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Review

Alternative Sources of Energy in Transport: A Review

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Abstract: Alternative sour2ces of energy are on the rise primarily because of environmental concerns, in addition to the depletion of fossil fuel reserves. Currently, there are many alternatives, approaches, and attempts to introduce alternative energy sources in the field of transport. This article centers around the need to explore additional energy sources beyond the current ones in use. It delves into individual energy sources that can be utilized for transportation, including their properties, production methods, and the advantages and disadvantages associated with their use across different types of drives. The article not only examines the situation in the Czech Republic but also in other nations. In addition to addressing future mobility, the thesis also considers how the utilization of new energy sources may impact the environment.

Keywords: alternative energy sources; transport; LCA; hydrogen

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1. Introduction

The automotive industry is facing great challenges in order to ban all conventionally fueled cars in cities by 2050, as stated in the EU White Paper. The European Union has taken various steps to enhance the proportion of renewable energy sources. The 2018/2001/EU Renewable Energy Directive was introduced with the goal of ensuring that the EU remains a prominent player in renewable energy and that it fulfills its obligations to reduce emissions as per the Paris Agreement. The new obligatory objective outlined in the directive aims to achieve a minimum of 32% renewable energy usage in the EU by 2030, following on from the previous target of 20% for 2020. To aid in achieving the target, the directive presents fresh measures targeting various economic sectors, with a focus on heating and cooling as well as transportation, where advancement has been sluggish.

The transportation industry, specifically, has accounted for 20% of the world's primary energy consumption, with fossil fuels comprising almost all of this demand (96%), and petroleum-based products (92%) dominating the sector. Renewable energy sources made up 7.6% of the EU's transportation sector in 2017, representing a 6.2% increase from 2004. As of 2019, the transportation sector in the EU was responsible for almost 30% of overall greenhouse gas (GHG) emissions, with road transport accounting for 72% of this total. In light of the current environmental conditions and the variability in both the sources and prices of petroleum-based fuels, the world is searching for sustainable alternatives to fuel and vehicles that are more effective, less detrimental, and friendlier to the environment [1–7].

The enhancement of urban air quality, the apprehensions regarding climate change, and the unwillingness to rely on non-renewable sources have served as the primary drivers for the creation of new technologies for electric vehicles and their associated applications. The impact of transportation activities on the environment is noteworthy, and comprises non-renewable resource depletion, polluting substance emissions (leading to climate change, photochemical smog formation, ozone layer depletion, acid rain, local air pollution, etc.), soil contamination, water eutrophication, ecotoxicity damage, accidents, noise pollution, and the disposal of vehicles and infrastructure. Gaseous pollutants such as SO_2, NO_x, CO, ozone, and Volatile Organic Compounds, persistent organic pollutants like dioxins, heavy metals including lead and mercury, and particulate matter are all examples of air pollutants. Air pollution has both immediate and long-term effects on human health, impacting various systems and organs. Additionally, road transport is responsible for creating noise pollution, which is another significant health concern. Environmental noise in Europe is primarily caused by road traffic, and research indicates that more than 25% of people in Europe are exposed to road noise levels exceeding 55 dB [2,3,8,9].

When comparing alternative fuel vehicles, conflicting objectives arise in terms of their environmental, economic, and social impacts. For instance, while electric vehicles may decrease greenhouse gas emissions, they may also lead to higher water consumption. Additionally, the generation of electricity and heat worldwide still relies heavily on coal and other hydrocarbons, and the existing infrastructure for fossil fuels makes them a cheaper source of energy [5,9,10].

Countless reviews and studies on the use of alternative fuels and their LCA have been carried out in the past, either with regard to passenger transport or the use of alternative fuels in urban public transport. However, in recent years, there have been several significant global events (the COVID-19 pandemic, the war in Ukraine) that have had a significant impact on both the price and availability of conventional fuels. This work is unique in that it provides an overview of studies mainly from 2019–2023 and thus provides the most up-to-date review on the given issue.

2. Terminology

2.1. Life Cycle Assessment

Life cycle assessment (LCA) is a valuable tool that can demonstrate the complex interactions between a product or technology and the environment. It considers the main categories of environmental impact, including effects on human health, use of natural resources, and impact on ecosystem quality, among others. As one of the best environmental management tools available, LCA is ideal for comparing the impacts of different products or process systems. The overall life cycle of a vehicle includes material extraction and processing, manufacturing and assembly, maintenance, and end-of-life considerations. By assessing all phases of a vehicle's life cycle, a comprehensive evaluation of its environmental impacts can be obtained. LCA is recommended for identifying environmental impacts throughout a product's life cycle, allowing vehicle designers and manufacturers, fuel producers and distributors, and policy makers to make informed decisions regarding the environmental consequences of the entire production and supply chain [1,3,10].

It is more challenging to predict and evaluate the environmental consequences in advance because they involve more variables, uncertainties, and interconnections. The Life Cycle Impact Assessment analyzes various types of environmental impacts, such as the Ozone Depletion Layer Potential, Abiotic Depletion Potential, Fossil Fuels Abiotic Depletion Potential, Global Warming Potential, Human Toxicity Potential, Photochemical Oxidant Formation Potential, Acidification Potential, and Eutrophication Potential [3].

In conducting an LCA study, there are four primary choices for establishing the system boundaries, and for vehicles, a well-to-wheel approach is utilized to examine the entire life cycle of the vehicle.

2.2. Cradle-to-Grave

This approach considers the entire material and energy production chain, encompassing all processes from the extraction of raw materials to the production, transportation, use phase, and end-of-life treatment of the product, including materials production, equipment manufacturing, maintenance, and end-of-life treatment of the vehicle and road infrastructure. The end-of-life stage involves dismantling and recovering vehicle parts, as well as shredding, recycling, and disposing of residues. The approach also accounts for vehicle and battery production, operation, maintenance, disposal, and road infrastructure. The operation of the vehicles includes direct emissions caused by fuel combustion and non-exhaust emissions, such as those resulting from brakes, tires, and road wear.

2.3. Cradle to Gate

This approach focuses on the processes involved in the production of a product, from the extraction of raw materials to the point of manufacture (factory gate). It aims to assess the environmental impact of the production phase only, without considering the use and disposal stages. It is a partial analysis, useful in large system LCA process.

2.4. Cradle to Cradle

This tool is a fundamental element of the circular economy, enabling the transformation of production processes to minimize waste and achieve a positive impact. In this context, the end-of-life phase is considered as a recycling process.

2.5. Gate to Gate

This approach focuses solely on processes within the production phase and is employed to evaluate the environmental impacts of individual production steps or processes.

2.6. Well to Wheel

The WTW stages encompass the extraction of energy resources, production and distribution of energy carriers, and the conversion of energy in the vehicle. This boundary is specifically defined to evaluate the overall energy consumption or efficiency of energy conversion and its impact on emissions [2,11].

3. Current Studies

The concentration of CO_2 in the atmosphere has shown a significant increase as compared to the preindustrial era. As of October 2016, the CO_2 concentration level stood at 402.31 ppm, approximately 42% higher than the mid-1800 levels (around 280 ppm). Additionally, there have been notable increases in CH_4 and N_2O levels. The transport sector is considered one of the most polluting sectors, which is why alternative technologies to traditional combustion engines and fuels are being explored, such as battery electric (BEV), hybrid electric (HEV), plug-in hybrid (PHEV), compressed natural gas (CNG), biogas (BG), and more [3,12].

3.1. Biodiesel from Various Oils

Renewable fuels derived from vegetable oils are seen as an appealing substitute to fossil fuels, with the European Union primarily focusing on biodiesel made from oil waste and fats, soybean, rapeseed, and palm oil. Some vegetable oils, such as palm, sunflower, jatropha, and rapeseed, share similar characteristics with diesel, although some have issues with low volatility and high viscosity. Blending higher chain alcohols with biodiesel leads to better performance than blending lower chain alcohols, and hydrogen performs similarly to standard diesel engines, with a notable reduction in NO_x.

While there are nearly different types of esters of edible oils, non-edible oil can be used as an alternative fuel with standard diesel. However, alcohols and ethers are the most suitable additives for improving performance, combustion, and emission characteristics. Studies have shown that the use of biodiesel results in reduced emissions of HC and CO and smoke and increased emissions of NO_x [13,14].

3.2. Biogas

Upgrading biogas to biomethane is a promising option to make the automotive energy sector more sustainable, especially for transportation. Bio-CNG and bio-LNG fuels are regarded as viable alternatives for freight, and the European biomethane industry demonstrates significant production capabilities, driven by rising demand. However, promoting biomethane to reduce GHG emissions must be done with caution since it can cause fugitive emissions, such as those resulting from gas transportation and combustion, which can offset the benefits. Furthermore, the current high costs of biomethane can limit its wider adoption as an alternative fuel. Despite these challenges, the European biomethane sector holds promising potential to meet the future energy demands of the European transportation sector [15].

3.3. Dimethyl Ether

Life cycle assessments conducted on dimethyl ether (DME) have demonstrated that bio-DME fuel produced using a CO_2-enhanced process can reduce its impact on climate change, toxicity, and ecotoxicity by at least 20%. Using pure DME can result in a 72% reduction in GHG emissions, and its impact on human health and ecosystems can be reduced by 55% and 68%, respectively. The use of DME fuel can also limit the emission of carcinogenic particulates, such as diesel soot, and decrease the toxicity of traffic emissions. However, when DME is mixed with diesel (15% DME by weight in diesel), the environmental impact is only slightly reduced by up to 7% compared to pure diesel. A CO_2-enhanced process for producing bio-DME can significantly reduce the environmental impact of the production process by recycling waste CO_2 as a gasifying agent. Bio-DME is considered a cleaner automotive fuel compared to pure diesel [16].

3.4. Electricity

The adoption of electric vehicles (EVs) is a significant step towards reducing environmental impact. Unlike vehicles with internal combustion engines, battery electric vehicles (BEVs) do not emit direct air pollutants during operation. However, the environmental performance of BEVs, as well as fuel cell vehicles (FCVs) and plug-in hybrid electric vehicles (PHEVs), may be worse than modern fossil fuel vehicles due to emissions from vehicle and fuel production chains. The performance of EVs also depends on regional driving patterns and the sources of electricity used, as demonstrated by the varying air pollution levels observed in different countries. Despite the potential drawbacks, EVs coupled with low-carbon electricity sources such as biofuels and natural gas are more sustainable from a life cycle perspective. To better understand the environmental impacts of future battery electric vehicles, life-cycle background databases must include data on the production phase and energy sources used. Recent research has indicated that the environmental impact of BEVs is strongly affected by the battery size and energy requirements. Alternative fuels, such as bioethanol, biodiesel, biomethanol, biogas, and solar energy, may be viable options for the future. As such, it is crucial to include future developments in the electricity sector in life-cycle background databases to gain a better understanding of the environmental impacts of BEVs. Additionally, the production phase and the energy sources used to manufacture these vehicles should also be taken into account, as BEVs are more sensitive to changes in the energy sector than traditional combustion vehicles [2,3,5,8,17,18].

One of the problems with battery vehicles is the question of having enough renewable energy to power electric fleets and whether there will be enough lithium and cobalt reserves to meet the demand for battery construction. As of 2022, lithium resources were estimated at approximately 98 million tons worldwide, with reserves in various countries such as the US, Bolivia, Argentina, Chile, Australia, China, and Germany. Additionally, if electric vehicles continue to be charged using fossil-fuel-generated electricity, the reduction in greenhouse gas emissions may not be significant. For instance, replacing 100% of the Brazilian fleet with electric vehicles would increase daily demand by 533 GWh/day or 194.55 TWh/year, equivalent to a 19.40% increase in electricity consumption. However, this could still be positive for the environment, as Brazil's electricity matrix was composed of 84.5% renewable energy sources, specifically 71% hydro, 23% thermal (8% natural gas, 7% biomass, 4% fuel oil, 2% coal, 1% nuclear, 1% other), and 6% wind in 2016, compared to the global average of only 23.65% in the same year [3,12,15,19–21].

Currently, the most commonly used electricity storage units in BEVs are lithium-ion batteries, specifically lithium manganese oxide and lithium iron phosphate. This is due to their favorable specific energy density and power characteristics. However, the overall environmental impact of these batteries is influenced significantly by the electricity used to charge them during their use phase, impacting categories such as climate change, particulate matter formation, human toxicity, and material depletion. To improve the environmental performance of these batteries, charging them with renewable electricity is crucial. Moreover, the recycling of materials is a major concern for both human toxicity and material depletion. Recycling has been shown to have a significant impact on the overall efficiency of equipment life cycles, and there is a need for more efficient large-scale recycling industries to achieve better results. Currently, only lead acid batteries have highly efficient recycling processes. Thus, to achieve better environmental outcomes, more efficient recycling processes are needed for the latest battery technologies [19].

The electricity mix is a critical factor in determining the life-cycle emissions of electric vehicles, but it can vary greatly from hour to hour. In Belgium, studies of BEV usage patterns have shown that drivers tend to charge their vehicles during the day when energy demand and costs are high. However, charging during off-peak hours (midnight to 8 AM) can result in the lowest emissions for all analyzed emissions. This is because off-peak hours are mainly supplied by base load nuclear plants, renewable energy sources, and some flexible natural gas plants with better efficiency. Charging during off-peak hours could reduce WTT CO_2, PM, NO_X, and SO_2 emissions per km by 12%, 15%, 13%, and 12%, respectively. Additionally, the charging mode (fast or normal) could impact the performance and durability of lithium batteries, with more cycles leading to greater durability. Finally, it should be noted that the efficient large-scale recycling of lithium-ion batteries is crucial to improving their environmental performance over their life cycle [12].

3.5. Hydrogen

The reason for the growing interest in hydrogen as an energy carrier and the drive to replace fossil fuels is due to its favorable characteristics—it releases a large amount of energy when reacting with oxygen, and the only byproduct is water. With advancements in technology for production, storage, and use, it has the potential to be a clean, safe, and sustainable energy source. However, currently, the majority of hydrogen production relies on fossil fuels, particularly natural gas, which accounts for about three-quarters of the world's production. Coal is also a significant raw material for hydrogen production. Various methods are used for producing hydrogen, including natural gas and light hydrocarbon conversion, water electrolysis, biomass gasification, and coal gasification. Biomass-based hydrogen production has similar efficiency as water-based methods, but offers lower operating costs and higher energy efficiency. To achieve a green hydrogen economy, it is crucial to shift to renewable feedstocks for hydrogen production instead of fossil fuels. Currently, a highly efficient pulverized coal boiler is being explored for industrial use, with thermal efficiencies above 90% and emissions comparable to natural gas boilers. While hydrogen poses challenges in storage, transport, and use, it remains an important fuel. Improving engine optimization and onboard storage systems can enhance the driving range of hydrogen vehicles. In the short-term, vehicles using hydrogen mixed with fossil fuels can serve as an initial push towards a hydrogen economy, while pure hydrogen vehicles remain a more preferable decarbonization solution. However, producing hydrogen with a high renewable content can be challenging due to the intermittency of renewable energy. Policy, technology, and natural resources can work together to overcome this challenge [1,3,8,19,22–26].

There are various types of hydrogen that differ based on their production method. Grey hydrogen is the most prevalent type of hydrogen at present. It is produced through steam methane reformation of natural gas or methane, but without capturing the greenhouse gases produced during the process.

Blue hydrogen is similar to grey hydrogen in that it is primarily produced using steam reformation of natural gas or coal, but with the added step of carbon capture and storage of CO_2, which sets it apart.

Turquoise hydrogen is generated through methane pyrolysis and solid carbon, and its cost is significantly impacted by the value of solid carbon and natural gas prices. The production of turquoise hydrogen using renewable natural gas will have a crucial role in achieving a clean energy transition in comparison to grey and blue hydrogen. Currently, it is still in the experimental stage of development.

Purple hydrogen, also known as pink or red hydrogen, is generated through a nuclear thermochemical cycle. Nonetheless, further technological advancements are required to enhance its efficiency and decrease costs on a worldwide level.

Green hydrogen, which is produced through water electrolysis using renewable resources, is a zero-carbon form of hydrogen and is crucial for deep decarbonization of the transportation sector. However, the production cost of green hydrogen is presently higher than that of blue hydrogen, primarily due to the cost of the electrolyzer, its capacity factor, and the cost of renewable electricity [19].

3.6. Waste

As the amount of waste increases, so does the demand for its processing. Land-filling is not a solution in the long term, so studies on the use of different types of waste as a source of alternative fuels are multiplying. In this chapter, several studies on the topic of processing different types of waste into fuel are presented.

One such method is converting tires into tire oil and then into fuel via pyrolysis. This process generates liquid oil, char, and pyro gas, which can be useful products. Through vacuum distillation, the resulting tire oil is purer than crude tire pyrolysis oil (TPO) and has similar properties to diesel fuel. Additional modification steps, such as moisture removal, desulfurization, and vacuum distillation, can further enhance the properties of the TPO. Overall, tire oil pyrolysis is a sustainable and effective method that can produce a high-quality fuel, is economically feasible, and offers an optimal solution for waste tire management and petroleum product replacement. To improve combustion quality and reduce emissions, some studies have suggested adding biodiesel and nanoparticles to the TPO-DF blend, which increases oxygen by weight. Ultimately, distilled TPO can serve as a viable alternative to diesel fuel [27].

An alternative choice is to utilize waste PET bottles to generate pyrolytic plastic oil. However, it is not advised to directly employ it in diesel engines. Instead, it is recommended to use it as an additive to diminish the quantity of diesel fuel utilized. Furthermore, it is suggested not to surpass a volume of 20% to maintain similar engine characteristics and emission rates to diesel fuel [28].

In the aftermath of the COVID-19 pandemic, there have been studies on the use of medical plastic waste generated during this period. The World Health Organization (WHO) declared the COVID-19 pandemic a public health emergency on 30 January 2020. As a result, many governments around the world recommended several preventive measures to reduce the risk of COVID-19 transmission, including the use of face masks, face shields, personal protective equipment kits, and gloves. The surge in waste, particularly plastics, in both the medical and general sectors was evident and posed a significant threat to the environment. In response to the increasing demand for PPE among healthcare workers, service employees, and individuals, China's production of single-use face masks increased to 116 million per day in February 2020, more than twelve times the average amount. Globally, supplements have seen a 40% increase in use for food packaging and a 17% increase for other purposes. Plastics are an essential component of modern society due to their durability and resistance to degradation from chemicals, physical forces, and biological factors. Medical plastic waste and infected plastic trash require sterilization before reuse. Among various sterilization techniques, microwave sterilization is a suitable method for medical plastic waste. Pyrolysis oil production is a promising method for managing COVID-19 medical waste. The pyrolysis technique yields mainly pyrolysis oil (70–80%) and a small amount of solid char (10–15%). Due to tests of physicochemical properties (calorific value, density, API gravity, kinematic viscosity, ash content, cetane number, pour point, flash point, and fire point) that were carried out by the Institute of Petroleum and the American Society for Testing and Materials, it was found that fuel obtained from various plastics has the potential to be a fossil fuel for internal combustion engines. However, pyrolysis requires optimal conditions, appropriate catalysts, and a gas cleaning system to mitigate concerns. Nonetheless, the high cost of collecting and recycling medical plastic waste remains the primary obstacle to widespread deployment of the technology. Improving the equipment, process design, scalability, building more facilities, and enhancing product properties could alleviate this challenge [29,30].

A different strategy is the utilization of Waste-to-Hydrogen, which provides a two-fold solution by simultaneously producing non-fossil-fuel-based hydrogen and promoting sustainable waste management. Gasification and fermentation are two primary WtH technologies that have been shown to reduce CO_2-eq emissions per kg of H_2 by 50–69% compared to the traditional steam methane reforming hydrogen production method used to fuel vehicles. In addition, gasification of municipal solid and wood waste exhibits lower global warming potentials than dark fermentation of wet waste and combined dark and photo fermentation. Gasification technology has been established since the 1970s, and numerous industrial or large-scale gasification processes for plastic waste have been developed as a result [31–33].

3.7. Microalgae

Microalgae are tiny aquatic photosynthetic organisms that require CO_2 for growth. They do not compete with food crops for resources, and their ability to absorb harmful CO_2 emissions makes them a promising biofuel source. Due to their high photon conversion efficiency, microalgae convert solar energy to chemical energy more efficiently than other crops used for biodiesel. Additionally, microalgae have a high oil content and a fast growth rate, which makes them suitable for biodiesel production. They can be cultivated on non-arid, non-productive land, including coastal land, brackish water, and wastewater, and their production is non-seasonal. Furthermore, microalgae are effective in bioremediation of wastewater, removing nitrogen and phosphorus, which are two of the most challenging elements to remove in wastewater treatment. The advantages of microalgae biodiesel production have led researchers to focus on improving cultivation and production processes. To produce biodiesel from algae, four consecutive stages must be undergone, including cultivation, harvesting, lipid extraction, and transesterification and fermentation. Research has demonstrated that the use of algae biodiesel blend in engines can improve performance beyond that of pure diesel, exhibiting a decrease in brake specific fuel consumption, an increase in brake thermal efficiency, a rise in heat release rate, exhaust temperature, peak pressure, and more, surpassing other biodiesel blends. A two-step process has also been tested, revealing that the calorific value of the produced biodiesel was lower than that of gasoline or diesel but higher than popular biodiesels such as palm and Jatropha. The viscosity and density of the algal biodiesel were almost identical to petro-diesel, and all properties fell within American Society for Testing and Materials standards. Moreover, the feedstock to oil conversion ratio obtained with algae is approximately 70% [34–37].

3.8. Alcohol Blends

Alcohol fuels are another promising category of renewable fuels for internal combustion engines. Methanol, a low-carbon-intensity electro-fuel, and ethanol, a low-carbon-intensity biofuel, show great potential. In fact, these two fuels can be produced synergistically. In a fully renewable scenario, gas fermentation and CO_2 to hydrocarbon catalysis can be combined with conventional ethanol production to co-produce ethanol and methanol at prices competitive with current gasoline costs. This co-production can significantly increase the yield of alcohol fuel per hectare of crop, all while remaining carbon-neutral and cost-competitive with conventional fossil fuels. Wet ethanol 80, for example, can be produced with lower carbon intensity than conventional fossil fuels at a cost comparable to the availability of other renewable fuels. Wet ethanol 80 emits slightly lower engine NO_x emissions, with a net fuel conversion efficiency penalty compared to methanol due to the effect of water dilution. A combination of wet ethanol 80 and methanol was found to behave similarly to pure wet ethanol 80 and pure methanol, suggesting that these fuels are interchangeable and can be blended to match the output of coproduction plants. An engine can be designed to operate on high-cooling potential alcohol fuels, such as wet ethanol, methanol, or a blend of the two, based on local availability. In Brazil, flexible fuel vehicles (FFVs) can also use 100% ethanol (E100) as fuel, which has led to FFVs accounting for over 90% of new car sales and around half of the country's light vehicle fleet. In 2014, the transportation sector was responsible for 32.5% of energy consumption and 46.3% of greenhouse gas emissions in Brazil, and it has experienced the highest growth rate in energy consumption (4.42% per year between 2002 and 2012) [3,38].

4. Results and Discussion

To compare the GHG emissions of BEVs with those of internal combustion engine vehicles (ICEVs) in Europe, it is necessary to take into account the entire power supply, which refers to the combination of primary sources used for electricity generation in each country. This is because the electricity generation mix can vary and result in different emissions for BEVs. This chapter presents the knowledge gained from current studies [39].

To be specific, EVs charged with the Belgian average electricity mix have the lowest emissions, followed by PHEVs and biomethane vehicles. It should be noted that the manufacturing process of EVs results in higher CO_2 emissions than FFVs, primarily due to the battery and its associated electrical components. However, the environmental impact of lithium batteries can be balanced by recycling. Recycling specific components, such as the battery pack, is beneficial for the environment, especially for EVs. FFVs with lower emissions include biomethane vehicles, followed CNG vehicles. The type of electricity used to power electric vehicles strongly affects their environmental impact, as they can be charged using a variety of sources including coal, gas, nuclear, and renewables like biomass, wind, and solar. When considering the photochemical oxidant formation impact category, BEVs have the lowest overall score, followed by CNG, PHEV, etc. In contrast, conventional vehicles have higher overall scores than CNG and electrified vehicles. In terms of the PMF impact category, BEVs and CNG vehicles have more or less the same total score, which is the lowest among the compared vehicle technologies. The BEV has the lowest score for particle matter emissions as it does not produce tailpipe emissions. The CNG vehicle has the lowest human toxicity potential among the compared vehicles, primarily due to the low toxic emissions from the WTW. However, for BEVs, specific components such as the lithium-ion battery, electric motor, and power electronics contribute significantly to the overall impact. It is important to note that these results have a significant level of uncertainty, which is reflected in the error bars. Toxic substances are primarily emitted during the raw material extraction processes for vehicle manufacturing and as an energy source for electricity. Comparing the life cycle assessments of various vehicle technologies shows that plug-in electric vehicles, such as BEVs and PHEVs, generally have the lowest greenhouse gas emissions, followed by biomethane vehicles. As electrification level increases from HEV to PHEV, EREV, and BEV, life cycle CO_2 emissions tend to decrease. In terms of local pollution, BEVs have the lowest score for photochemical oxidant formation POF, while both CNG and BEVs have similar levels of PM emissions during the life cycle. However, when considering local emissions within the Belgium perimeter, the BEV performs better than all other compared vehicles [12].

The current technologies with the lowest life cycle GHG emissions in regions where gasoline vehicles cause the highest emissions are CNG and diesel hybrids, as well as BEV charged with the EU electricity mix. By 2030, the BEV is expected to have the best performance in terms of potential impacts on climate change, reducing emissions by almost half compared to the current level. In addition, other vehicle technologies are also projected to reduce their lifetime GHG emissions by 2030, primarily due to increasing fuel efficiency, such as a reduction in fuel demand and the expected drop in GHG intensity of the European electricity mix. The production of BEV and FCV generates higher GHG emissions compared to ICEV due to the additional burdens from battery and fuel cell production. However, these increases in emissions are relatively insignificant compared to the exhaust emissions of ICEV and can be easily offset by using electricity or hydrogen produced from renewable energy sources. The full potential of BEV and FCV to reduce GHG emissions can only be realized if the electricity and hydrogen used to power these vehicles have very low GHG intensities, meaning they are generated without fossil fuels. In terms of human toxicity potential, ICEV gasoline consistently outperforms both BEV and FCV, regardless of the fuel generation technology used, due to the high contributions from fuel chains and battery and fuel cell manufacturing. A comparison of BEV and FCV using hydrogen produced through electrolysis reveals a loss in overall fuel-chain efficiency for the FCV. The BEV charged with electricity from a coal power plant produces the highest burdens in the acidification and PM formation categories. However, BEVs charged with electricity from all other sources result in less acidification potential and less PM formation than gasoline ICEV, while all FCVs generate higher burdens. In the photochemical oxidant formation category, compared to gasoline ICEV, BEV and FCV have the lowest burdens. The production of fuel cells, hydrogen, and electricity results in lower impacts in comparison to other damage categories. In order for BEV and FCV to significantly reduce the life cycle GHG emissions, it is imperative that they are powered by electricity and hydrogen that are produced using non-fossil energy resources. This could lead to a reduction of up to 80% in the carbon footprint of passenger vehicles. However, the use of fossil fuels for electricity and hydrogen production may lead to an increase in GHG emissions. Although BEV charged with "clean electricity" results in slightly lower burdens than fossil-fueled ICEV, FCV tends to generate higher burdens regardless of the hydrogen generation pathway [8].

A study conducted in Brazil, a country with a significant proportion of renewable energy sources in its electricity grid mix and widespread use of ethanol as fuel, revealed that no vehicle technology performs well in all environmental impact categories. However, among the technologies studied, BEV had the lowest environmental impact, followed by internal combustion engine vehicles fueled by hydrous ethanol, which also had lower environmental impact. In contrast, ICEVs fueled by gasoline or a mixture of gasoline and ethanol had the highest overall environmental burden. This suggests that an isolated analysis of specific impact categories is necessary to achieve the intended objective. Although ethanol fuel offers advantages in terms of energy savings from fossil fuels and reducing greenhouse gas emissions, it has negative impacts on acidification potential, eutrophication potential, and photochemical oxidant formation potential. Regarding Abiotic Depletion Potential, Fossil Fuel Depletion Potential, and Global Warming Potential, PHEVs and ICEVs fueled by gasoline exhibit similar trend lines, with ICEVs fueled solely by gasoline having a higher impact due to their widespread use. If 50% of the ICEV gasoline fleet were replaced by ICEVs fueled by hydrous ethanol, annual carbon emissions would decrease by approximately 33% of the total emissions. On the other hand, if 50% of the ICEV gasoline fleet were replaced by a BEV fleet, carbon emissions would decrease by approximately 24% of the total emissions. However, BEVs and PHEVs exhibit higher results in terms of human toxic potential due to the impacts of Li-ion battery production. The production of battery-powered vehicles has a significant human toxic potential due to the materials used in battery manufacturing. Overall, the technology categorized as BEV shows better environmental impact results in categories such as Persistent Organic Pollutants, Acidification Potential, and Eutrophication Potential due to Brazil's electric grid mix [3].

The study found that ICEVs fueled with gasoline have a significant impact on damage assessment, with the impact on human health and resources contributing the most at 38% and 42%, respectively. ICEVs fueled with diesel had a 28% lower total environmental damage, with both human health and resources impacts contributing equally. On the other hand, the BEV powered by the 2015 electricity mix had almost no damage to ecosystems and had a total impact that was 42% and 57% less than ICEV-diesel and ICEV-petrol, respectively. Moreover, the environmental damage of the BEV with the 2050 electricity mix was 54% less than the BEV with the 2015 electricity mix and 73% and 80% less than the ICEVs fueled with diesel and gasoline, respectively. These findings indicate that the integration of RES in electricity production has the potential to provide environmental benefits for the performance of BEVs in the transport system [2].

A comparative analysis of electric vehicles and internal combustion engine vehicles in Poland and the Czech Republic revealed that electric vehicles have lower greenhouse gas (GHG) emissions and fossil fuel depletion in both the present and future. However, electric vehicles were found to cause higher levels of acidification, eutrophication, human toxicity, and particulate matter formation compared to internal combustion engine vehicles. When considering charging sources, electric vehicles charged exclusively from renewable sources demonstrated lower levels of GHG emissions, fossil fuel depletion, terrestrial acidification, and particulate matter formation compared to other variants of electric vehicles and internal combustion engine vehicles analyzed. Additionally, when analyzing freshwater eutrophication and human toxicity, charging electric vehicles exclusively from renewable sources resulted in significant reductions in negative impacts compared to other charging variants, including those using the electricity mix in Poland and the Czech Republic. The impact categories for ICEVs were found to be lower than EVs when using RES. Among the renewable energy sources analyzed for electricity production, hydroelectricity yielded the lowest environmental indicators for all impact categories when charging EV batteries. Thus, the study suggests that using EVs with renewable energy sources has the potential to reduce negative environmental impacts. The type of electricity used to charge EV batteries was found to be the main determinant of the environmental impact of EVs. It was observed that environmental indicators in all impact categories were higher for EVs in Poland than in the Czech Republic. Hence, the type of electricity used for recharging EV batteries was identified as the main determinant of all impact categories analyzed for EVs in both countries [40].

In Qatar, it was found that PHEVs, BEVs, and HEVs have significantly lower impacts on Global Warming Potential, Particulate Matter Formation, and Photochemical Ozone Formation compared to ICVs, and electric vehicles demonstrate better performance when charged with solar energy. Specifically, BEVs charged with solar energy exhibit superior performance, capable of reducing up to 100%, 98%, and 99% of GWP, PMF, and POF emissions, respectively. However, BEVs perform the worst in the category of water withdrawal compared to other options, although they perform slightly better than ICVs in the impact of water consumption category. Additionally, BEVs, particularly those powered by solar panels, have the lowest energy inputs and land use impacts compared to other options, with the potential to reduce impacts by up to 95% and 72%, respectively. Although the study showed that over 97% of the impact of land use occurs outside of Qatar, the majority (over 92%) of the energy input takes place within Qatar for all vehicle alternatives. In terms of human health impacts, ICVs were found to have the highest negative impact, while BEVs were the most beneficial, especially when powered by solar energy, which could reduce human health impacts by up to 99%. The majority of these impacts were observed within Qatar, except for BEVs that were solar-powered. Despite these positive environmental impacts, the use of electric vehicles is hindered by economic considerations. For instance, BEVs scored poorly in total, tax, GDP, and operating surplus generation compared to other options. Moreover, solar-powered EVs could slightly enhance the performance of EVs in operating surplus, but would negatively impact total tax and have no effect on GDP [41].

The assessment results indicate that BEVs can significantly decrease the impact on climate change due to the absence of exhaust emissions during operation. However, the manufacturing process of BEVs results in a larger environmental load compared to ICEVs, particularly due to the high usage of metals, chemicals, and energy in specific components of the electric powertrain like the high-voltage battery. Other environmental impacts such as acidification, human toxicity, particulate matter, photochemical ozone formation, and resource depletion are higher in BEVs than in ICEVs, primarily because of the substantial environmental burdens associated with construction and manufacturing. An evaluation of electric cars cannot be conducted using a single indicator and should instead rely on a more comprehensive evaluation system. Thus, the market penetration of BEVs should be accompanied by a cautious policy that considers all aspects of life cycle management. Electric mobility is presently viewed as an effective strategy to reduce greenhouse gas emissions in areas where electricity is generated from sources that have limited contributions from fossil fuels [42].

Earlier research has demonstrated that BEVs and FCEVs can have a positive impact on the environment, but this outcome can be influenced by several factors, such as the amount of CO_2 present in the electricity utilized to charge the battery and produce hydrogen, the distance covered by the vehicle over its lifespan, and the energy consumption of the vehicle [5].

As the proportion of RES in the electricity grid increases, it becomes increasingly important to consider the entire fuel supply chain when estimating the life-cycle impacts of transportation technologies. With greater use of renewables, the production costs of FCVs decrease and the demand range for BEVs increases, leading to increased competitiveness between the two in terms of cost and environmental impact. Given the low CO_2 intensity of the electricity mix, it is advisable to promote the use of BEVs for short distances and delivery traffic, and FCVs for long-distance passenger and freight transport. Both vehicles have their advantages—the high energy efficiency of BEVs and the long-distance capability of FCVs—which can be utilized while minimizing their disadvantages. By focusing on using BEVs for short-haul routes and FCVs for long-haul routes, the number of charging stations along highways and hydrogen gas stations in cities can be reduced [43].

Using hydrogen directly in fuel cell vehicles has several advantages over converting it to fuels for combustion engines, such as higher well-to-wheel efficiency, lower greenhouse gas and pollutant emissions, and lower fuel costs. However, the volumetric energy density of hydrogen is much lower than liquid fuels, resulting in shorter driving ranges. Among the three combustion engine fuels, methane has slightly lower greenhouse gas emissions due to its lower CO_2 feedstock requirement and lack of electricity usage during production. DME, on the other hand, has slightly lower fuel costs and electricity demand per distance driven because of its more efficient use of hydrogen during production. Despite these differences, other factors like pollutant formation, range, handling, and infrastructure can also play a significant role. Nonetheless, the cost of fuel and overall electricity consumption are mostly determined by the supply of hydrogen [44].

The utilization of hydrogen in fuel cell buses offers a sustainable alternative to decarbonize transportation in Argentina and can help reduce significant GHG emissions. The hydrogen production stage accounts for at least 80% of the energy consumption in the hydrogen life cycle. Biomass reforming is one option for hydrogen production, and biogas reforming technology is found to be 47% less energy-intensive than solid biomass gasification. It is concluded that the hydrogen production stage is the most energy-demanding stage in terms of the LCA with an energy demand of 80% to 90% of the total, regardless of the studied scenario and its energy balances [45].

Hydrogen engines have a higher direct injection rate of around 30% compared to gasoline engines. Ethanol, when properly mixed with gasoline, can lead to an 80% reduction in CO emissions. The popularity of natural gas fueling stations is on the rise. Hydrogen can be utilized at a high compression ratio compared to gasoline due to its higher-octane number, and it has lower toxic chemical emissions than gasoline. The use of natural gas vehicles and fuel stations is rapidly increasing. Biogas, a renewable and environmentally friendly fuel, is a fresh source of energy that can be substituted for liquefied petroleum gas and natural gas, and its HC and CO emissions are lower than those of gasoline. Given limited resources, alternative fuels are preferable to traditional fuels. These fuels are appealing to environmental concerns due to their lower emissions. The fuel cell can also be enhanced by the use of these fuels. A promising prospect is the combination of the primary fuel and the alternative fuel, known as "dual fuel," which can offer superior performance in the future. Although alternative fuels have some benefits and drawbacks, some of them can emit much fewer pollutants or none at all. However, certain alternative fuels can emit more pollutants than gasoline. Furthermore, alternative fuels can affect emissions and engine efficiency differently. In the future, research could be conducted to identify a suitable hybrid fuel that could eliminate all emissions, enhance engine performance, and achieve higher engine efficiency, thus surpassing all other alternative fuels [46].

5. Conclusions

The objective of this review was to provide recent information on the topic of alternative fuels and LCA, which has gained importance due to the rising demand for environmental protection and geopolitical instability. The study concentrated on recent research from 2017–2023 to provide the most current conclusions and insights into a broad range of alternative fuels. Hydrogen and electricity were the most emphasized terms for alternative fuels. The environmental impact of electricity largely depends on its primary sources, whether it utilizes fossil fuels or renewable energy sources in its electrical grid mix. The environmental impact of a fuel and the entire life cycle of a vehicle largely depend on each other. Hydrogen is the second most well-known alternative fuel and is ideal in terms of its properties, but its production cost can be a barrier. Therefore, researchers are continuously seeking new ways to produce hydrogen at a lower cost to justify its commercial use. Biogas in various forms and mixed alcohols are already used commercially as alternative fuels, while DME and microalgae-based biodiesel are considered as special categories. Additionally, waste can also be utilized to produce alternative fuels.

The question of energy sources has evolved into a pressing matter. It is crucial to investigate how to shift from fossil fuel sources to renewable ones, which would create a solid foundation for electric vehicles. Meanwhile, it is imperative to maximize the potential of available resources like waste, oil, biomass, and other materials.

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