific literature focusing on four main thematic areas, reflected in the structure of the work: (I) the role of electric and hybrid vehicles in reducing fossil fuel consumption, (II) the potential and limitations of hydrogen and biofuels as alternative energy carriers, (III) the impact of renewable energy sources (RES) in the energy mix on the actual environmental performance of vehicles, and (IV) climate regulations and legal frameworks determining the implementation of propulsion technologies.

The literature included in this review was identified through searches in bibliographic databases: Scopus, Web of Science, Elsevier, and supplemented with publishing platforms and websites of international organizations (e.g., IEA, European Commission, EEA, UNEP). The search strategy was based on combinations of keywords related to: “electric vehicles,” “battery electric vehicles (BEVs),” “plug-in hybrid electric vehicles (PHEVs),” “fuel cell electric vehicles (FCEVs),” “hydrogen mobility,” “biofuels in transport,” “renewable energy integration,” “life cycle assessment (LCA),” “well-to-wheel emissions,” “transport decarbonization,” “transport regulations,” “Fit for 55,” “EU transport policy,” and related terms.

The main time horizon of the search was limited to the years 2019–2025, as the authors intended to reflect the most up-to-date state of knowledge in a rapidly developing field characterized by dynamic technological and legislative progress. Earlier key studies on the topics discussed in the article were also included, as long as they remained relevant to understanding long-term trends and mechanisms.

The inclusion criteria covered peer-reviewed scientific articles and review publications in English concerning: (I) the environmental and energy efficiency of vehicle propulsion technologies (often based on LCA or well-to-wheel analyses), (II) the integration of renewable energy into transport systems, and/or (III) regulatory and policy instruments influencing the decarbonization of transport. In addition, selected policy documents and technical reports prepared by international and European institutions were included due to their key role in shaping the climate and transport policy framework. Exclusion criteria included publications without full-text access, local case studies without a clear reference to decarbonization pathways, and works on sectors unrelated to transport.

Due to the broad scope and diversity of the issues addressed, a full systematic review (as defined by the PRISMA protocols and quantitative meta-analysis) was neither possible nor consistent with the authors’ intentions. Their aim is to provide an integrative, cross-sectional synthesis of available publications that identifies key trends and issues relevant to transport decarbonization. Selected publications are analyzed to identify key trends and issues relevant to transport decarbonization. Selected publications are analyzed to identify key trends and issues relevant to transport decarbonization. Their intention is to provide an integrative, cross-sectional synthesis of available publications to identify key trends and issues relevant to the decarbonization of transport. Selected publications were analyzed thematically and grouped according to the main issues presented in Sections 3–7.

3. Electric and Hybrid Vehicles—Reducing Fossil Fuel Consumption

In the face of global climate challenges, the development of electromobility has become a key element of the energy transition and the pursuit of carbon neutrality. The increase in the number of electric vehicles (EVs) and hybrid vehicles (HEVs) on global markets is one of the most important tools for reducing fossil fuel consumption and greenhouse gas emissions [46–48]. With the growing share of renewable energy sources (RES) in the energy mix, electromobility contributes to synergies between the energy and transport sectors, reducing dependence on oil and improving air quality in cities [49–51].

3.1. The Development of the Electric and Hybrid Vehicle Market

Since 2015, global sales of electric vehicles have increased more than tenfold, reaching over 20 million units per year in 2025 [52]. The market leaders are China, Europe, and the United States, which together account for over 90% of global EV sales [53–55]. In Europe, the introduction of the Fit for 55 package has accelerated the implementation of policies to reduce CO_2 emissions from transport, including a ban on the sale of new combustion engine vehicles after 2035 [56,57].

HEVs and plug-in hybrids (PHEVs) are an important transitional link between combustion engine technology and full electromobility. Their market share is growing more slowly than EVs, but remains stable, especially in countries where charging infrastructure is limited [58].

3.2. Comparison of Energy Consumption Between Electric Vehicles and Internal Combustion Engine Vehicles

From an energy consumption perspective, electric vehicles require substantially less energy during operation than internal combustion engine vehicles. The average energy consumption of EVs is approximately 18 to 20 kWh per 100 km, while internal combustion engine cars consume the equivalent of about 60 to 70 kWh per 100 km [59,60]. Figure 1 presents a comparison of energy consumption and CO_2 emissions for electric and internal combustion engine vehicles during operation.

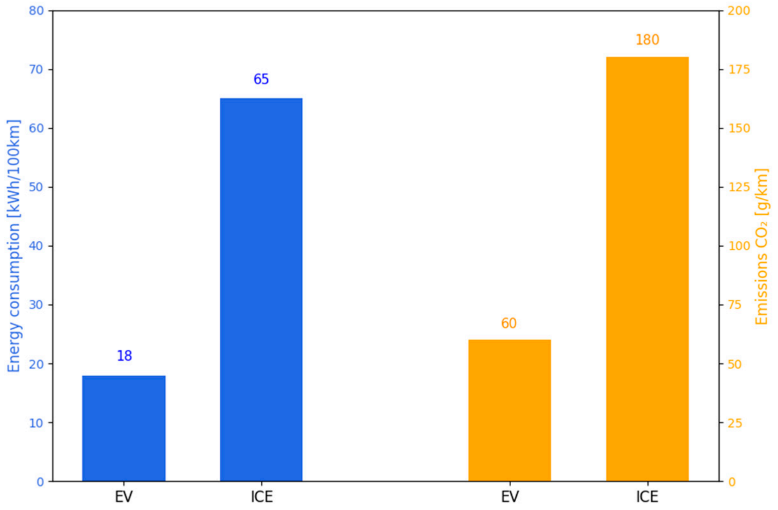

Figure 1. Comparison of energy consumption and CO_2 emissions over the life cycle of electric and internal combustion engine vehicles [16,32].

Research by the International Council on Clean Transportation (ICCT) shows that total life cycle CO_2 equivalent emissions for an electric vehicle charged with the average European electricity mix are on average 60 to 70 percent lower than for an internal combustion engine vehicle of the same class [61]. In countries where the share of renewable electricity exceeds 50 percent, the reduction can reach about 80 percent [62]. It should be noted that the ICCT values refer to total life cycle emissions, whereas Table 1 reports well to wheel CO_2 emissions. Table 1 presents a comparison of selected parameters of electric and internal combustion engine vehicles.

Table 1. Global comparison of EV and Internal Combustion Engine (ICE) parameters [32].

Indicators	EV	ICE	Ref.
Drive system efficiency [%]	15–25	18–28	[63,64]
Energy consumption [kWh/100 km]	16–21	60–82	[65,66]
CO_2 emissions [g/km, WtW]	80–95	160–200	[67,68]
Operating costs [€/100 km]	2.6–3.0	7.5–9.0	[69,70]
Share of renewable energy sources in power supply [%]	30	0	[71,72]

While Figure 1 and Table 1 clearly indicate lower energy use and potentially lower emissions for EVs, a critical interpretation requires accounting for grid carbon intensity and methodological differences between indicators, since these factors can materially change the comparison with combustion vehicles.

3.3. Environmental and Energy Benefits

Replacing combustion engine vehicles with electric and hybrid vehicles brings numerous environmental and energy benefits, which are key arguments for their widespread implementation.

EVs do not generate local emissions of nitrogen oxides (NO_x), sulfur dioxide (SO_2), particulate matter (PM2.5, PM10), or carbon dioxide (CO_2) at the point of use [73,74]. In cities with high traffic volumes, this means a significant improvement in air quality, which translates into a reduction in respiratory and cardiovascular diseases [75].

According to studies by the WHO and the European Environment Agency (EEA), road transport emissions account for approximately 30% of total CO_2 emissions in EU countries and 70–80% of air pollution in urban agglomerations [76]. Replacing combustion engine vehicles with electric ones can therefore significantly reduce the negative impact of transport on health and the environment.

EVs and PHEVs contribute to reducing fossil fuel consumption by replacing gasoline and diesel with electricity. IEA analyses show that global oil consumption in the transport sector could fall by 6 million barrels per day by 2030 if the share of electric vehicles in new car sales reached 40% [32]. For oil-importing countries, this means increased energy security and reduced-price risk resulting from the instability of commodity markets [77].

One of the greatest advantages of electromobility is its potential for integration with RES. Electric vehicles can be charged during periods of surplus energy generation from wind or photovoltaic farms and, in the future, may also serve as mobile energy storage units (Vehicle-to-Grid, V2G) [77,78]. Research conducted by the National Renewable Energy Laboratory (NREL, 2023) indicates that the implementation of V2G technology can increase the stability of the power grid and reduce peak demand by 5–10% [79].

Electromobility can also contribute to improving the efficiency of the entire energy system. Instead of burning fossil fuels in low-efficiency engines, energy can be produced centrally in higher-efficiency sources (gas, wind, or nuclear power plants) [80,81]. As a result, even with the current energy mix, electric vehicles are more advantageous in terms of energy balance and emissions than combustion engine cars [82].

3.4. Technological and Infrastructure Challenges

One of the main limitations is the insufficient network of charging stations, especially in cities and peripheral regions [83]. In 2024, there were approximately 1.02 million public charging points in Europe, which is still insufficient in relation to the number of electric vehicles, especially with the growing sales of EVs and PHEVs [84]. In addition, differences in charging standards (AC, DC, CCS, CHAdeMO) are a problem, as they can hinder compatibility and increase investment costs [85].

Lithium-ion batteries are the largest cost component of electric vehicles. Despite a decline in prices from approximately $1200/kWh in 2010 to $115/kWh in 2024, costs remain higher than those of comparable components in combustion engine vehicles [86]. In addition, battery production requires rare raw materials (lithium, cobalt, nickel), which raises the risk of raw material constraints and ethical issues related to mining [87].

The production of electric vehicles, and batteries in particular, generates a significant carbon footprint, which can partially offset the benefits associated with their use. Life Cycle Assessment (LCA) analyses show that an electric car needs to travel approximately 50,000–70,000 km to "make up" for the emissions generated during production compared to a combustion engine vehicle [87,88].

Another challenge is the recycling of lithium-ion batteries. Currently, recycling technologies are costly and often inefficient in terms of raw material recovery [87]. The development of recycling infrastructure and the design of batteries in line with the circular economy are important for reducing the carbon footprint of the entire EV life cycle [85].

The increase in the number of electric vehicles increases the demand for power during peak hours. Without smart charging and integration with renewable energy sources, there is a risk of overloading the power grid [85]. V2G systems and optimization of charging schedules can reduce these constraints, but require significant investment and standardization of technology [89].

3.5. The Role of Maritime Transport

In the context of the global energy transition and efforts to reduce the consumption of fossil fuels, it is also worth taking into account the maritime transport sector, which—despite progress in other areas—remains a significant and still growing source of emissions and fossil fuel use. According to the latest report by the ICCT, between 2016 and 2023 total "tank-to-wake" (TTW) greenhouse gas emissions from the global fleet increased by around 12%, indicating that maritime transport continues to contribute to the rise in global emissions despite a decline in emission intensity per ton-kilometer [90].

The shipping sector currently accounts for a substantial share of global CO_2 emissions. In 2018, emissions from ships were estimated at approximately 1 billion tonnes of CO_2 annually, representing about 3% of global anthropogenic emissions. Maritime transport emissions include not only CO_2 but also sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM), which have significant implications for air quality and public health, especially in ports and coastal areas [91].

4. Hydrogen and Biofuels as Alternative Energy Carriers: Potential and Implementation Barriers

Despite the rapid growth of electromobility, the complete decarbonization of the transport sector requires the use of a diverse portfolio of low-emission technologies. Not all modes of transport, in particular heavy goods transport, maritime transport, and aviation, can be easily electrified due to technical, range, and infrastructure limitations. In this context, alternative energy carriers such as hydrogen and biofuels, which complement the development of electric vehicles, are becoming increasingly important. Both solutions offer significant potential for reducing greenhouse gas emissions and diversifying energy sources, but their implementation requires overcoming a number of technological, economic, and environmental barriers.

4.1. The Potential of Hydrogen as the Fuel of the Future

Hydrogen (H_2), as an energy carrier, is characterized by a high calorific value (141.8 MJ/kg, HHV) and can be used in a wide range of applications, from proton exchange membrane fuel cells (PEMFCs) in transport to industrial processes and energy storage. In the context of mobility, so-called "green hydrogen" produced by electrolysis of water using renewable energy is particularly important. Only such hydrogen can make a real contribution to climate neutrality and reducing the carbon footprint.

4.1.1. How FCEV Technology Works and Its Advantages

Hydrogen fuel cell electric vehicle (FCEV) technology has advantages over battery electric vehicles (BEVs), especially in heavy-duty, long-distance transport and segments with high energy requirements. The main barriers to development include the high cost of hydrogen production (especially green hydrogen), the lack of extensive refueling infrastructure, and challenges related to hydrogen storage and transport due to its low energy density under standard conditions.

FCEVs are one of the most promising solutions in the context of the low-carbon transformation of the transport sector. Their operation is based on the electrochemical conversion of hydrogen and oxygen into electricity in fuel cells, most commonly PEMFC [92]. The only by-product of this reaction is water vapor, which makes FCEV technology completely emission-free during operation.

Compared to BEVs, FCEVs offer a number of practical advantages, in particular shorter refueling times (usually less than 5 min) [93,94] and greater range, which is particularly important in fleet, long-distance, and heavy-duty applications. It is worth noting that the chemical energy density of hydrogen (approximately 120 MJ/kg) significantly exceeds that of conventional lithium-ion batteries, allowing for the design of lighter and more efficient powertrains for long-distance transport.

4.1.2. Technological, Economic, and Infrastructure Barriers

Despite its many advantages, the development of FCEV technology faces significant barriers. The most important ones include the high cost of fuel cell production (related, among other things, to the use of platinum catalysts) [95], limited hydrogen refueling infrastructure, and issues related to its production and storage [64]. As shown in Figure 2, the development of FCEV technology faces a number of technological, economic, and infrastructural barriers.

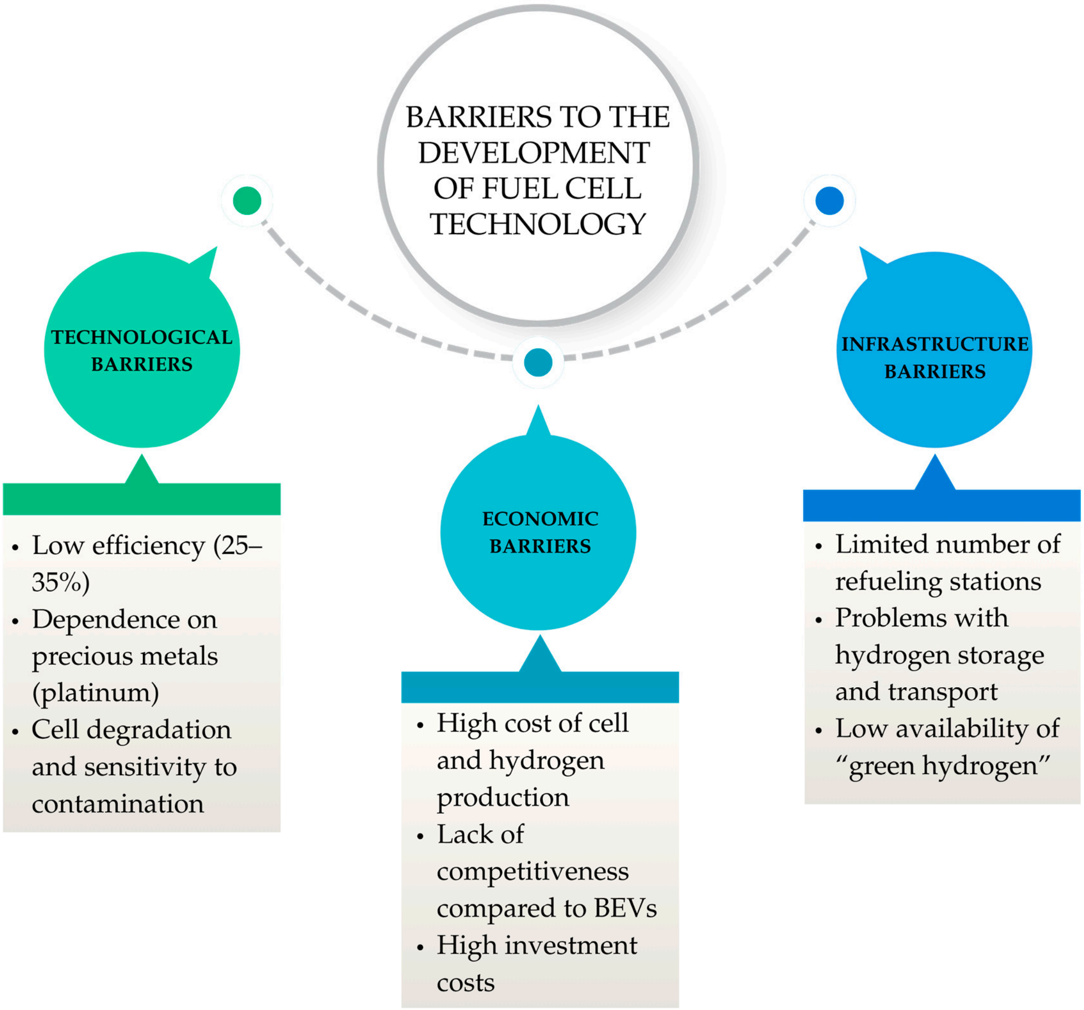

Figure 2. Main barriers to the development of FCEV [95,96].

From a sustainable development perspective, the source of hydrogen is also crucial. The production of so-called green hydrogen (through electrolysis using renewable energy) allows for the complete decarbonization of the entire vehicle life cycle [97].

When analyzing the individual limitations, each of them should be discussed in order. FCEV technology based on hydrogen-powered fuel cells is one of the key alternatives to combustion engines and traditional BEV [98]. Despite numerous advantages, such as zero emissions during operation, short refueling times, and long range, the development of FCEVs faces significant technological, infrastructural, and economic barriers that hinder its effective development worldwide [99].

One of the fundamental problems with FCEV technology is how to obtain hydrogen. Currently, the dominant method is steam methane reforming (SMR), which involves carbon dioxide emissions, which contradicts the assumptions of transport decarbonization [100]. The production of so-called "green hydrogen" through the electrolysis of water using renewable energy is still costly and energy-inefficient [101]. As a result, hydrogen as a fuel remains uncompetitive in both ecological and economic terms [102].

Another limitation is the efficiency of fuel cells. Fuel cells used in FCEVs, most often of the PEM (Proton Exchange Membrane) type, are less efficient than direct battery power supply to electric motors. The total energy efficiency of the chain from hydrogen production to vehicle propulsion is only 25–35%, while in the case of battery vehicles it can reach up to 70–80% [103].

In addition, fuel cells require the use of precious metals such as platinum, which increases their production cost. Fuel cells are also more sensitive to pollution (e.g., sulfur and nitrogen oxides in the air) than traditional electrical systems, which can affect their service life and require additional filtering systems. Furthermore, cyclic changes in cell load can lead to their degradation, limiting the durability of the entire drive system [104].

4.1.3. Hydrogen Infrastructure and Safety of Use

Due to high investment costs, the global hydrogen refueling infrastructure (HRS) is underdeveloped [105]. The construction of a single hydrogen station that meets pressure (up to 700 bar), safety, and storage requirements can cost several million euros. In most countries, such a network is limited to a few locations, mainly near large urban agglomerations, which significantly limits the operational capabilities of FCEVs [106,107]. In addition, the selection of these locations should be verified on the basis of thorough analyses using a variety of tools, such as GIS or, for example, AI agent systems, to ensure their optimal distribution and maximum network efficiency [108–111]. Hydrogen as a fuel also has a low energy density per unit volume. In order to store it in gaseous form, it must be compressed to very high pressure, which entails additional energy costs and safety requirements. Liquid or chemically bound forms are an alternative, but they are also technologically complex and energy-intensive.

FCEV vehicles are significantly more expensive than their battery-powered or combustion engine counterparts. The high costs are due, among other things, to limited production scale, the use of expensive materials (e.g., platinum), the complex design of pressure systems, and the lack of a sufficiently developed supply chain. The retail price of FCEV vehicles exceeds the equivalent of €60,000–70,000 [112], which, compared to the average annual salary for an employee in the EU of €37,900 [113], makes them unaffordable for the average consumer.

FCEV technology requires consistent regulations on technical standards for hydrogen tanks, refueling procedures, component certification, and safety of use. The lack of uniform international standards hinders the development of infrastructure and the wider implementation of vehicles. In addition, low-emission vehicle subsidy policies in many countries favor battery drives, marginalizing hydrogen technologies [114].

4.2. Biofuels in the Energy Transition Transport

4.2.1. Classification of Biofuels (I–IV Generation)

Biofuels have been classified into four generations depending on the type of feedstock and the proportional technology used to process them. First- and second-generation biofuels are one of the key alternatives to fossil fuels in the context of decarbonizing the transport sector. The first generation consists of products from edible plant raw materials, including corn, rapeseed, soybeans, or sugar cane, and the production process is fermentation (biomethanol production) or transesterification (biodiesel) and is competitive with typical agri-food production [115]. Second-generation biofuels are produced from raw materials derived from agricultural waste that is not suitable for food production (e.g., cereal husks, straw, wood), where the production technology involves thermochemical processes (including pyrolysis and fermentation). These biofuels do not compete directly with agri-food production [116]. Third-generation biofuels, on the other hand, are produced using microalgae (cultivated in photobioreactors) as the main raw material, which can produce vegetable oils for biodiesel production [117]. Algae as a raw material does not compete with food production. The fourth generation of biofuels is the production of synthetic fuels (e-fuels) through the conversion of solar energy or carbon dioxide using the process of photosynthesis. This technology is currently under development and has the potential for zero carbon emissions into the environment [118].

As shown in Figure 3, the four generations of biofuels differ in terms of the type of raw material, technological sophistication, environmental impact, and competition with food production. With the development of subsequent generations, there has been a gradual decrease in emissions and an increase in decarbonization potential, making third- and fourth-generation biofuels particularly promising in the context of sustainable transport development.

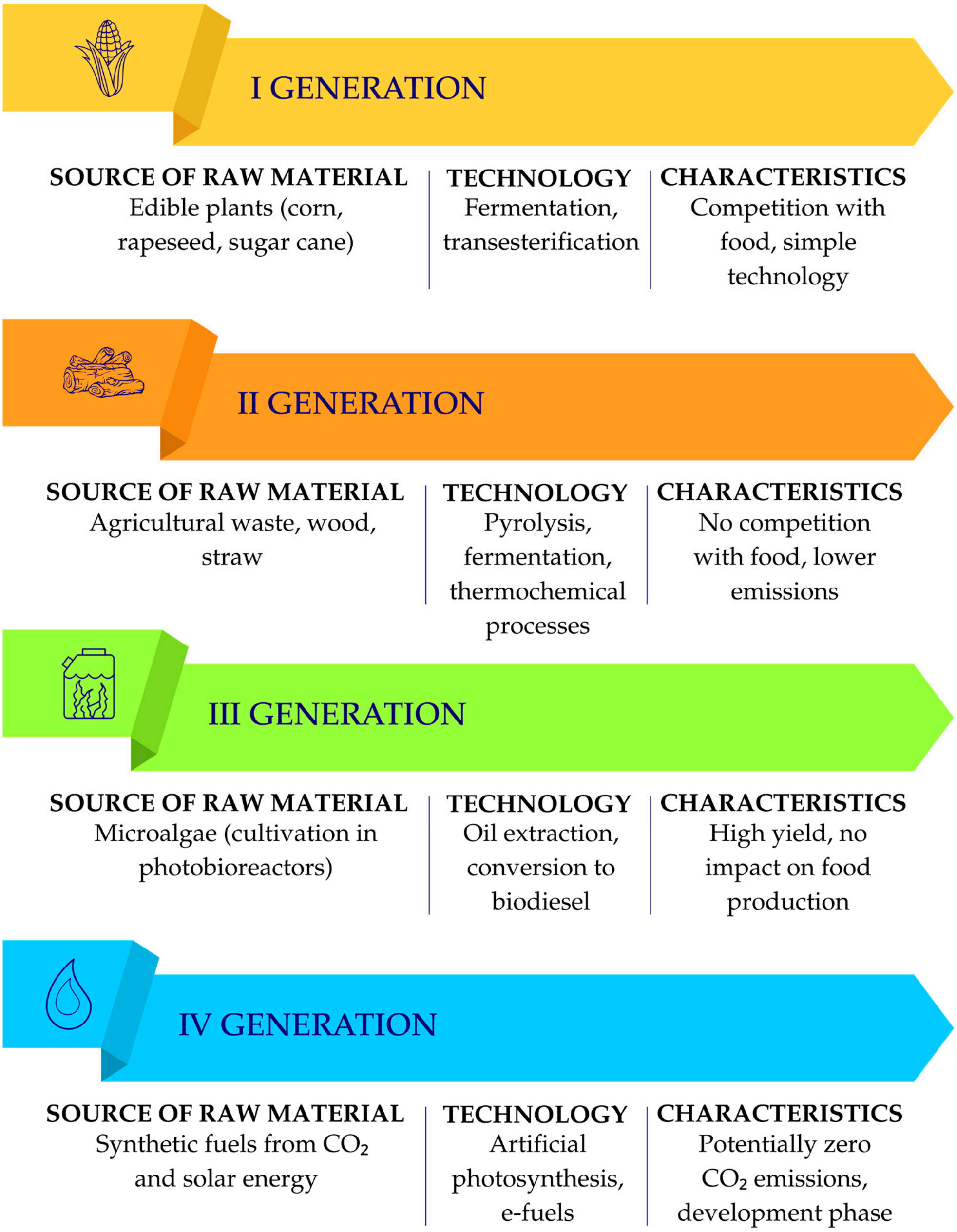

Figure 3. Classification of biofuel generations and their characteristics [115–118].

4.2.2. Emission Reduction Potential and Use in Existing Infrastructure

With regard to biofuels themselves, bioethanol, biodiesel, and biomethane are products of biomass conversion that can be used in existing combustion engines with little or no modification. However, their production and use are controversial due to technological, environmental, and social barriers, including competition with food production and limited availability of raw materials. Biofuels, especially second-generation (from organic waste) and third-generation (from microalgae), are another important alternative to fossil fuels. Their main advantage is that they can be used in existing combustion engines and distribution infrastructure, making them an attractive solution during the transition period. In the case of liquid biofuels such as bioethanol, biodiesel, or HVO (hydrotreated vegetable oil) [119], it is possible to significantly reduce greenhouse gas emissions, by up to 80 percent compared to conventional diesel fuel, depending on the type of raw material and production technology [120].

However, more detailed analyses indicate that achieving such emission reductions depends on a number of conditions, including the type of crops, land use changes, energy conditions of production, and the efficiency of the entire production chain. For example, first-generation biofuels that use edible raw materials may have negative effects related to competition for arable land, increased food prices, and emissions released in the process of land use change [121]. Second generation biofuels, on the other hand, although theoretically less controversial from a "food vs. fuel" perspective, face economic and technological barriers. These include the need for advanced pretreatment processes, higher investment costs, and often lower production efficiency [122].

Furthermore, third and fourth generation biofuels offer significant opportunities to reduce environmental impact and competition with food production, for example through microalgae and synthetic fuels. However, these options are still in the development or early commercialization phase [123]. Their full implementation requires technological, economic, and regulatory breakthroughs. It is also worth noting that the technical and environmental indicators (including LCA results) for these directions are still very diverse and require further research [124]. As a result, although biofuels can play a role in the transformation of the transport sector, their importance and effectiveness depend on local and technological conditions and on a coherent strategy combining raw material availability, conversion technologies, and a sustainable policy framework [125].

To illustrate the differences between the most commonly used types of biofuels, Table 2 summarizes their main operational, environmental, and technological characteristics.

Table 2. Characteristics and comparison of the operational and environmental properties of selected transport biofuels [118,119,126–131].

Feature-Fuel	Bioethanol	Biodiesel (FAME)	Biomethane (Bio-CNG and Bio-LNG)	Ref.
Raw material source	Corn, sugar cane, wheat	Vegetable oils, waste fats	Organic waste, manure, sewage	[118]
Production method	Alcoholic fermentation	Transesterification	Anaerobic fermentation + purification	[126,127]
Application	Gasoline engines (E5–E85)	Diesel engines (B7–B100)	Gas engines (CNG, LNG)	[119,126]
CO_2 emissions (lifecycle)	Reduction to ~60–70% compared to gasoline	Reduction to ~80% vs. diesel	Even negative emissions (when from waste)	[126]
NO_x and particulate emissions	1–2 g/kWh	~7.5–9 g/kWh	≈1–2 g/kWh	[128–130]
Vehicle compatibility	E10 without modification; E85—FlexFuel	B7—no modification required; B100—modification required	Requires a dedicated CNG/LNG engine	[119]
Calorific value (MJ/kg)	27	37–40	50 (for CH_4)	[126]

Table 2. *Cont.*

Feature-Fuel	Bioethanol	Biodiesel (FAME)	Biomethane (Bio-CNG and Bio-LNG)	Ref.
Disadvantages	Hygroscopic, less caloric	Poor cold resistance	High infrastructure costs	[131]
Threat to food	High	High or medium (depending on the raw material)	Low (mainly waste)	[132–134]

Analysis of the data presented indicates that individual biofuels differ in terms of their emission reduction potential, environmental impact, and raw material availability. These differences determine their suitability for implementation in various transport segments and the scale of potential climate benefits.

4.2.3. Technological, Environmental, and Social Constraints

Despite the varying potential of individual types of biofuels, as presented in Table 2, their widespread use in transport faces numerous technological, environmental, and socioeconomic constraints [135]. These factors significantly determine the possibilities for further development and scaling up of biofuel production, and also influence their actual contribution to the decarbonization of the transport sector [136].

The limitations of biofuels stem from the risk of competition with the food sector (first-generation biofuels), the limited availability of waste raw materials, and the energy intensity of processing [137]. In this case, there is a significant risk of food price increases, which negatively affects the public perception of this technology. There are also limitations in the context of pressure for changes in land use, including deforestation [138].

A key factor for the sustainable development of this segment is the implementation of advanced conversion biotechnologies and the development of logistics chains based on local biomass resources [139]. The solution to this problem is second-generation biofuels. In this case, the limitation is the availability of sufficient quantities of waste and higher requirements for processing technology. Hence, this technology has limited global potential. In this case, there is competition with the chemical industry, the energy sector, and agriculture for the same type of raw material [140–142].

It is also worth noting that, despite the general perception of biofuels as carbon neutral, the production of energy from first-, second- and third-generation biofuels causes emissions of NO_x, CO, and particulate matter when burned in an engine. These emissions obviously depend on the quality of the biofuels and the engine technology used [126,127]. In the case of biomethane, methane emissions may occur during extraction and transport ("methane slip") [131].

Biofuels such as bioethanol, biodiesel, and biomethane can be successfully used in existing internal combustion engines, offering partial decarbonization of transport at a relatively low technological cost. Their implementation does not require radical infrastructure changes, making them an attractive transitional solution during the energy transition. However, their development is limited by environmental (emissions, land use changes), social (competition with food production), and technological (scalability, availability of raw materials) issues. Long-term strategies should focus on second- and third-generation biofuels and the integration of waste systems with energy production [143–145].

Despite its significant environmental and operational advantages, FCEV technology currently faces many barriers limiting its widespread use. These require coordinated action in the areas of infrastructure development, reducing hydrogen production costs (especially using low-emission methods), technical standardization, and legislative support. In the short term, FCEVs have greater potential for use in heavy, mass, and long-distance transport sectors, where charging time and battery weight limitations are particularly important [146].

4.3. Comparative Analysis of Hydrogen and Biofuels—Selected Case Studies

Hydrogen (green) has the potential to significantly reduce emissions, especially in heavy transport sectors where batteries are practically difficult to use (e.g., heavy trucks, maritime transport). Biofuels, especially advanced ones, can quickly replace some liquid fuels using existing infrastructure, but their scaling up is limited by raw material and production capacity constraints.

Table 3 compares the main technological, economic, and environmental criteria of both solutions, along with examples of international implementation projects that illustrate the practical applications of hydrogen and biofuels.

Table 3. Comparison of green hydrogen and advanced biofuels—selected projects.

Criterion	Fuel Type	Applications (Global Projects)	Ref.
GHG emission reduction	Green hydrogen (H_2 from RES)	HYBRIT—Sweden: CO_2-free steel (SSAB, LKAB, Vattenfall). Reduction > 90%.	[147,148]
	Advanced biofuels (SAF, HVO)	Neste MY SAF—Finland: up to 80% reduction in aviation emissions (Air France, KLM).	[136,149]
Technological maturity	Green hydrogen	NEOM Project—Saudi Arabia: 4 GW RES → 650 t H_2/day (Air Products, ACWA Power).	[150]
	2G biofuels (lignocellulosic)	UPM Biofuels—Lappeenranta (Finland): HVO biofuel from wood waste; industrial scale.	[139]
Infrastructure and logistics	Green hydrogen	Hydrogen Mobility Germany (H2Mobility DE): >100 H_2 stations, integration with truck fleets.	[149,151]
	Biofuels (HEFA/SAF)	Rotterdam BioPort—Netherlands: biofuel logistics hub (Neste, Shell, bp).	[149,152]
CAPEX/OPEX costs	Green hydrogen	Gigafactory H_2 Lingen—Germany: 200 MW electrolyzer (bp + Ørsted); reduction of production costs to €3/kg by 2030.	[147,150]
	Biofuels	World Energy SAF—USA (Los Angeles): first commercial aviation biofuel refinery.	[136,139]
Sectoral applications	Green hydrogen	Coradia iLint—Germany: Alstom train powered by H_2. Toyota Mirai Fleet—Japan: hydrogen vehicles (taxis, city fleets).	[148,153]
	Biofuels (SAF, HVO)	KLM + Neste SAF—Amsterdam: transatlantic flights using 50% biofuel. GoodFuels—Netherlands: fuel from waste for Maersk shipping.	[126,150]
Raw material availability	Green hydrogen	Requires large amounts of renewable energy and water; best locations: Australia, MENA, Scandinavia.	[147,148]
	Biofuels	Waste biomass (plant residues, used oils, lignin)—limited global supply.	[136,139]
Regulations and sustainability	Green hydrogen	RFNBO (EU) certification requirement, guarantees of energy origin.	[148,152]
	Biofuels	RED III: ILUC reduction, traceability, double counting of waste.	[151,152]
Scaling perspective (2030–2040)	Green hydrogen	Large projects >1 GW (NEOM, HyDeal, Iberdrola); 10–20× increase in global production by 2035.	[148,149]
	Biofuels	Scaling in aviation and shipping—raw material constraints; leaders: Finland, Netherlands, USA.	[136,149]

Table 3 shows that both green hydrogen and advanced biofuels can significantly reduce GHG emissions, but they differ in deployment conditions and sectoral fit. Green hydrogen offers very high decarbonization potential, especially for hard to abate industry and selected transport modes, yet it requires large renewable electricity supply, water, and dedicated infrastructure and remains capital intensive. Advanced biofuels are generally easier to integrate into existing fuel logistics and are therefore well suited for near term emission reductions in aviation and shipping, although their long-term scaling is limited by sustainable feedstock availability and regulatory sustainability constraints.

4.4. Comparative Analysis of Propulsion Technologies—Managerial Perspective

Hydrogen and biofuels offer complementary pathways for decarbonizing transportation. Biofuels provide an immediate, low-risk solution by leveraging existing engines and infrastructure while reducing lifecycle CO_2 emissions, making them ideal for passenger vehicles, aviation, and marine transport. Hydrogen, with zero tailpipe emissions and high energy density, is better suited for long-haul fleets and heavy-duty applications but requires significant infrastructure investment and green production. From a managerial perspective, a portfolio approach is recommended to adopt biofuels in the short term to achieve quick emission reductions, invest strategically in hydrogen infrastructure and pilot programs over the medium term, and gradually transition key fleets to hydrogen in the long term while aligning with broader electrification and sustainability goals.

5. The Impact of Renewable Energy Sources in the Energy Mix on the Real Environmental Performance of Vehicles

The prevailing view in scientific literature is that the environmental friendliness of electric vehicles is largely determined by the source of the energy used to charge them [154]. A similar analytical approach, based on LCA, was used by Malinowski et al. when analyzing the environmental impact of a heat storage system in a stone battery powered by photovoltaic energy, which emphasizes the need for a comprehensive assessment of sustainable energy technologies [155].

An electric car itself does not emit exhaust gases while driving, but its actual impact on the climate is mainly determined by the "emissivity of the electricity" that powers its battery [156]. This means that whether a given BEV is truly a low-emission solution depends primarily on the cleanliness of the electricity mix in a given country or region [154–156].

Meta-analyses indicate that the variability of LCA results for electric vehicles is largely due to differences in the composition and intensity of emissions in energy generation systems [157–159]. This means that the same BEV model can have significantly different "plug-to-wheel" emission levels depending on the country or even the region in which it is operated [160,161]. In energy systems heavily reliant on fossil fuels, especially coal, the potential for CO_2 emissions reduction by electric vehicles is significantly weakened and, in extreme cases, may be completely negated. Examples from carbon-intensive markets show that, under certain conditions, the total emissions associated with the use of BEVs may exceed those of a comparable combustion engine vehicle [161–163].

However, it is not only the source of energy that matters, but also the time of consumption. From a climate perspective, marginal emissions, i.e., those resulting from an additional megawatt-hour fed into the power system, are crucial. In many cases, these are higher than average, and charging vehicles during off-peak hours can paradoxically increase their carbon footprint if the system relies mainly on fossil fuels at that time [164–166]. As a result, in countries with a still "dirty" energy mix, the environmental advantage of electric vehicles may be limited or even disappear, while in countries with low-carbon generation sources, such as renewable energy or nuclear power, BEVs enable a reduction in emissions throughout their entire life cycle [167–169].

From a practical perspective, this leads to an unambiguous conclusion: the environmental friendliness of electric vehicles increases with the progressive decarbonization of the electricity sector and responsible planning of charging strategies that take into account both time and location. This means that transport and energy policies should be designed in a coherent manner so that they reinforce each other and enable the full potential of transport electrification to be realized.

It should also be noted that the production of electric vehicles also has a significant environmental impact. This is related, among other things, to the production of batteries [170]. As shown in Figure 4, the ecological balance of electromobility includes both the environmental costs associated with emissions and the consumption of raw materials in the production process, as well as the benefits resulting from the absence of emissions during the use phase and the possibility of recycling. Furthermore, analyses show that in some impact categories, such as environmental acidification, dust emissions, and raw material consumption, electric vehicles may perform less favorably than combustion engine cars [171,172]. This is mainly due to the intensive use of metals and energy in battery production processes, which is a compromise between the various categories of environmental impact. Furthermore, the depletion of resources, including rare metals, in the production of electric cars is also significant [173,174].

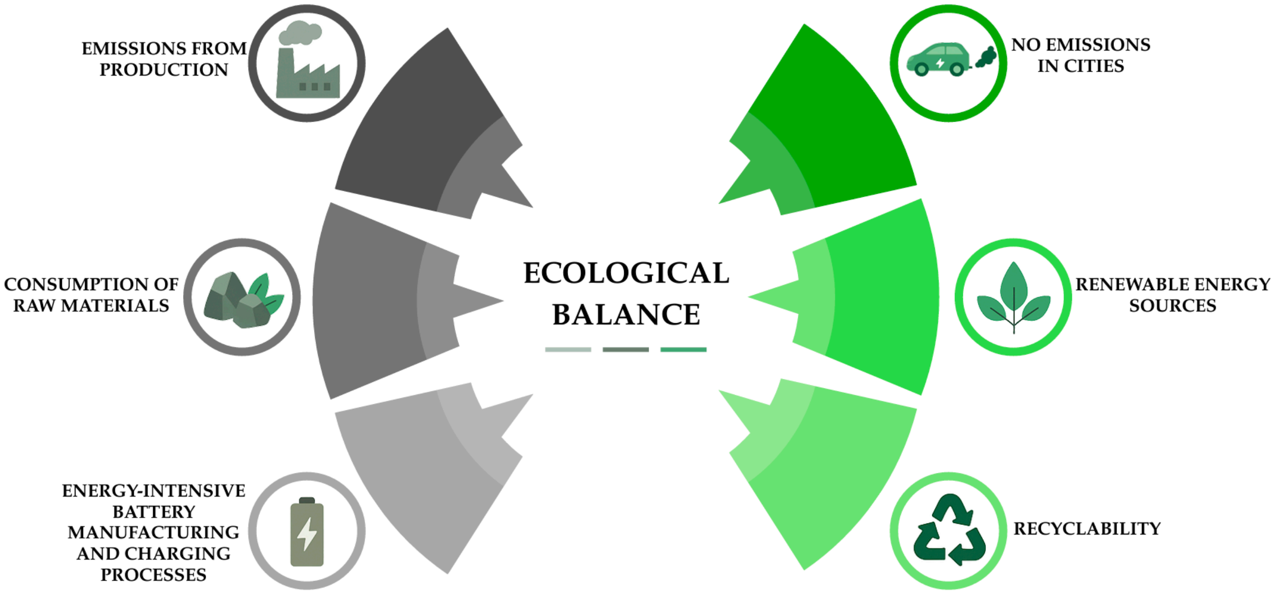

Figure 4. The environmental balance of electric vehicles [170–174].

This effect is offset to some extent by the recovery and recycling of materials, including batteries [175]. As indicated in the literature, at the end of an electric EVs life cycle, raw material recovery rates can reach 90–95%, with the battery recycling path and the efficiency of high-value metal recovery processes being of key importance [176–178]. It is emphasized that further development of battery recycling and reuse technologies can significantly improve the environmental balance of the entire electromobility system [179].

It is also important to note that although the overall environmental performance of electric vehicles depends on the energy mix, their impact on air quality in densely populated areas is positive. Even if the CO_2 emissions balance over the entire life cycle is comparable to that of combustion engine vehicles, it should be emphasized that BEVs do not emit exhaust gases or pollutants directly in cities [180–182]. This reduces emissions of nitrogen oxides, particulate matter, and other toxic substances, which translates into improved air quality and living conditions in urban environments.

It is also worth noting that the service life of modern electric cars is comparable to that of gasoline vehicles, and in many cases even higher, which further improves their performance in life cycle analysis [183,184]. This is because longer service life translates into lower unit emissions per kilometer traveled.

To sum up the assessment of the environmental performance of electric vehicles, it should be noted that the climate benefits of electromobility development largely depend on the structure of the energy mix. In countries where coal remains the dominant energy source, the potential for reducing CO_2 emissions from electric vehicles is limited, as emissions from electricity generation partially offset the gains achieved during the vehicle's use phase [185,186]. Therefore, for electromobility to become a viable tool for decarbonization, it is necessary to increase the share of renewable sources, i.e., photovoltaics, wind energy, biogas, nuclear energy, etc., i.e., decarbonization of the electricity sector [187–189]. Only with the progressive increase in the share of green energy will electric vehicles become truly "cleaner" and their environmental balance improve.

6. Climate Regulations in the Transport Sector and Legal Framework for Propulsion Technologies

6.1. Global Regulations (UN and International Agreements)

Global climate regulations form the foundation of international actions to limit greenhouse gas emissions and combat climate change. The United Nations (UN) and related negotiation and program forums, including the United Nations Framework Convention on Climate Change (UNFCCC), the Conference of the Parties (COP), and the 2030 Agenda for Sustainable Development, play a central role in shaping these policies [190–192]. Table 4 provides an overview of the principal global climate regulations and initiatives that influence policies and actions within the transport sector

Table 4. Overview of Global Climate Regulations and Their Implications for the Transport Sector.

Document/Initiative	Scope and Legal Basis	Main Objectives	Impact on Transport Sector
Paris Agreement (2015)	Global treaty under UNFCCC	Limit global warming to 1.5–2 °C; Nationally Determined Contributions (NDCs)	Accelerated shift to zero-emission transport systems [190]
UN 2030 Agenda for Sustainable Development	Strategic framework (17 SDGs)	Goal 13: Climate Action; integrate sustainability in mobility	Promotion of sustainable public transport [191]
COP Conferences	Annual UNFCCC meetings	Negotiate and implement Paris Agreement outcomes	Develop global norms and financing mechanisms [192]

These global frameworks, particularly the Paris Agreement, Agenda 2030, and annual COP summits, create the international foundation for transport sector decarbonization.

6.2. European Union Law

The European Union (EU) has developed one of the most comprehensive climate regulatory frameworks worldwide. Its overarching objective is to achieve climate neutrality by 2050, as outlined in the European Green Deal [193], supported by the 'Fit for 55' legislative package [194]. Table 5 outlines the main legislative instruments adopted by the European Union to implement its climate objectives and support the decarbonization of the transport sector.

Table 5. Key EU Climate and Transport-Related Legislative Instruments.

Legislative Instrument	Objective	Key Measures	Relevance to Transport
European Green Deal (2019)	Achieve EU climate neutrality by 2050	Comprehensive policy framework; European Climate Law	Supports low-emission transport innovation [193]
Fit for 55 Package (2021)	Reduce GHG emissions by 55% by 2030	Revision of ETS, ESR, LULUCF, and new CO_2 norms	Stimulates deployment of zero-emission vehicles [194]
Regulations EURO 6/7, AFIR (2023)	Set emission limits and infrastructure obligations	Ban sale of ICE vehicles after 2035; expand EV/hydrogen networks	Mandates zero-emission transport transition [195]
RED II and RED III Directives	Increase share of renewables to 14.5% in transport	Certification and sustainability criteria	Encourage use of biofuels and synthetic fuels [152]

The European Green Deal and the ‘Fit for 55’ Package provide a coherent legal pathway to decarbonize transport. Complementary regulations like AFIR and RED III strengthen infrastructure and renewable fuel frameworks [152,193–195].

The diversity of legal regulations affects not only the pace of implementation of different propulsion technologies but also the investment decisions of enterprises and the directions of scientific research. In countries with more advanced legal and financial support systems, alternative propulsion sources such as electric or hydrogen technologies tend to develop more rapidly. At the same time, the lack of regulatory coherence among EU Member States may create administrative barriers and limit competitiveness within the single European market. Therefore, efforts toward regulatory harmonization are essential to enable balanced technological progress while ensuring high environmental and safety standards.

6.3. Polish Law

Polish climate and transport law is primarily defined by the Act on Electromobility and Alternative Fuels (2018, as amended) [196], the ‘My Electric’ and ‘NaszEauto’ programs [197,198], and the Polish Energy Policy 2040 (PEP2040) [199]. These initiatives collectively promote electromobility and the transition towards a low-carbon transport system. Table 6 presents the main national legal and strategic instruments that shape Poland’s transition toward sustainable and low-carbon transport.

Table 6. National Legal and Strategic Framework for Sustainable Transport in Poland.

Area	Legal and Political Instrument	Key Provisions	Effect on Transport Sector	Ref.
Legal Framework	Act on Electromobility and Alternative Fuels (2018)	Defines EV charging, carsharing, zero-emission zones	Facilitates EV infrastructure growth	[196]
Support Programs	‘My Electric’, ‘NaszEauto’	Subsidies for EVs and charging infrastructure	Stimulates market adoption	[197,198]
Energy Policy	Polish Energy Policy 2040 (PEP2040)	Sets long-term targets for RES and transport decarbonization	Strategic planning framework	[199]
Implementation Challenges	AFIR and hydrogen law gaps	Insufficient charging network coverage	Delays in infrastructure deployment	[195,196]

Although national law supports electromobility through subsidies and regulatory incentives, implementation still faces challenges due to infrastructural and legislative delays. The presented instruments confirm Poland’s growing commitment to sustainable mobility; however, progress is limited by infrastructure gaps, insufficient network coverage, and the need for better alignment with EU regulations.

6.4. Summary of the Role of Law

Law acts as a primary driver of the transport sector's transformation, providing both regulatory obligations and financial incentives. Through binding emission targets, tax exemptions, and innovation funding, legal frameworks establish a stable foundation for the transition towards sustainable mobility.

6.5. Specific Legal Regulations on Propulsion Types

Distinct legal frameworks apply to different propulsion technologies. These define emission standards, infrastructure requirements, and financial support mechanisms. EU and national acts jointly shape the technological and market evolution of propulsion systems [152,190–195,197–199].

Table 7 summarizes the distinct EU and national legal frameworks applicable to different propulsion types, highlighting their regulatory coverage, support mechanisms, and implementation barriers.

Table 7. Overview of Legal Frameworks by Propulsion Type.

Propulsion Type	Legal Basis	Regulatory Scope	Support Instruments	Implementation Challenges
Electric (BEV)	AFIR; RED III; Electromobility Act; 'My Electric', 'NaszEauto'	Charging infrastructure and zero-emission zones	Subsidies, fee exemptions	Uneven network coverage [152,195,197,198]
Hybrid (PHEV/HEV)	Regulation (EU) 2019/631; Fit for 55	CO_2 and NO_x reduction; phase-out post-2035	Fleet transition allowances	Limited lifespan of support [194]
Hydrogen (FCEV)	RED III; AFIR; Hydrogen Strategy; draft Hydrogen Law	H_2 infrastructure, certification	IPCEI Hydrogen, NFOŚiGW	High costs, incomplete law [184,195,199]
Biofuels	RED II; RED III; Act on Biocomponents; PEP2040	Sustainability criteria and blending targets	NCW system, excise reliefs	Limited 2G biofuels [183,199]
Gas (CNG/LNG)	AFIR; Energy Law; Electromobility Act	Alternative fuel infrastructure and safety	Excise exemptions	Dependence on fossil methane [195]
Synthetic Fuels (e-fuels)	Regulation (EU) 2023/851; CEN/CENELEC	Certification of synthetic fuels	Innovation Fund, IPCEI	Lack of standardization [200]

The diversity of propulsion regulations reflects the maturity of technologies and climate priorities. Harmonization of certification and safety standards remains a core challenge.

7. Analysis and Discussion of Contemporary Trends in Propulsion Technology Development

7.1. Characteristics and Energy Efficiency of Propulsion Technologies

The analysis of contemporary trends in the development of propulsion technologies indicates a dynamic pursuit of solutions aimed at increasing energy efficiency and reducing greenhouse gas emissions, including carbon dioxide. In the context of the European Union's climate policy and global commitments arising from the Paris Agreement, the comparison of alternative propulsion systems such as electric, hydrogen, hybrid, and biofuel-based constitutes a key element in assessing the potential for transformation within the transport sector [201–204].

The electric drive is characterized by the highest energy efficiency among currently available technologies, reaching 70–90% in the well-to-wheel cycle [201]. Its high efficiency results from the direct conversion of electrical energy into mechanical energy with minimal losses. In comparison, hydrogen fuel cells demonstrate an overall efficiency of about 30–40%, mainly due to the energy-intensive processes of hydrogen production, compression, and storage [205,206]. Hybrid and internal combustion engines powered by biofuels achieve efficiencies in the range of 25–40%, but their advantage lies in the possibility of utilizing the existing fuel infrastructure, which significantly reduces the costs of their economic implementation [204,207].

In the context of the transformation of the transport sector, it is important not only to compare the energy efficiency of individual technologies but also to analyze their advantages and limitations in practical applications. As shown in Figure 5, propulsion technologies based on hydrogen, biofuels, and electricity differ in both efficiency and technological maturity.

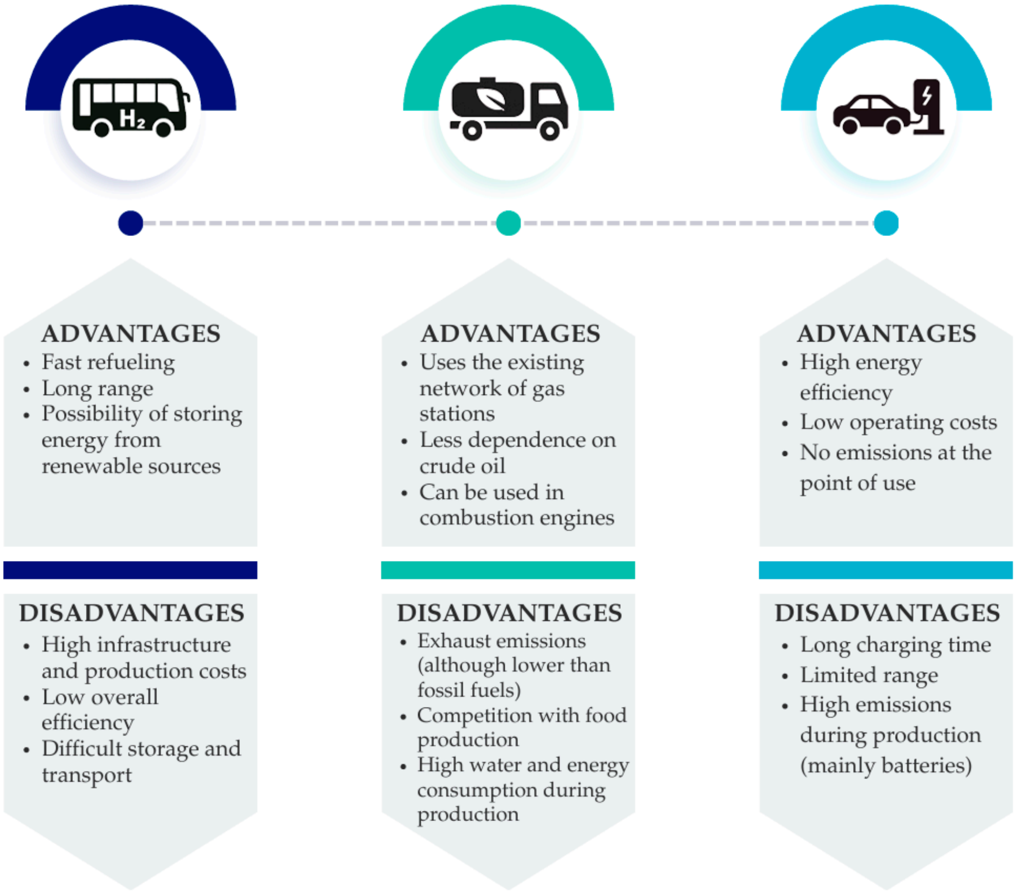

Figure 5. Summary of the advantages and disadvantages of selected drive technologies in the well-to-wheel cycle [208,209].

The presented comparison indicates that each of the analyzed propulsion technologies has a distinct development potential and scope of application. The choice of the optimal solution should consider not only energy efficiency but also resource availability, operating costs, and the possibilities for integration with the existing transport infrastructure.

7.2. Emissions and the Impact of the Energy Mix on the Carbon Balance

From the perspective of greenhouse gas emissions, electric vehicles do not generate direct emissions at the point of use; however, their overall carbon footprint depends on the structure of the energy mix in a given country or region [203]. In regions with a high share of renewable energy, the environmental benefits are significant, whereas in countries dominated by fossil fuels, they are considerably limited [210].

In the case of hydrogen propulsion, the origin of the feedstock is of key importance. Only so-called "green hydrogen," produced from renewable energy sources, ensures genuine climate neutrality [205]. Second-generation biofuels and synthetic fuels (e-fuels) may, in the long term, represent an important component of the fuel mix, contributing to the reduction of net CO_2 emissions, although their production requires a high energy input [207,211].

To systematize the presented information regarding energy efficiency and environmental conditions, Table 8 summarizes the key parameters of the compared propulsion technologies.

Table 8. Comparison of main propulsion technologies in terms of energy efficiency and environmental impact.

Powertrain Type	Energy Efficiency (Well-to-Wheel)	CO_2 Emissions (Life Cycle)	Technology Advantages	Limitations-Challenges	Development Outlook	Ref.
Electric (BEV)	70–90%	Depends on energy mix	High efficiency, zero local emissions	Battery cost, range, charging infrastructure	Rapid growth, renewable energy integration	[201,203]
Hydrogen (FCEV)	30–40%	Low with "green" hydrogen	Short refueling time, long range	High costs, lack of infrastructure	Potential in heavy transport	[205,206]
Hybrid (HEV/PHEV)	30–45%	Lower than ICE	Flexibility, reduced emissions	Dependence on fossil fuels	Transitional technology	[203,204]
Biofuel (ICE-Biofuel)	25–40%	Lower net CO_2 emissions	Uses existing infrastructure	Limited biomass resources	Short-term solution	[207,211]
Synthetic fuels (e-fuels)	30–50%	Low (if produced with renewables)	Compatible with combustion engines	High production costs	Potential for aviation and shipping	[205,206]

Based on Table 8, battery electric vehicles stand out with the highest well to wheel efficiency, which makes them the most energy effective option wherever direct electrification is feasible. By contrast, fuel pathways relying on conversion processes, such as hydrogen and e fuels, exhibit lower overall efficiency but offer operational advantages in use cases requiring long range, fast refueling, or high energy density, which is particularly relevant for heavy duty transport and selected segments of aviation and shipping. Hybrid powertrains and biofuel use in combustion engines can provide incremental improvements and near-term compatibility with existing vehicle fleets and infrastructure, yet they are typically positioned as transitional or niche solutions given their efficiency and scaling constraints.

7.3. Perspectives on the Development of Propulsion Technologies

In the short term, the most feasible development path appears to be the increasing adoption of BEVs, HEVs and PHEVs, supported by the expansion of charging infrastructure and the declining cost of lithium-ion batteries [203,204].

In the long-term perspective, hydrogen technologies and synthetic fuels may play a significant role, particularly in heavy-duty, maritime, and aviation transport, where full electrification remains technically limited [205,206,212]. In this regard, the use of synthetic fuels in engines, including marine and aircraft engines, with minimal modifications is of particular importance, as it significantly accelerates the deployment of these technologies under real economic and industrial conditions.

7.4. Biofuels as a Transitional Solution in the Decarbonization Process

Biofuels can serve as a transitional solution in the process of transport decarbonization [207,211]. This is primarily due to their limited feedstock availability and the challenges associated with sourcing raw materials that compete with agricultural production. The biomass resources designated for energy purposes are restricted by the need to maintain a balance between food production and fuel generation. Intensive land use for biomass cultivation may lead to changes in land use patterns, including deforestation and soil degradation, which can offset the potential climate benefits associated with biofuel use. Biofuels may therefore play an important role in the short-term decarbonization of transport; however, their long-term application requires careful balancing of climate benefits with feedstock limitations and impacts on agricultural systems.

The strategy for biofuel utilization should thus be regarded as part of an integrated approach to the energy transition in transport, complementing the development of electric and hydrogen fuels rather than serving as a final or standalone solution.

The above analysis indicates that there is no single, universal propulsion technology capable of fully meeting the requirements of energy efficiency, emission reduction, and ease of implementation. The optimal development path lies in a diversified technological mix that accounts for local energy, economic, and infrastructural conditions. Only a systemic approach that integrates various technologies in a complementary manner will enable effective long-term decarbonization of the transport sector [210,211]. Such an approach will also help mitigate the risks associated with dependence on a single technology while maintaining the continuity and flexibility of the transport system.

8. Conclusions and Future Research

The literature review conducted and the key trends and issues relevant to transport decarbonization outlined in the article are not exhaustive and have certain limitations. The synthesis presented in this paper is limited by the time frame and geographical scope of the source literature. The review focuses mainly on studies published in recent years and is largely based on data from the European Union and other highly developed economies, where data availability and policy precision are greatest. As a result, the conclusions drawn and trends identified may not fully reflect the specific characteristics of low- and middle-income countries, including many developing tropical regions, which are characterized by different patterns of transport demand, vehicle fleets, and institutional conditions. This limits the possibility of directly generalizing the results to all geopolitical and socio-economic contexts. What is more, the key parameters that translate into the emissions of individual solutions and the conditions of their operation, i.e., production technologies (including batteries), vehicle efficiency, the emissions of the energy mix or the restrictiveness of climate and air quality regulations, among others, may change in the future, which may shed a different light on the issues discussed.

Therefore, the comparative assessments and compromises discussed in this article should be treated as a snapshot of the current state of knowledge, rather than definitive conclusions that will remain unchanged over time. Finally, the publications analyzed are highly diverse in terms of scope, model assumptions, and performance indicators used. This diversity makes it difficult to directly compare results and prevents a formal meta-analysis from being conducted. Although we have attempted to identify the most consistent quality patterns and convergent conclusions, certain discrepancies between studies remain, resulting from both methodological differences and technological factors. Overcoming these limitations, for example through a more standardized evaluation framework and systematic reviews focused on specific technologies, regions, or policy instruments, should be the direction of further research on technologies that reduce road transport emissions.

The development of new types of propulsion systems represents one of the key pillars of the energy transition in the transport sector. The electrification of mobility, in the form of both fully BEVs, HEVs and PHEVs, already contributes in many countries to the reduction of fossil fuel consumption and greenhouse gas emissions. However, LCA studies have not confirmed an unequivocal global advantage of electric vehicles over internal combustion vehicles. The emission balance of BEVs strongly depends on the carbon intensity of the electricity mix, and in many countries with a high share of fossil fuels, it remains comparable or, in some cases, less favorable. Nevertheless, as the emission intensity of electricity generation decreases, the environmental advantage of BEVs gradually increases.

Today, many researchers consider hydrogen and biofuels as complementary development pathways, particularly in transport segments where electrification faces technological limitations. Low-emission hydrogen produced from renewable energy sources has the potential to decarbonize heavy transport, shipping, and aviation; however, further technological advances and the expansion of production, storage, and distribution infrastructure are required. Similarly, next-generation biofuels produced from waste and agricultural residues can contribute to emission reductions in the existing vehicle fleet, though their potential depends on sustainable supply chains, stable regulatory frameworks, and supportive policy measures.

A key condition for fully realizing the potential of these propulsion systems is the transformation of the entire energy system. The greater the share of renewable energy sources—such as solar, wind, hydro, and nuclear—the lower the carbon footprint of the energy that powers transport. A high degree of integration between the energy and transport sectors, the development of energy storage, and intelligent vehicle charging management may, in the long term, lead to a significant reduction of operational emissions and enhance the stability of the power system.

The transformation of propulsion technologies, however, requires not only technological innovation but also investments in infrastructure and changes in user behavior. The availability of charging and refueling points, system interoperability, and drivers' environmental awareness are essential conditions for the successful deployment of new technologies. Education on the efficient use of electric and hybrid vehicles, including charging during low-emission hours, can substantially strengthen environmental benefits.

It is also worth emphasizing that the evaluation of new propulsion technologies increasingly relies on the LCA methodology. This approach enables a comprehensive analysis of the environmental impact throughout the entire life span of a product or system, from raw material extraction and production through operation to end-of-life disposal or recycling. As demonstrated by Malinowski et al., the application of LCA methods in various sectors, including construction and demolition waste recovery, allows for the identification of key areas for emission reduction and resource efficiency improvement. These findings are of a universal nature and confirm that effective transport decarbonization requires a systemic perspective encompassing the entire life cycle of applied energy and material technologies [213].

Implementing an integrated approach requires linking climate goals with coherent strategies that combine the development of renewable energy sources, technological innovation, and appropriate regulations. This means ensuring consistency between national energy and climate plans and transport policy at the national, regional, and local levels. Support mechanisms may include, among others, dynamic tariffs that encourage charging during periods of high renewable energy supply and initiatives that integrate charging infrastructure with local energy systems. It should also be noted that a certain stability of public policies is crucial for reducing investment risk and making long-term decisions.

The results indicate that achieving sustainable transport goals requires a systemic approach in which technological solutions are complemented by demand side measures. Therefore, alongside electrification and the development of alternative fuels, an important element of the transformation strategy should be shaping a more efficient mobility mix.

Integrating non-motorized transport, walking and cycling into the mobility mix brings tangible benefits for sustainable transport because it reduces energy use and emissions by replacing a share of short car trips. At the same time, it decreases congestion, relieves pressure on infrastructure, and mitigates negative impacts in urban areas, which strengthens the effects of decarbonization efforts focused on vehicle technologies. Importantly, active transport supports lasting changes in mobility behavior and helps reduce the risk that technological progress will be partially offset by growing travel demand or other behavioral effects. Consequently, non-motorized transport should be treated as a complementary addition to electrification and other low emission solutions, improving the coherence and effectiveness of the overall transformation of the transport sector.

From a research and policy perspective, it is necessary to differentiate the strategies for implementing propulsion technologies in line with regional conditions. In highly developed economies, the priority should be to gradually increase the share of low-emission propulsion technologies and better integrate them into the energy system, where the share of renewable energy sources is growing. This includes the development of various solutions, including electric drives, hydrogen, advanced biofuels, and improving the efficiency of conventional engines, selected according to the specific characteristics of individual transport segments and the available infrastructure. In lower-income countries, the costs of available technologies, the development and quality of public transport, and the condition and origin of vehicles imported from abroad are of key importance. Future research should take into account both technical and economic conditions, user behavior, and social and distributional consequences in order to better support decision-makers in their search for solutions that combine environmental and economic goals with social expectations and expert knowledge in the process of transport decarbonization.

In summary, new propulsion technologies represent not only a technological direction for transport development but also an essential component of the broader energy transition. Their actual climate impact depends on the synergy between technological progress, infrastructure development, social change, and the pace of power sector decarbonization. Only integrated actions across these areas will enable electromobility, hydrogen, and biofuels to become lasting pillars of a low-carbon economy.

Author Contributions: Conceptualization, A.K., T.Z. and I.P.; methodology, A.K., T.Z. and I.P.; formal analysis, A.K., A.P. and I.P.; writing—original draft preparation, A.K., A.P., T.Z., Z.B., U.Z., P.G., L.A., A.A., A.D.W. and I.P.; writing—review and editing, A.K., T.Z., Z.B., U.Z., P.G. and I.P.; visualization, A.K. and I.P.; supervision. A.K. and T.Z.; project administration, A.K., U.Z. All authors have read and agreed to the published version of the manuscript.

Funding: The article presents the result of the Project no 026/GGR/2024/POT co-financed from the subsidy granted to the Krakow University of Economics.

Data Availability Statement: Data sharing is not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AFIR	Alternative Fuels Infrastructure Regulation
BEV	Battery Electric Vehicle
CCS	Combined Charging System
CO_2	Carbon Dioxide
CNG	Compressed Natural Gas
COP	Conference of the Parties (UNFCCC)
EEA	European Environment Agency
E-Fuels	Synthetic Electrofuels
EPA	U.S. Environmental Protection Agency
ETS	Emissions Trading System
EV	Electric Vehicle
FAME	Fatty Acid Methyl Esters (Biodiesel)
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gas
HEV	Hybrid Electric Vehicle
HRS	Hydrogen Refueling Station
HVO	Hydrotreated Vegetable Oil
ICE	Internal Combustion Engine
IEA	International Energy Agency
IPCEI	Important Project of Common European Interest
LCA	Life Cycle Assessment
LNG	Liquefied Natural Gas
NCW	National Indicative Target System (Poland)
NDC	Nationally Determined Contributions
NO_x	Nitrogen Oxides
PEMFC	Proton Exchange Membrane Fuel Cell
PEP2040	Polish Energy Policy 2040
PHEV	Plug-in Hybrid Electric Vehicle
PM	Particulate Matter
RED II/III	Renewable Energy Directive II/III
RES	Renewable Energy Sources
SAF	Sustainable Aviation Fuel
SMR	Steam Methane Reforming
SUV	Sport Utility Vehicle
UNFCCC	United Nations Framework Convention on Climate Change
V2G	Vehicle-to-Grid

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