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Review

Sustainable Vehicles for Decarbonizing the Transport Sector: A Comparison of Biofuel, Electric, Fuel Cell and Solar-Powered Vehicles

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Abstract: Climate change necessitates urgent action to decarbonize the transport sector. Sustainable vehicles represent crucial alternatives to traditional combustion engines. This study comprehensively compares four prominent sustainable vehicle technologies: biofuel-powered vehicles (BPVs), fuel cell vehicles (FCVs), electric vehicles (EVs), and solar vehicles. We examine each technology's history, development, classification, key components, and operational principles. Furthermore, we assess their sustainability through technical factors, environmental impacts, cost considerations, and policy dimensions. Moreover, the discussion section addresses the challenges and opportunities associated with each technology and assesses their social impact, including public perception and adoption. Each technology offers promise for sustainable transportation but faces unique challenges. Policymakers, industry stakeholders, and researchers must collaborate to address these challenges and accelerate the transition toward a decarbonized transport future. Potential future research areas are identified to guide advancements in sustainable vehicle technologies.

Keywords: electric vehicle; sustainable vehicles; fuel cell electric vehicles; biofuel vehicles; hybrid electric vehicles

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1. Introduction

The global automotive sector has emerged as a highly significant industry, exerting influence not just economically but also in the realm of research and development. The growing number of vehicles on the road has facilitated convenient and swift transportation. The rising prevalence of internal-combustion vehicles, reliant on non-renewable conventional fuels, has given rise to concerns related to both energy consumption and environmental impact [1]. Nevertheless, this surge in fossil fuel-powered conventional vehicles has contributed to a notable rise in air pollution within urban areas, characterized by increased levels of pollutants such as particulate matter (PM), nitrogen oxides (NO_x), carbon monoxide (CO), and sulfur dioxide (SO_2), among others [2]. As per a European Union report, the transportation industry is accountable for approximately 28% of the overall carbon dioxide (CO_2) emissions, with road transport contributing to more than 70% of the emissions within the transport sector [2].

The transportation industry is facing a critical juncture wherein it must promptly tackle environmental issues and shift toward more sustainable methods. Consequently, numerous nations have introduced new energy vehicles (NEVs) as substitutes for traditional automobiles, aiming to diminish reliance on oil and mitigate the air pollution associated with conventional vehicle usage [1].

In this context, the substitution of renewable energy-powered automobiles for those running on fossil fuels is one revolutionary idea that is gaining traction. Vehicles that run on renewable energy fuels, like electricity, hydrogen, or biofuels, provide an opportunity to move toward more environmentally friendly and sustainable modes of transportation. New energy vehicles (NEVs), such as those powered by biofuels, electricity (electric vehicles), or hydrogen (fuel cell electric vehicles), provide a route toward more environmentally friendly and sustainable modes of transportation [1]. This change is in line with the larger international pledge to attain carbon neutrality and lessen the negative effects of human activity on the environment. The integration of advanced technologies into vehicles has become more prevalent, aiming to enhance the safety of both occupants and pedestrians.

1.1. Literature Review and Research Gap

There are many articles published in the literature covering the different types of new energy vehicles that run by using biofuels, electricity, hydrogen fuel cell technology and solar energy. In the literature on vehicles searched through the Scopus database, the documents published on various vehicle types are majorly patents (82–94%) and then followed by research articles and conference papers. Interestingly, the conference papers are also in equivalent number with the research articles on specific vehicles. Patents are predominantly filed in this area, which could be due to the commercial value available in the market for inventions in vehicle fuels and designs. The distribution of documents that are published as patents, articles and conference papers over various types of vehicles is given in Figure 1.

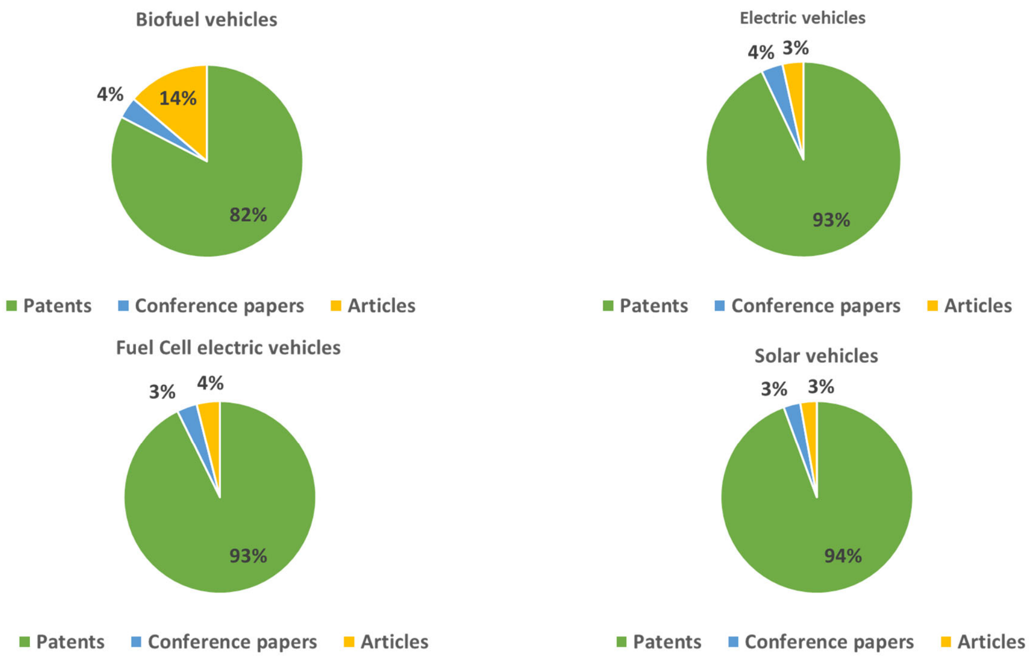

Figure 1. The pictorial representation of percentage share of articles, conference papers and patents on various vehicles.

There are many review articles published on different vehicles that run with various kinds of fuels. An article published recently presented the discussion on the emission analysis, engine performance and fuel characteristics of different kinds of various mustard seed-based biodiesels used in automobiles [3]. The mustard seed biodiesel showed engine performance lower than the other biofuels and diesel. Similarly, the potential of cashew nutshell liquid as biodiesel was reviewed for heavy-duty vehicles in sub-Saharan Africa [4]. Tanwar et al. reviewed the chemical and physical properties of bioalcohols and their blends with conventional diesel used in compression ignition vehicles [5]. Mallouppas et al. reviewed the research and development, innovative proposals on the application of biogas and biomethane as maritime fuels, along with their market potential as fuels [6]. The recent review articles on battery electric vehicles majorly focused on the discussion of the design, reliability, and challenges with various battery thermal management strategies for electric vehicles [7–10].

Waseem et al. in their article reviewed the current state of the art of fuel cell electric vehicles, challenges and recommended policy requirements for future growth of the vehicles [11]. A few more articles reviewed the current progress on fuel cell vehicles [12], comparisons of optimal sizing and power management for hybrid fuel cell vehicles (fuel cell/battery/supercapacitors) [13], and proton exchange membrane-based fuel cell application for road transport [14]. The reviews on recent trends in incorporating photovoltaics into boats [15], passenger vehicles [16] and effective factors on the performance of vehicle integrated photovoltaics to run on solar energy are published in the literature [17]. So, there are many articles in the literature that review single-technology vehicles, i.e., either on biofuel-based vehicles or electric vehicles or fuel cell vehicles or solar vehicles.

Sandaka et al. reviewed the challenges in using electricity, hydrogen and biofuels as the vehicular fuels [18]. Shahzad et al. reviewed the low-carbon-emission technologies like hybrid, electric and fuel cell vehicles, with a focus on discussing the merits, demerits and government policy complications of the technologies for adoption in vehicles for reduced emissions [19]. The comparison of fuel cell vehicles and electric vehicles is reviewed through analysis of various parameters, like fuel storage and performance, cost and performance, etc., to decide the better one for an alternative to fossil fuel vehicles [20]. One of the review studies investigated the energy use, greenhouse gas emissions, and additional environmental impacts of electrified vehicles [21]. The study highlighted the need for a more holistic approach in assessing the environmental impacts of electrified vehicles. The other study highlighted that the vehicle electrification, particularly through hybrid technology, plays a crucial role in reducing greenhouse gas emissions and promoting renewable transportation based on life-cycle assessment [22].

Within our knowledge, from the literature review, it is clear that many articles discussed about one technology of vehicles and very few articles critically compared two or three different new energy vehicles in the literature. So, our work presents four different technology vehicles and a critical comparative analysis between these four types of vehicles, i.e., biofuel, electric, fuel cell and photovoltaic vehicles.

1.2. Novelty Statement

Unlike previous studies that have primarily focused on individual aspects of sustainable transportation technologies, such as electric vehicles or biofuels, our research provides a comprehensive comparison of a wider range of green vehicle technologies, including biofuel-powered vehicles, fuel cell vehicles, electric vehicles, and solar vehicles, to decarbonize the transport sector. Furthermore, the current study provides a more comprehensive understanding of the technical aspects and state of the art regarding the various green vehicle technologies. Through this comprehensive analysis, we contribute fresh insights and advancements to the existing body of knowledge, thereby paving the way for informed decision-making and strategic interventions in the pursuit of sustainable transportation solutions.

1.3. Research Objectives and Organization of the Study

The main objective of the present work is to cover the discussion on various new energy vehicles, with a focus on four main categories of vehicles with growing attention in the automobile industry for reducing carbon emissions, i.e., biofuel vehicles, electric vehicles, fuel cell electric vehicles and solar vehicles. Furthermore, the discussion is presented with a critical analysis and comparison between the four categories of vehicles in terms of their performance, cost and carbon emission reductions, along with comments on the future scope and research developments concerning the new energy vehicles.

On this note, the organization of the present paper is as follows. Section 1 discusses the need for the new energy vehicles and provides a brief background to the study and presents the objective and significance of the study. Section 2 discusses about the biofuel-based vehicles' history and background, with discussion on various types of biofuels and their utilization in vehicles. It also discusses the components and working of the biofuel-based vehicles. It concludes by presenting the commercially available biofuel-based vehicles and the pros/cons of biofuel-based vehicles. In a similar way, Sections 3–5 will discuss about the aspects of electric vehicles, fuel cell vehicles and solar vehicles, respectively, in each section, covering the history, background, types, commercially available vehicles, pros and cons of the specific vehicles. Section 6 presents the critical analysis of the comparison of all four categories of vehicles in terms of their costs, characteristics and environmental impacts. Section 7 discusses the future scope and conclusions of the present study. Figure 2 shows the pictographic representation of the structure and organization of the present study.

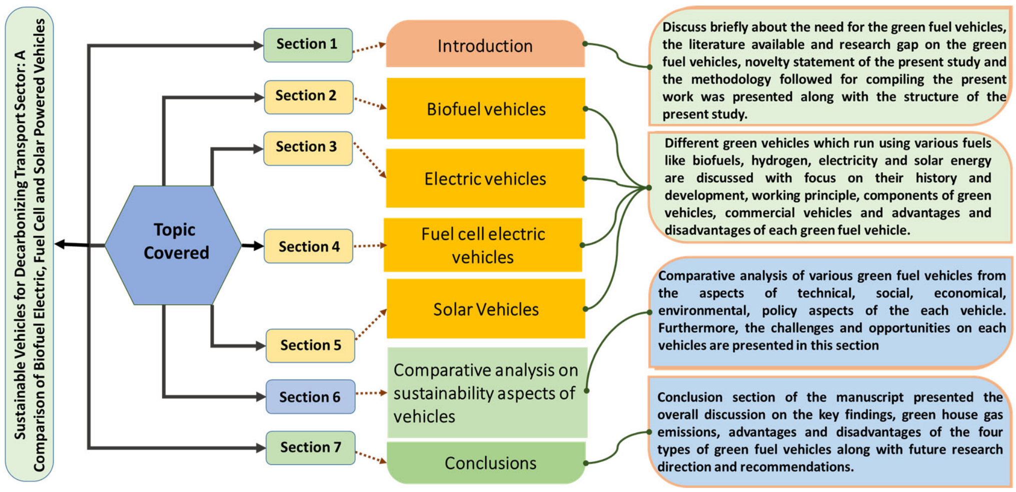

Figure 2. Structure and organization of the study.

1.4. Methodology

The comprehensive literature identification on sustainable vehicles like biofuel vehicles, electric vehicles, fuel cell electric vehicles and solar vehicles was carried out by searching various literature databases using different sets of keywords for each type of the vehicle. The distinct sets of keywords used for searching the literature on the four vehicles were as follows:

Biofuel vehicles: "biofuel vehicles", "vehicles", in conjunction with "biofuels", "ethanol.

Electric Vehicles: "electric vehicles", "electric cars", "vehicles" in conjunction with "electric", "plugin", "hybrid".

Fuel cell electric vehicles: "fuel cell electric vehicles", "electric vehicles" in combination with "fuel cell" "hydrogen" "hybrid".

Solar Vehicles: "solar vehicles", "vehicles" in combination with "solar", "photovoltaic", "solar car".

The exploration was carried out across well-regarded electronic databases such as Google Scholar, Scopus, and Web of Science. We implemented rigorous filters, restricting the search to publications from the last ten years, prioritizing peer-reviewed articles, conference proceedings, and technical reports. This thorough approach aimed to capture the most current and credible information within the field. Our investigation entailed a thorough examination of multifuel-based vehicles, covering their attributes, operational principles, market availability, and a discussion on their pros and cons. This systematic methodology ensured a comprehensive grasp of the array of eco-friendly fuel vehicle options for reducing carbon emissions in the transportation sector, thereby offering valuable insights to the broader conversation on sustainable transportation systems.

2. Overview of Biofuel Vehicles

A total of 80% of the world's primary energy comes from fossil fuels, of which the transportation sector uses a large amount [23]. Approximately 10% of the world's primary energy supply is made up of bioenergy. Bioenergy is expected to play a bigger part in modern bioenergy than traditional biomass utilization, leading to a projected 145 EJ rise in production by 2060 from the current level of 56 [24]. Large-scale energy generation is often proposed using a variety of bioenergy feedstocks, such as algae, crops, and lignocellulosic biomass. The potential for usage as biofuel energy resources includes a variety of vegetation, including wood, plants, grass/herbal plants, and other crops, including oleaginous seeds and sugar crops with high starch contents [25]. Because biofuels are produced from natural feedstocks, they are a more globally distributed form of renewable alternatives than fossil fuels. Biofuels and bioenergy are produced by processing biomass, or organic matter, from plants, crops, and their waste products. Biofuel can displace fuels made from petroleum because it comes from renewable sources. The only alternative energy source that can provide liquid fuels to take the place of fossil fuels is bioenergy. Biofuels are a viable alternative to meet future demand while reducing greenhouse gas emissions and environmental effects [26]. Biomass is an organic material that comes from a variety of sources, including grasses, trees, flowers and stems. It is not formed from fossils. It is a feasible substitute energy source because of its innate chemical energy. It is anticipated that by 2050, biomass will account for almost two-thirds of all direct renewable energy sources [27]. Since developing nations frequently experience extreme energy insecurity and have thriving agricultural sectors that can support the production of biofuels from energy crops, using biofuels as a mode of transportation presents a great opportunity. The increasing use of internal-combustion engines and the resulting high demand for petroleum-based fuels have negative effects on the environment, human health, and global warming. By lowering emissions from cars that run on biofuels, the development of biofuels promises to significantly improve air quality. Several developing nations have already started to produce and use biofuels for local transportation needs [28].

2.1. History and Development

Plant and seed oils have been used since 1500 BCE, and in the middle of the 1800s, they were used as fuel for combustion engines. Engines that ran on pure oil, blends of plant oils and petroleum, or other fuel mixtures were created by inventors like Diesel and Otto. Diesel's oil-powered 10-iron cylinder with a flywheel at the base was the first car to run on biofuel. Nicolas Otto gave a demonstration of the peanut oil-powered engine that was on display at the World Expo. August 10 is recognized as International Biodiesel Day, the day Rudolf Diesel used SVO to demonstrate his internal-combustion engine [29,30]. Vegetable oil transesterification was first identified in the middle of the 19th century, but it took another 50 years for people to recognize the fuel's potential. Before World War II, biodiesel and pure vegetable oil were in use, and the 20th century's energy crises spurred a global rush to produce these fuels. The petroleum industry has dominated the automotive sector for many years because it can produce fuels at a significantly lower cost than fuels derived from biomass. The use of petroleum fuels has led to a century's worth of increased pollution and carbon emissions [31]. The development of infrastructure, research, and technology for biomass-based fuels like biodiesel was hindered by this monopoly. Henry Ford, an American automobile entrepreneur, created the "soybean car" in 1941 and had an interest in alternate fuels. Ford produced one experimental soybean car during World War II, but it was never put on the assembly line because of the conflict [30,32]. Figure 3 shows the history and timeline of biofuels from the 19th century to 2030.

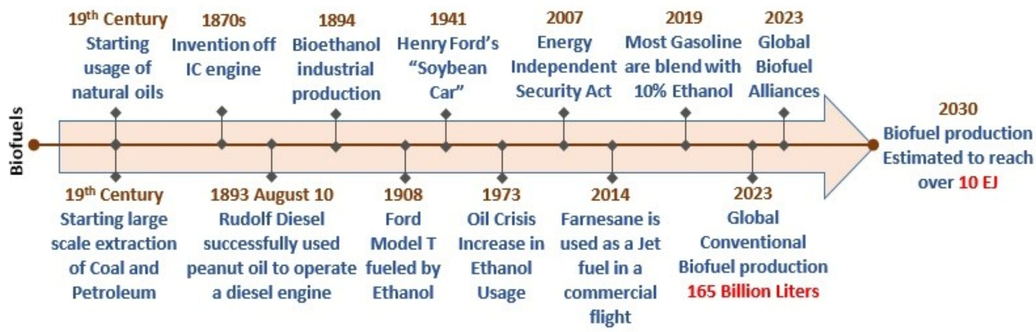

Figure 3. The history and timeline of biofuels.

2.2. Classification of Biofuels

Over 70% of all petroleum fuel usage is accounted for by the transportation industry. It is predicted that the globe will experience a petroleum oil scarcity by 2070–2080 as a result of the notable growth in petroleum consumption. Because of the greenhouse gas emissions caused by the overuse of petroleum, worries about health and global warming have been raised. By 2040, it is anticipated that greenhouse gas emissions will total about 43 billion metric tons. For this reason, more readily available, easily renewable power sources are necessary. Because they come from renewable sources, are non-toxic, sulfur-free, and biodegradable, biofuels are being developed to replace petroleum. Biofuels are divided into five generations including zero-, first-, second-, third-, and fourth-generation biofuels [33], depending on the feedstock. The classifications of biofuels is shown in Figure 4. Natural oils that were obtained straight from nature and used as biofuels are known as zero-generation biofuels. First-generation biofuels are made from plants based on oil, sugar, and starch yields. Genetically modified yields have been developed ever since they were first introduced in 1996–1997. Generally speaking, first-generation liquid biofuels are produced on a large scale using conventional and well-established technology. Ethanol derived from sugar and starch, biodiesel derived from oil crops and hydrogen derived from renewable source are considered as alternative fuels [34]. The first generation of biofuels sparked a controversy about fuel or nutrition; however, the second-generation biofuel made from sustainable lignocellulosic biomass minimizes issues with food safety [35]. Second-generation biofuels are made primarily from agricultural and forest leftovers and came from non-food yields [31]. Advanced biofuel forms are generally derived from biomass that is not food, such as grass, switchgrass, jatropha, and a range of other non-food crops, as well as the stem, leaves, and husks that remain after agricultural production is harvested [36]. Nonetheless, it is commonly known that expensive and advanced technology is needed to extract second-generation biofuels. Moreover, a number of obstacles, such as the need for expensive enzymes, impede the commercialization of second-generation biofuels [37–39]. The creation of lignocellulosic biofuels contributes to the alleviation of food and environmental crises. Algal-derived third-generation biofuels are highly recognized, easily refined, and able to be generated on a massive scale while absorbing CO_2. Using microalgae and microbes, the third generation of biofuels creates liquid biofuels such as biodiesel [40,41]. Algae can be grown in many different types of habitats, including marginal farmland, the ocean, barren drylands, and wastewater. Additionally, they do not compete with food crops in watery environments or on agricultural land. Additionally, a variety of genetically engineered microalgae are being produced, and they exhibit great promise for the production of biofuel. According to Abdullah [42] and Patel [43], biofuel generated through genetic engineering of microalgae is referred to as "fourth-generation biofuel". In the progression of biofuel technologies, fourth-generation biofuels represent a sophisticated stage that seeks to address some of the drawbacks of previous generations. Fourth-generation biofuels concentrate on using advanced feedstock and cutting-edge production techniques, in contrast to first-generation biofuels, which are made from food crops, and second-generation biofuels, which are made from non-food crops and trash.

Engineered cyanobacterial development is a novel and quickly developing field that is used in the fourth generation of biofuels [33]. This classification highlights the industry's continuous attempts to develop cleaner, more efficient, and economically viable alternatives to conventional fossil fuels, underscoring the dynamic growth of biofuel technologies. The term "bioenergy" describes the secondary energy produced from biomass, such as power production, biomass briquette fuel, bioethanol, biogas, biodiesel, and biohydrogen.

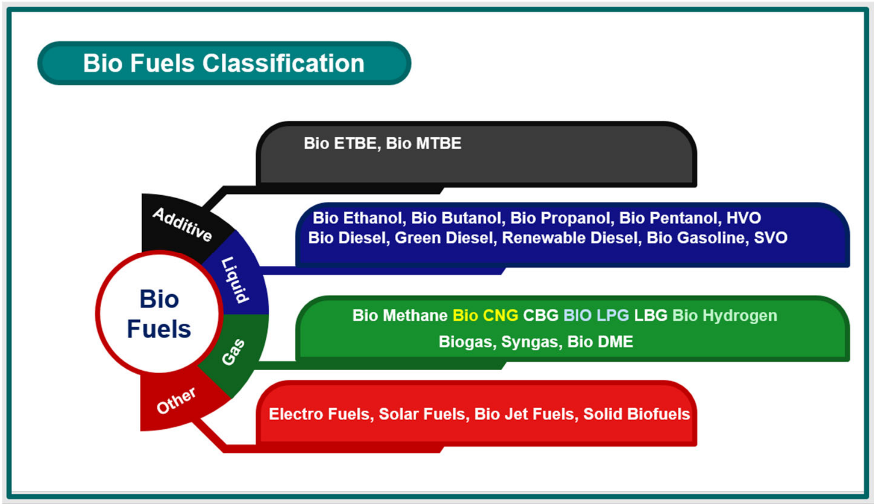

Figure 4. Classification of biofuels.

Unlike fossil fuels, which are formed by extremely slow natural processes, biofuel is a fuel that is created quickly from biomass. An example of this is oil. Biofuels, a broad class of fuels derived from biological sources, are an essential part of the renewable energy landscape. Based on their manufacturing methods and feedstock, these environmentally friendly substitutes for conventional fossil fuels are divided into many generations [44]. Biofuels can also be divided into the liquid, gas, and solid categories according to their physical states. Because of its carbon-based structural makeup and ability to be converted straight into liquid fuel, biomass is now regarded as the most potential renewable energy source that can contribute to the world's long-term energy supply. Liquid and gaseous biofuels derived from fossil fuels come in a range of forms that can be used in different kinds of vehicles [45]. As substitutes for goods derived from petroleum, biodiesel and hydrogenated vegetable oils (HVOs) have recently gained popularity [46,47].

The global switch to sustainable and renewable energy from a variety of sources is greatly aided by liquid biofuels. These comprise a range of forestry residues, agricultural materials related to food crops, including non-food energy crops like eucalyptus and switch grass, solid biogenic waste, etc. With a large amount of feedstock accessible, these emerging choices can create biofuel for transportation with minimum or maximum risk dependent on sustainability, which is associated with any changes in land utilization as well as competition over food production. Between 2015 and 2045, liquid biofuels offer a more expansive view, with a variety of technological features for advanced biofuels, particularly liquid transport fuels for usage in transportation, shipping, and aviation. According to the International Renewable Energy Agency (IRENA), by 2030, 10% of the energy used in the transportation sector will come from liquid biofuels, which comprise biodiesel and both conventional and advanced forms of ethanol [48]. Because of its remarkable properties, including a higher cetane number, a remarkable heat for vaporization, and sustainability, bioethanol is recognized as a superior substitute for fossil fuels like petrol and diesel [49,50]. Because bioethanol and petrol are similar, using them does not necessitate significant engine modifications. Its pure form is soluble in water, ether, acetone, benzene, and some other organic solvents, making its low-cost manufacture more feasible. In the next 20 years, it is anticipated to overtake all other biofuels as the most popular one for the world's transport sectors in the next 20 years. Bioethanol has the ability to be used in its pure form or in combination with petrol in some newly developed advanced flex-fuel hybrid vehicles [33]. Because biomethanol has a higher specific energy yield than bioethanol, it is superior. Due to its high volumetric energy density and ease of storage and transportation, methanol is a good biofuel. It is also liquid at room temperature. Additionally, it is a simple, basic material that can be used to create a wide range of beneficial organic compounds with significant commercial applications. It can take the place of related compounds, including hydrocarbons generated from petroleum [51]. Both biological and thermochemical techniques can be used to create methanol. Conversely, not enough is known about the biological conversion processes, which are still being studied in laboratories. Understanding the microorganisms, their metabolic pathways, and the enzymes involved in the bioconversion process is crucial for the biochemical synthesis of methanol. It also involves knowledge of many parameters that are necessary for scaling up laboratory results to full-scale production facilities [52].

Biobutanol is being explored as a second-generation biofuel, alongside other alcoholic fuels. Biobutanol, a biofuel, is a recent addition to the fuel market. Multiple studies have demonstrated the advantageous effects of incorporating biobutanol into diesel and other fuel mixtures. Biobutanol outperforms bioethanol and biomethanol due to its reduced demixing issues in biobutanol–petroleum blends, lower corrosiveness, decreased vapor pressure, higher energy content, and higher flash point. The primary negative of biobutanol, despite its notable advantages over other bioalcohols, is its low productivity [53,54]. Long-chain alcohols, such as biobutanol and biopentanol, have superior qualities in comparison to lesser alcohols, such as ethanol and methanol. They can serve as blending constituents with diesel in a compression-ignition engine (CIE). Butanol and pentanol can be generated through the processes of biomass fermentation, conversion of bio-syngas, or biosynthesis from glucose using genetically modified microorganisms and cyanobacteria. The current scientific research aims to identify methods for reducing production costs. The conversion of bio-syngas via chemical catalysis enables the production of a blend of methanol, ethanol, and butanol [55].

Straight vegetable oil (SVO) is an alternative term for vegetable oil used as a fuel. Vegetable oil is a lipid composed of free fatty acids linked together by a glycerin backbone. Using biofuels or straight vegetable oils (SVOs) directly in compression-ignition (CI) engines, which are commonly used in transportation, is not recommended due to their challenging properties. The SVOs have high density, high viscosity, large molar masses, and low volatility due to the presence of unsaturated fats, which contribute to undesirable shower characteristics. These problematic characteristics lead to a more fragmented atomization process and exacerbate concerns about the blending of air and fuel. Carbon deposition in Jatropha is indeed higher than in diesel fuel, which can result in an increase in smoke emissions [56]. Out of these several alternative fuels, the most encouraging one is undoubtedly hydrotreated vegetable oil (HVO), which offers numerous benefits. HVO is synthesized via the hydrotreating of vegetable oils or animal fats, utilizing the same raw materials as biodiesel. Typically, additional processes, such as isomerization, are employed to enhance the cold flow characteristics. HVO can be co-produced with bio jet oil and green naphtha, depending on the catalyst type and operational conditions. This adds flexibility to the production process for HVO. HVO 100 is an environmentally friendly alternative to conventional fuel, derived from renewable and sustainable resources [57]. Diesel vehicle owners can transition to using HVO 100 fuel without necessitating any alterations to their engines. High-volatility oxygenate (HVO) significantly decreased the time it took for fuel to ignite because of its elevated cetane number. This characteristic also resulted in a decreased amount of energy released during the combustion process when the fuel and air were combined. The aforementioned study also indicated that this eco-friendly fuel exhibited reduced levels of soot and NOx emissions in comparison to petrodiesel. This can be attributed to the absence of aromatic components and the decreased mixing rate, respectively. Hydrotreated vegetable oil (HVO), sometimes known as "green diesel" in the industry, is a type of diesel fuel that is generated from biomass and has a paraffinic composition. HVO belongs to the category of "renewable diesels", which include Fischer–Tropsch diesel (FT diesel) as well [58].

Biodiesel has gained popularity in the worldwide fuel market due to increased awareness of energy security. Biodiesel is an alternative to petroleum diesel that consists of a blend of alkyl esters derived from free fatty acids. It has gained considerable interest due to its low toxicity and great ability to be broken down by natural processes. Biomass oils are primarily used for their generation. Biodiesel is named as such because it is derived from biological sources and exhibits comparable performance to petrodiesel. Biodiesel is considered a clean energy source due to its ability to reduce the emissions of direct and indirect greenhouse gases such as CO_2, CO, SO_2, and HC; therefore, offering environmental protection [59]. Therefore, the use of biodiesel can contribute to the preservation of ecological equilibrium, as opposed to the use of fossil fuels. Biodiesel may be seamlessly blended and utilized in compression-ignition engines (CIEs) without requiring any alterations. To address potential stability and breakdown problems, biodiesel is commonly mixed with regular diesel at a ratio of 7–10% by volume (referred to as the B7–B10 blends). In order to enhance the mix percentages, engines must undergo modifications to improve their operational characteristics, such as injection timing, compression ratio, and injection pressure. Europe already has instances of captive fleets utilizing blending grades of B20, B30, and B100 [60].

Renewable diesel is composed of hydrocarbons that do not contain any aromatic components. Renewable diesel presents a superior alternative for addressing the problem of rapidly depleting fossil fuels and the limitations of biodiesel. The feedstock utilized for the production of renewable diesel, much like biodiesel, encompasses vegetable oils, animal fats, spent cooking oil, and lignocellulosic biomass. Renewable diesel is manufactured with the same objective as biodiesel production, which is to minimize the effects of CO_2 emissions and offer a more environmentally friendly combustion alternative compared to petroleum diesel. Renewable diesel, unlike FAME biodiesel, can be stored for an extended period of time since it shares similar qualities with petroleum diesel. It consists of a combination of straight-chain and branched saturated hydrocarbons (C15 to C18) and does not include any oxygen [61]. In addition, renewable diesel has exceptional cold-weather performance due to its high cetane number, making it easier to ignite compared to biodiesel. Renewable diesel has several benefits over traditional petroleum diesel, including a high heating value, comparable energy densities, excellent storage stability, and non-corrosiveness. These positive features make renewable diesel a superior solution for enhancing our energy sources. Renewable diesel is a broad term that describes the latest generation of diesel fuels made from biomass. There are two categories of technology that can be used to produce renewable diesel: hydroprocessing (HVO) and thermochemical processes such as pyrolysis and gasification. These fuels can be used in conventional automobiles without the need for blending, as stated in reference [62]. HVO is devoid of oxygen, aromatics, and sulfur, making it superior to both FAME and diesel in terms of qualities such as a higher cetane umber, a higher heating value, and improved oxidative stability features. HVO lacks the lubricating properties that make FAME particularly advantageous. The utilization of customized green diesel blends, which consist of a combination of petrodiesel and oxygenated biochemicals, has great potential for addressing the environmental problem. Green diesel is an alternative term used to refer to renewable diesel fuel. Green diesel, with equal chemical properties to petrodiesel, can be used either in its pure form or as a blend with petrodiesel [63].

Bio-gasoline is a form of gasoline derived from biomass, such as algae. Similar to conventionally manufactured gasoline, it consists of hydrocarbons containing 6 (hexane) to 12 (dodecane) carbon atoms per molecule and is suitable for use in internal-combustion engines. Contrary to conventional gasoline derived from oil, bio-gasolines are mostly derived from plants, such as beets and sugarcane, or cellulosic biomass, which is typically seen as plant waste. Several governments and prominent multinational organizations have backed the growth of several types of algae as a source of liquid fuel. However, green algal petrol has not been included so far [64]. Although algae biodiesel is a very sustainable substitute for traditional petrol and has received significant investment, bio-gasoline is distinct from other biofuels, such as biobutanol and bioethanol, as it is not an alcohol. However, it shares chemical similarities with biodiesel, which is also derived from carbon-based sources. Bio-gasoline, due to its lighter components, exhibits reduced pollutant emissions during combustion, owing to its distinct physical features. Moreover, the energy obtained from bio-gasoline is significantly greater than that from corn-based ethanol when mixed with regular gasoline due to the larger molecular weight of the components derived from algae [64]. In the present research areas, numerous thermochemical pathways exist to transform biomass into synthetic fuels suitable for transportation purposes. The precise nomenclature for this collection of biofuels has not been established, and "synthetic liquid biofuels" is the most suitable categorization currently available. The process of biomass gasification, which generates syngas, and the subsequent thermochemical pathway are commonly known as "biomass to liquids". Synthetic biofuels provide comparable or even superior characteristics to their fossil fuel counterparts [65].

Gaseous biofuels, such as biogas, biomethane, biohydrogen, and syngas, can be employed to produce both thermal and electrical energy. The energy generation system described is commonly referred to as a sustainable energy system due to its ability to reduce harmful emissions and contribute to economic development. Subsequently, biohydrogen is acknowledged as the most feasible alternative to the conventional energy sources. It is mostly derived from renewable and non-renewable hydrocarbon resources, serving as a secondary energy source. Biohydrogen is anticipated to have a vital function in future global energy sectors as an energy provider [66]. Biogas is a form of gaseous biofuel that is used in the energy industry. Microbes facilitate the production of biogas through the anaerobic degradation of organic matter. Biogas can be utilized through several processes to generate a range of transportation fuels, including CBG, LBG, hydrogen, methanol, dimethyl ether, and Fischer–Tropsch (FT) fuels, which are the most probable alternatives [67]. Biomethane derived from biomass is an environmentally friendly substitute for supplying compressed natural gas vehicles. Biomethane can be produced by the process of anaerobic digestion or the bio-syngas methanation process. The initial procedure, which is a well-developed technique, generates biogas from organic substances. Subsequently, biogas can undergo a purification process to produce biomethane, also known as upgraded biogas. Biosynthetic natural gas (bio-SNG) refers to the biomethane that is produced from bio-syngas. Currently, the profitability of biomass gasification technology for SNG production remains unattainable [68]. Bio-DME, or dimethyl ether, is an ether that may serve as both a fuel additive and a standalone fuel in internal-combustion engines (CIEs). Bio-DME is generated through the process of biomethanol dehydration or from bio-syngas in conjunction with biomethanol. Under normal settings, dimethyl ether (DME) exists in a gaseous state, which limits its use to specialized vehicles equipped with a pressurized fuel chamber, similar to those used for liquefied petroleum gas (LPG) [69]. Bio-ETBE and bio-MTBE are types of bio-ethers, which are fuels commonly employed as additives to enhance the performance of fuel in the combustion chamber. The synthesis of bio-ETBE/bio-MTBE involves the chemical reaction between isobutylene and bioethanol/biomethanol [70]. Biohydrogen can be generated from biomass and subsequently utilized for energy generation via fuel cells (FCs). To generate biohydrogen, bio-syngas that is high in H2 can be created by gasifying biomass in the presence of water. The water–gas shift reaction is utilized to enhance the H2 concentration, as indicated by the references. Additional methods for generating biohydrogen include biomethane reforming, bioethanol reforming dark fermentation, and photo-fermentation [71]. Biopropane, often known as bio-LPG, has the potential to serve as a substitute for fossil LPG. It can be generated using a single-step catalytic synthesis of the syngas produced from biomass gasification and also as a by-product of HVO. Bio-LPG is already produced in small quantities as a by-product of various biofuel synthesis techniques [72].

Biogas is being converted into compressed biomethane (CBG) in several countries. CBG is a renewable alternative to compressed natural gas (CNG) and is mostly used in vehicles, particularly cars and buses. In recent years, there has been a growing fascination with liquefied biomethane (LBG) as a substitute for liquefied natural gas (LNG) in the field of heavy transportation. Additionally, there are alternative choices accessible [73]. In addition to CBG and LBG, biogas can be utilized for the generation of syngas, which can then be employed for the production of sustainable variants of fuels such as hydrogen, methanol, or DME. These fuels possess distinct attributes and capacities compared to CBG and LBG, rendering them potentially viable for other components of the renewable energy infrastructure that require development [74]. Liquid biogas (LBG) has developed as a viable alternative fuel for both heavy road and sea transportation. Multiple truck manufacturers have commenced the production of engines capable of operating on methane fuel. When considering CBG, LBG, or methanol as maritime fuels, it is evident that all of these alternative fuels provide distinct advantages over traditional fuel oil in terms of their environmental impact. To use biogas as a fuel for vehicles, it is necessary to purify it by removing CO_2 and other contaminants [69]. This process enhances the methane concentration and thus increases the heating capacity of the biogas. Bio-CNG is a fuel derived from biodegradable waste that is both environmentally friendly and sustainable. Bio-LNG, derived from organic sources such as household trash, sludge, manure, or agricultural waste, is an optimal environmentally friendly fuel for heavy transportation. By converting garbage into fuel, it contributes to the concept of a circular economy [75].

2.3. Key Components and Technological Features of Biofuel Vehicles

In the context of biofuels, liquid biofuels are often utilized by either blending them with conventional petrol or diesel or by completely substituting them for traditional fuels. Typically, the utilization of liquid biofuels does not require further particular modifications. The major components and technological aspects of liquid biofuel vehicles closely resemble those of traditional petroleum-based fuel vehicles [76]. In this section, we shall examine gaseous biofuel cars. Biogas cars are ideal for high-mileage, centrally fueled fleets, as they offer comparable fuel range support for applications that operate inside a location that has dependable compressed biogas refueling infrastructure. Biogas offers several benefits as a transportation fuel, such as its abundant supply within the country, extensive distribution infrastructure, and lower greenhouse gas emissions compared to traditional petrol and diesel fuels. Experienced retrofitting specialists can efficiently and securely convert a wide range of vehicles to run on biogas using aftermarket conversion equipment. CBG and LBG are regarded as alternative fuels that provide promising prospects in this domain [73,75]. The general components of a gaseous biofuel vehicle are shown in Figure 5.

There are three types of versatile cars that run on gaseous biofuel. Specialized cars are exclusively engineered to operate solely on gaseous biofuel. Bi-fuel vehicles are equipped with two distinct fueling systems, allowing them to operate on either gaseous biofuel or petrol. Dual-fuel automobiles are equipped with fuel systems that operate on natural gas but rely on diesel fuel for ignition assistance. This layout is often restricted to vehicles designed for heavy-duty applications. Gaseous biofuel cars store biogas in pressurized tanks, maintaining it in a gaseous condition [77]. LBG enables more fuel storage capacity in vehicles due to its liquid state, resulting in a higher energy density compared to CBG. LBG is highly suitable for Class 7 and 8 trucks that require an extended range. Frequently, the selection of fuel is influenced by factors such as the specific requirements of the vehicle's application (e.g., power needs) and the desired driving distance. The range of gaseous biofuel vehicles is often shorter than that of similar diesel or petrol vehicles because natural gas has a lower energy density. Supplementing storage tanks might extend the distance that can be covered, but the extra weight might reduce the amount of goods that can be carried. When utilized as a fuel for vehicles, gaseous biofuel can provide advantages in terms of the greenhouse gas (GHG) emissions over its entire life cycle compared to traditional fuels [78]. However, the extent of these benefits depends on factors such as the type of vehicle, its usage pattern, and the calibration of its engine. Furthermore, natural gas mitigates certain engine pollutants. Tailpipe emissions are the by-product of gasoline combustion in an automobile's engine. The emissions of major concern encompass the regulated hydrocarbon emissions, nitrogen oxides (NOx), carbon monoxide (CO), and carbon dioxide (CO_2) [79].

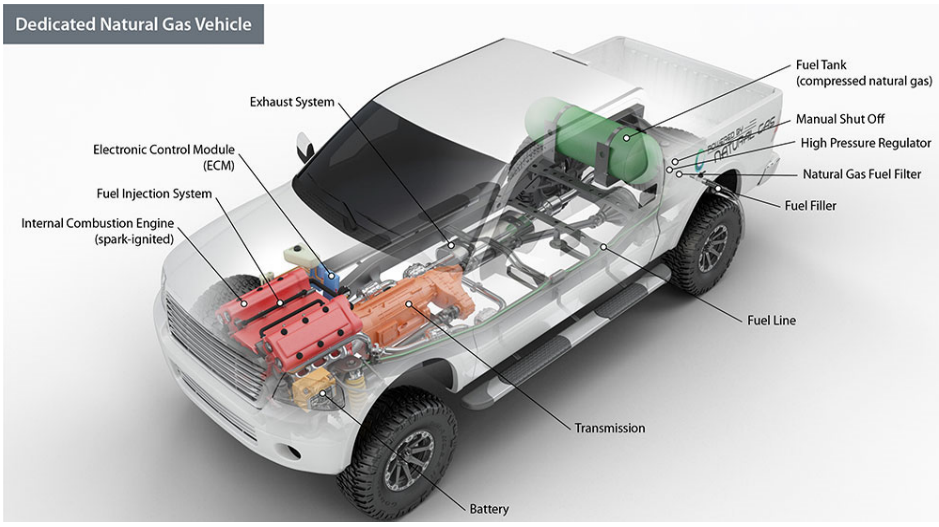

Figure 5. Technical components of biofuel(gas) vehicle inner assembly. Reprinted from Ref. [80].

2.4. Commercial Biofuel Vehicles

There are various gas vehicles available commercially on the market manufactured through various companies. Table 1 lists some of the vehicles and their specifications that are available on the market.

Table 1. Biofuel vehicles by various companies and their specifications.

Company Name	Vehicle Model	Specifications
Cadillac	Cadillac Escalade 2WD (2024) 	Fuel: Biodiesel (B20) Type of Vehicle: SUV Conventional Fuel Economy: 23 mpg Engine/Motor(s): 3.0L V6 Transmission: Auto Drivetrain: RWD
GMC	GMC Yukon/Yukon XL 2WD (2024) 	Fuel: Biodiesel (B20) Type of Vehicle: SUV Conventional Fuel Economy: 23 mpg Engine/Motor(s): 3.0L V6 Transmission: Auto Drivetrain: RWD
Chevrolet	Chevrolet Silverado 2WD (2024) 	Fuel: Biodiesel (B20) Type of Vehicle: pickup Conventional Fuel Economy: 26 mpg Engine/Motor(s): 3.0L V6 Transmission: Auto Drivetrain: RWD

Table 1. *Cont.*

Company Name	Vehicle Model	Specifications
Ford	Ford Explorer AWD FFV (2022) 	Fuel: Ethanol (E85) Type of Vehicle: SUV Alternative Fuel Economy: 13 mpg Conventional Fuel Economy: 19 mpg Engine/Motor(s): 3.3L V6 Transmission: Auto Drivetrain: AWD
Dodge	Dodge Challenger SRT Demon 170 (2023) 	Fuel: Ethanol (E85) Type of Vehicle: sedan/wagon Alternative Fuel Economy: 15 mpg Conventional Fuel Economy: 9 mpg Engine/Motor(s): 6.2L V8 Transmission: Auto Drivetrain: RWD
GMC	GMC Sierra 2WD (2023) 	Fuel: Ethanol (E85) Type of Vehicle: pickup Alternative Fuel Economy: 13 mpg Conventional Fuel Economy: 18 mpg Engine/Motor(s): 5.3L V8 Transmission: Auto Drivetrain: RWD

2.5. Pros and Cons of Biofuel Vehicles

The biofuel vehicles have advantages and disadvantages when used in the transportation system. Table 2 discusses the pros and cons of biofuel vehicles.

Table 2. Pros and cons of biofuel vehicles [81].

Pros	Cons
Biofuels are renewable and promote sustainability.	Biofuels require pre-treatment processes before use.
Offer higher reliability.	Developing biofuel technologies can be expensive.
Can be produced locally.	Need to improve the efficiency of biofuel production technologies.
Reduce dependence on foreign energy sources.	Procurement of subsidies for biofuel production is needed.
Can help stabilize energy prices.	Funding for research and development is needed.
Biofuels support rural development.	Scaling up biofuel production to commercial levels can be challenging.
Biofuels help reduce air pollution.	Establishing an efficient collection network for biofuel feedstock can be complex.
Biofuel production can make use of marginal lands and agricultural waste.	Biofuels require specialized storage facilities.
Biofuels enable carbon sequestration.	Biofuel production can compete with food production.

3. Overview of Electric Vehicles (EVs) and Hybrid Electric Vehicles

Growing worries about climate change and energy supply security are pushing a transition in the transportation industry away from fossil fuels and toward innovative electric vehicle propulsion technologies capable of ensuring long-term sustainability. Electric cars are a potential technology for drastically reducing emissions from road transportation [82]. Simultaneously, electric passenger vehicles in development are not yet competitive with conventional vehicle technology [83]. EVs, together with shared mobility and public transportation, will play a critical role in smart cities in the next years [84]. As a result, greater efforts to simplify the charging procedure and enhance batteries are required. The biggest disadvantage of EVs is their lack of autonomy. Researchers, on the other hand, are working on new battery technology to boost the driving range while decreasing the charging time, weight, and cost. These elements will eventually determine the future of electric vehicles [85].

3.1. History and Development

The history of electric vehicles dates back to the early 1900s, when a Detroit Electric Model 47 was used by Clara Ford. Figure 6 shows the timeline of the developments of electric vehicles (EVs) and battery electric vehicles (BEVs) in the latter part of the 1900s. This electric vehicle, with a top speed of 30–40 km/h, belonged to 38% of American families. Mostly, in the early 1900s, women used electric cars for transportation. The history of electric vehicles (EVs) dates back to the 19th century when inventors started experimenting with electric-powered cars [86]. In the early 1800s, inventors like Robert Anderson and Ányos Jedlik created some of the earliest electric vehicles, and with advancements in technology, electric cars gained traction. In 1881, Gustave Trouvé, a French inventor, built a three-wheeled electric vehicle. By the late 1800s, electric cars were quite popular, especially among the elite, due to their ease of use and lack of noise compared to steam-powered vehicles. Around this time, electric taxis were common in cities like New York and London [84]. Despite the initial success, the mass production of internal-combustion engine (ICE) cars, led by Henry Ford and others, became dominant due to the ease of refueling and cheaper gasoline prices, leading to a decline in the popularity of electric vehicles. Concerns about pollution and the environment brought back interest in electric vehicles. In the 1990s, car manufacturers started experimenting with modern electric cars, like the GM EV1 and Toyota RAV4 EV [87]. Technological advancements, improvements in battery technology, and concerns over climate change led to a significant resurgence in EVs. Companies like Tesla popularized electric cars, with models like the Roadster and the Model S showcasing the potential for long-range electric vehicles [88]. Various governments worldwide introduced incentives, subsidies, and regulations to promote the adoption of electric vehicles [89]. Programs aimed at reducing carbon emissions and dependence on fossil fuels have further accelerated the growth of the EV market. Today, the electric vehicle market includes a wide range of options, from affordable compact cars to luxury vehicles and even electric trucks. Numerous automakers are investing heavily in electric vehicle technology, aiming to make EVs more accessible and widespread.

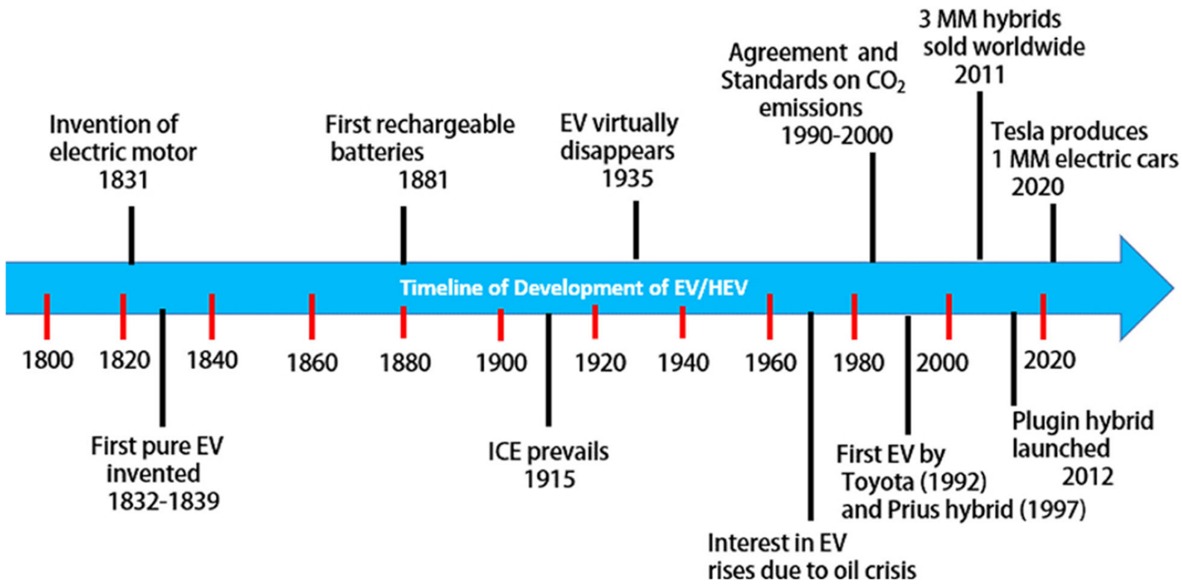

Figure 6. The history and timeline of electric vehicles (EVs) and battery electric vehicles (BEVs). Reprinted from Ref. [90].

3.2. Classification of Electric Vehicles

This section provides a taxonomy of the many types of electric cars, as well as comments on their primary qualities. The broad classification of electric vehicles is shown in Figure 7 and the components and technological features of important electric vehicle types are given in Figure 8.

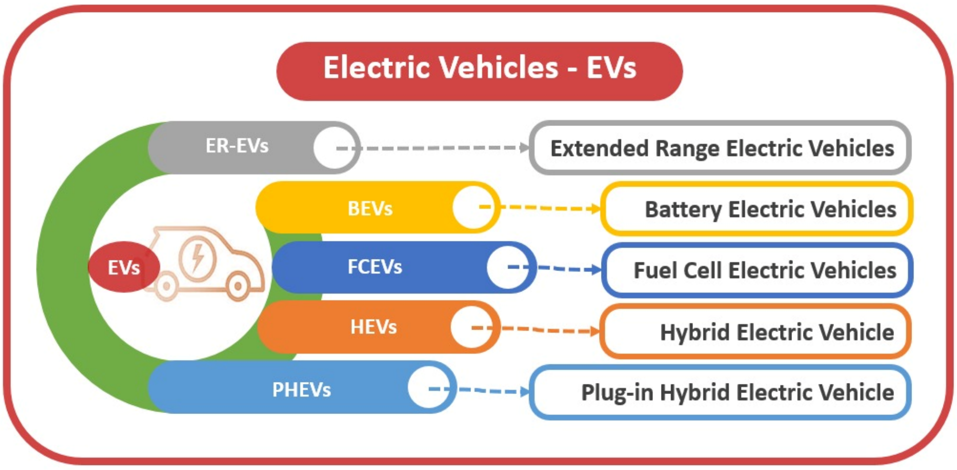

Figure 7. Classification of electric vehicles.

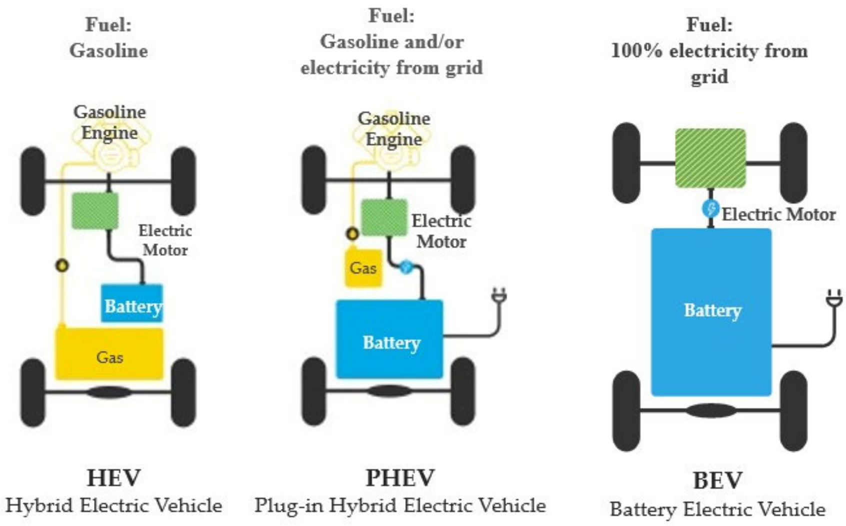

Figure 8. Different components and technological features of various types of electric vehicles.

Plug-In Hybrid Electric Vehicles (PHEVs): Hybrid cars that are powered by a normal combustion engine and an electric engine that is charged by a pluggable external electric source. In normal driving circumstances, PHEVs can store enough power from the grid to drastically cut their gasoline usage. The Mitsubishi Outlander PHEV [91] has a 12 kWh battery that allows it to go around 50 km using only the electric engine. However, it is worth noting that the fuel consumption of PHEVs is greater than claimed by vehicle manufacturers [92].

Hybrid Electric Vehicles: Hybrid vehicles are propelled by a combination of a conventional internal-combustion engine and an electric engine [93]. The difference with regard to PHEVs is that HEVs cannot be plugged into the grid. In fact, the battery that provides energy to the electric engine is charged thanks to the power generated by the vehicle's combustion engine. In modern models, the batteries can also be charged thanks to the energy generated during braking, turning the kinetic energy into electric energy. Based on the available information on the Toyota Prius model, the battery requires approximately 3.2 kWh of electricity along with 1.1 L of gasoline to achieve a range of 40 km (25 miles) [92].

Fuel Cell Electric Vehicles (FCEVs): These vehicles are provided with an electric engine that uses a mix of compressed hydrogen and oxygen obtained from the air, having water as the only waste resulting from this process. Although these kinds of vehicles are considered to present "zero emissions", it is worth highlighting that, although there is green hydrogen, most of the used hydrogen is extracted from natural gas. The Hyundai Nexo [94] FCEV is an example of this type of vehicle, being able to travel 650 km without refueling.

Extended-Range EVs (ER-EVs): These cars are extremely similar to those classified as BEVs. However, the ER-EVs are also equipped with a secondary combustion engine that can charge the vehicle's batteries if necessary. This engine, unlike those found in PHEVs and HEVs, is just utilized for charging and is not connected to the vehicle's wheels. The BMW i3 [95] is an example of this sort of car, with a 42.2 kWh battery that provides 260 km of autonomy in electric mode and an extra 130 km in extended-range mode.

3.3. Key Components and Technological Features

Electric vehicles (EVs) incorporate various key components and technological features that distinguish them from traditional internal-combustion engine vehicles. The main components and operational steps of the electrical vehicles from charging point to wheel is shown in Figure 9.

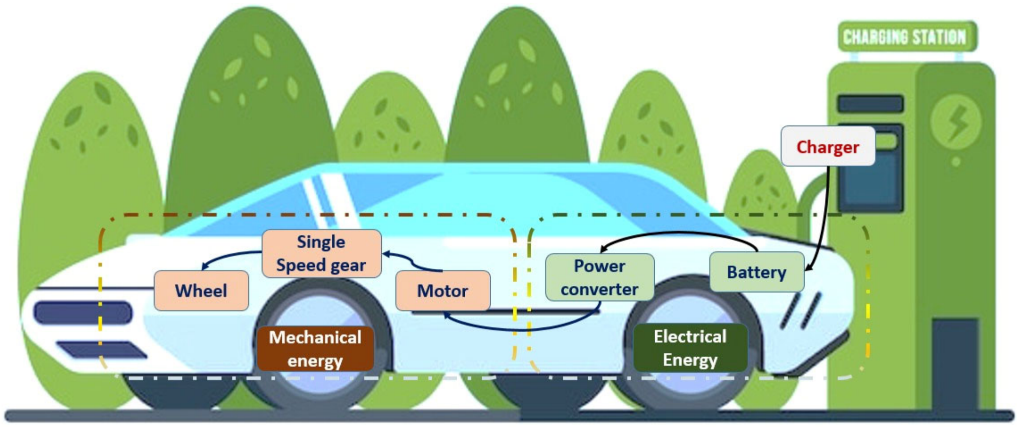

Figure 9. Operational steps of electric vehicle from charging to wheel.

Electric Motor: The primary propulsion system of an EV is the electric motor, which converts electrical energy from the battery into mechanical energy to drive the wheels. These motors can be AC (alternating current) or DC (direct current) and vary in design for different vehicle types. Electric vehicles commonly utilize AC motors, particularly induction motors, for their straightforwardness, durability, and cost-efficiency. These motors operate via electromagnetic induction, generating a rotating magnetic field in the stationary part (stator) while inducing a current in the moving part (rotor), generating torque to propel the vehicle. Their brushless and commutator-free design makes AC motors low-maintenance and efficient. Their notable advantage lies in their impressive torque-to-weight ratio, enhancing acceleration and overall performance. Furthermore, AC motors can function across a wide range of speeds without needing a gearbox, streamlining the drivetrain and reducing mechanical losses. However, compared to DC motors, AC motors typically demand more intricate control systems. DC motors, also known as brushed motors, are another option for powering electric vehicles. These motors use brushes and a commutator to switch the direction of the electric current in the motor windings. DC motors have a simpler design compared to AC motors and are known for their high starting torque, making them suitable for applications requiring frequent acceleration and deceleration. In the context of electric vehicles, DC motors are often used in smaller vehicles or specific applications, such as electric bikes and scooters. They are less complex and more affordable than AC motors. However, DC motors suffer from higher maintenance requirements due to the brushes and commutator, which can wear out over time and require replacement. DC motors are generally less expensive upfront, making them an attractive option for smaller EVs or budget-conscious applications [96]. AC motors often come at a higher cost but provide better long-term efficiency and performance.

Battery Pack: EVs are powered by rechargeable battery packs composed of lithium-ion cells. These battery packs store electrical energy and supply it to the electric motor. Advancements in battery technology focus on improving the energy density, charging speed, and overall longevity [97]. A battery pack is a device that stores electrical energy for the purpose of supplying power to an electrical system, such as an electric vehicle (EV) or an energy storage system (ESS). In the battery pack, energy is stored in cells that are all linked to one another. Battery packs require a minimum voltage level to supply sufficient power, which a single cell cannot reach. To increase the voltage, many cells are linked in series. Some designs make use of low-capacity cells. Cells are linked in parallel to improve the capacity and acquire the necessary battery energy [98]. Parallel cells deliver electricity as if they were a single, bigger cell. Battery packs are made up of several smaller portions known as battery modules (or subpacks). There are fewer modules in this category. Different types of battery packs used in electric vehicles are given in Figure 10.

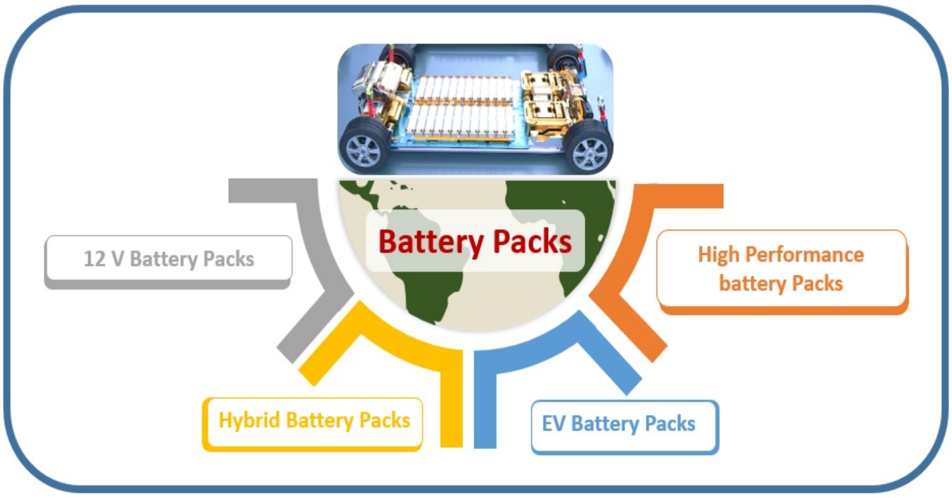

Figure 10. Classification of battery packs used in electric vehicles.

There are also other versions available to provide the best trade-off based on the application. The lithium-ion cell (Li-ion cell) is the most prevalent chemical in the EV sector. Alternative chemistries, such as nickel-metal hydride (NiMH), are occasionally utilized since they have a little longer lifespan.

The main component of an electric vehicle (EV) is indeed the battery technology, and it has undergone significant advancements in recharging, cycles, capacity, and charge density in recent years. Table 3 describes the various energy storage technologies used in electric vehicles, plug-in electric vehicles and hybrid vehicles.

Power Electronics: This includes the inverter, which converts DC power from the battery into AC power for the electric motor. Additionally, it manages the flow of electricity between the battery and the motor, controlling the speed and torque. Power electronics facilitate functions like managing the charging and discharging of the battery, controlling the speed and torque of the electric motor, and enabling regenerative braking to capture and store energy back into the battery. Their advanced technology enhances the overall reliability, efficiency, and performance of electric vehicles, contributing significantly to their widespread adoption and advancement in the automotive industry.

Table 3. Various energy storage technologies used in electric vehicles.

Energy Storage Technology	Characteristics	Parameters
Li-ion Battery	High energy storage capacity [99] Rapid charging [100] Low self-discharge rate Wide range of operating temperature	Temperature Range: −20 °C to +60 °C Specific Energy: 100–240 Wh/kg [100] Cost: 0.3 to 0.6 €/Wh Efficiency: 95% [99]
Hybrid Supercapacitor	Higher specific energy density than Li-ion battery More cycles of charging Good thermal management Very fast discharge rate	Temperature: −20 °C to 70 °C Specific Energy: 10–15 Wh/kg Cost: 0.3 to 20 €/Wh Efficiency: 95%
New-Gen EDLCs	Higher capacitance than electrolytic capacitor Lower cost than Li-ion or hybrid supercapacitor Ideal for fast energy release Very minimal degradation	Temperature: −40 °C to +70 °C Specific Energy: 30–70 Wh/kg Cost: 0.3 to 2 €/Wh Efficiency: 95%

Regenerative Braking: EVs often utilize regenerative braking systems that capture kinetic energy during braking and convert it into electrical energy, which is then fed back into the battery. This process helps increase efficiency and extend the vehicle's range. The generated electricity is then sent back to the vehicle's battery, where it can be stored and used later to power the vehicle or assist in its acceleration. This process helps increase the overall efficiency of the vehicle by reclaiming some of the energy that would otherwise be lost during braking, thereby extending the driving range and reducing the amount of energy required from the battery or external charging sources. Regenerative braking contributes to the enhanced energy management and sustainability of electric and hybrid vehicles.

Charging System: EVs can be charged through various methods: standard electrical outlets, dedicated charging stations (level 2 chargers), or fast-charging stations (DC fast chargers). The characteristics of two types of charging systems for electric vehicles are shown in Figure 11. The charging times and capabilities vary based on the charging infrastructure and the vehicle's compatibility. The charging system in an automotive context generally refers to the components and processes involved in replenishing a vehicle's battery or electrical storage system with energy. In the case of electric vehicles (EVs), it specifically refers to the infrastructure, technology, and mechanisms utilized to provide electrical energy to the vehicle's battery for powering the electric motor(s) and other electrical systems.

The HEV powertrain is made up of two or more engines. The ICE is the primary source of energy, responsible for the majority of the vehicle's energy and extended driving range, while the EM is the auxiliary source, responsible for high-vehicle-power needs and the ICE's fuel economy. The EM charges the batteries by regenerating vehicle kinetic energy and using extra ICE power when it is not needed by the vehicle. The design and operation of such powertrains necessitate modern control algorithms and EMS, which maximize a variety of objectives, including ICE fuel economy and the battery's state of charge (SoC), with system and driving restrictions. The HEV system design is made up of a drive train, an ESS, and a controller unit. On the basis of different operation modes, HEVs are divided into two types.

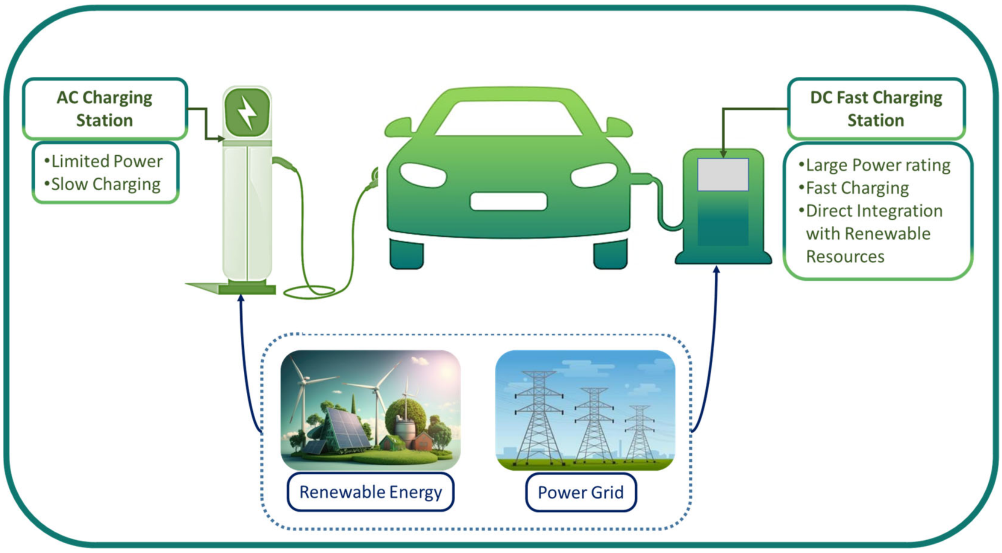

Figure 11. Comparison of AC charging stations and DC fast-charging stations.

3.4. Commercial Electric Vehicles

The commercial vehicle sector is experiencing a significant shift toward electric vehicles (EVs) due to the growing emphasis on the motor capacity, different battery, battery range and driving range. This transition is not only driven by environmental concerns but also by the economic advantages associated with electric commercial vehicles. Table 4 displays some of the electrical vehicle models available on the market.

Table 4. Commercial EV vehicles available on the market.

Company Name	Electric Vehicle Model	Specifications
NETA	Neta V 	Battery Electric Vehicles Battery Type: Lithium Battery Electric motor: 135.33 kW Battery capacity: 38.54 kWh Driving Range: 380 km Maximum Torque: 160 Nm Top Speed: 120 km/h
Smart	#1 Pro 	Battery Electric Vehicles Battery Type: LFP Battery Electric motor: 147.09 kW Battery capacity: 66/44 kWh Driving Range: 315/440 km Maximum Torque: 343 Nm Top Speed: 180 km/h
BYD	Atto 3 	Battery Electric Vehicles Battery Type: LFP Battery Electric motor: 203 Battery capacity: 60.48/49.92 kWh Driving Range: 410/480 km Maximum Torque: 310 Nm

Table 4. *Cont.*

Company Name	Electric Vehicle Model	Specifications
Tesla	Model Y 	Battery Electric Vehicles Battery Type: LFP Battery Electric motor: 255 kW Battery capacity: 62 kWh Driving Range: 455 km Maximum Torque: 420 Nm Top Speed: 217 km/h
Hyundai	Ioniq 6 RWD 	Battery Electric Vehicles Battery Type: Lithium Battery Electric motor: 168 kW Battery capacity: 77 kWh Driving Range: 614 km Maximum Torque: 310 Nm
Tesla	Cybertruck 	Battery Electric Vehicles Battery Type: Lithium Battery Electric motor: 450 kW Battery capacity: 123 kWh Driving Range: 350 km Maximum Torque: 310 Nm

3.5. Pros and Cons of Electric Vehicles

Electric vehicles offer advantages such as zero emissions and long ranges, but they face challenges related to the infrastructure, cost, and competition from other electric vehicle technologies. The success of EVs depends on overcoming these challenges through technological advancements, increased investment, and supportive government policies. Table 5 lists the positives and limitations of electric vehicles.

Table 5. Pros and cons of electric vehicles.

Pros	Cons
Higher efficiency of powertrain	Limited refuel infrastructure
Higher energy density than other conventional fuels	Higher upfront cost
Improved acceleration and power transmission compared to combustion-engine technology	Production cost of the vehicle is high
Rechargeability of the battery system	Highly flammable
Noise-free working of the motor	Cost of battery and battery degradation

4. Overview of Fuel Cell Electric Vehicles (FCEVs)

Automobiles are one of the reasons for the increasing of greenhouse gas emissions and thereby rising global warming. Moreover, most of the passenger vehicles like cars are still consuming fossil fuel-based petroleum oil. The burning of fossil fuels produces more greenhouse gases. So, at present, to address these pollution issues, petroleum-based vehicles are being replaced with electricity-driven vehicles [101]. Fuel cell-based electric vehicles are better than battery-based electric vehicles because of their short refueling time and light weight. Fuel cell electric vehicles (FCEVs) are a subset of electric vehicles that power an electric motor with the electricity produced by a fuel cell within the vehicle.

FCEVs employ hydrogen gas conversion to produce energy, in contrast to standard electric vehicles that store electricity in batteries [101]. The fuel cell plays an important role in the functioning of FCEVs. Fuel cell development and its utilization for automobiles have a long history to cover. The timeline of important historical events regarding the fuel cell electric vehicle development is shown in Figure 12.

4.1. History and Development

The fuel cell is an electrochemical device that works opposite to the process of electrolysis, where hydrogen and oxygen chemical energy is used to generate electricity and water as a by-product using two electrodes, anode and cathode and in the presence of an electrolyte [102]. The fuel cell was first demonstrated by a scientist named Willam Grove in 1839, which was named as a gas battery. Furthermore, the first alkaline fuel cell was built by Thomas Francis Bacon in 1939, which used hydrogen and oxygen for generating electricity and water and paved the way for development of various types of fuel cells [103]. There are different kinds of fuel cells at present, like the alkaline fuel cell (AFC), solid oxide fuel cell (SOFC), molten carbonate fuel cell (MCFC), proton exchange membrane fuel cell (PEMFC), phosphoric acid fuel cell (PAFC), direct methanol fuel cell and reversible fuel cells [103].

Fuel cells have been utilized for a variety of purposes since their creation in 1838, including stationary power plants, submarines, and spacecraft. General Motors (GM) created the first fuel cell-powered vehicle, the GMC Electrovan, in 1966 using a Union Carbide fuel cell [104]. It was the product of a two-year development project headed by Dr. Craig Marks and made use of 32 fuel cell modules with a 32 kW continuous output and a 160 kW peak capacity. Pure liquid oxygen and hydrogen were employed as fuel. With a range of 120 miles, the Electrovan could reach a top speed of 70 miles per hour [104]. However, because of the enormous hydrogen and oxygen tanks and the piping, the entire fuel cell system reduced the capacity of the six-seat van to two seats. The work on fuel cell-based vehicles was discontinued then due to its high making cost compared to gasoline-based vehicles and the lack of required infrastructure facilities for refueling. In the 21st century, with the rise in fuel prices and rising greenhouse gas emissions, FCEVs are gaining traction. A number of companies, like Toyota, Honda, BMW, General Motors and Hyundai, etc., are working on developing efficient fuel cell-based electric vehicles [105].

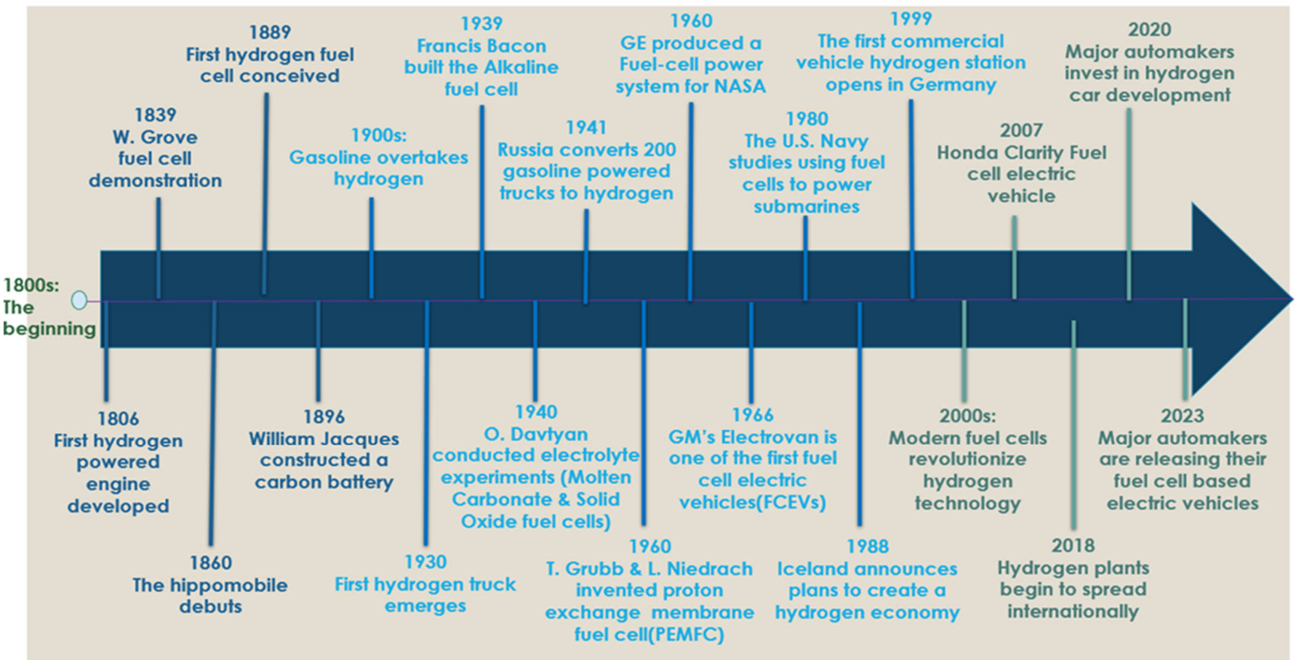

Figure 12. The history and timeline of the fuel cell vehicles [106–108].

4.2. Classification of Fuel Cells

There are different types of fuel cells available for various application based on their electrode properties and electrolytes [109]. Mainly there are five types of fuel cells reported in the literature. The different properties of different fuel cells and the electrochemical reactions that occur at the anode and cathode are given in Table 6.

Table 6. Basic electro-chemical reactions and properties of different fuel cells [109].

Fuel Cell	AFC	SOFC	PEMFC	PAFC	MCFC
Cathode reaction	$1/2\ O_2 + H_2O + 2\ e^- \rightarrow 2\ (OH)^{-1}$	$1/2\ O_2 + 2\ e^- \rightarrow O^{2-}$	$1/2\ O_2 + 2\ H^+ + 2\ e^- \rightarrow H_2O$	$1/2\ O_2 + 2\ H^+ + 2\ e^- \rightarrow H_2O$	$1/2\ O_2 + CO_2 + 2\ e^- \rightarrow CO_3^{-2}$
Anode reaction	$H_2 + 2\ OH^- \rightarrow 2\ H_2O + 2\ e^-$	$H_2 + O^{2-} \rightarrow H_2O + 2\ e^-$ $CO + O^{2-} \rightarrow CO_2 + 2\ e^-$ $CH_4 + 4\ O^{2-} \rightarrow 2\ H_2O + CO_2 + 8\ e^-$	$H_2 \rightarrow 2\ H^+ + 2\ e^-$	$H_2 \rightarrow 2\ H^+ + 2\ e^-$	$H_2 + CO_3^{-2} \rightarrow H_2O + CO_2 + 2\ e^-$
Electrolyte	KOH aqueous solution	Yttria-stabilized zirconia (YSZ)	Polymer membrane	Phosphoric acid (H_3PO_4)	Molten carbonate
Stack size	1–200 kW	1 kW–2 MW	<1 kW–100 kW	100 kW	300 kW–3 MW
Operating temperature	≤100 °C	≤1000 °C	≤120 °C	≤200 °C	≤700 °C
Fuels	Hydrogen, Ammonia	Natural gas, Methanol, Ethanol, Biogas, Coal gas	Hydrogen	Hydrogen, Methanol	Natural gas, Methanol, Ethanol, Biogas, Coal gas
Electrical efficiency (LHV)	≤70%	≤60%	≤60%	≤50%	≤50%

4.2.1. Alkaline Fuel Cell (AFC)

The first fuel cell technology created and extensively employed in the American space program for generating water and electricity on board spacecraft were alkaline fuel cells (AFCs) [110]. They can use a variety of non-precious metals as a catalyst on the anode/cathode and employ an electrolyte consisting of potassium hydroxide dissolved in water. Novel AFCs that use an alkaline membrane rather than an acid membrane as the electrolyte have recently been created. These fuel cells are closely connected to regular PEM fuel cells. Because of the speed at which electrochemical reactions occur, AFCs operate well and have shown efficiencies in space applications exceeding 60%. They are vulnerable to CO_2 poisoning, though, which can seriously impair the longevity and efficiency of the cells. These issues are addressed by alkaline membrane fuel cells (AMFCs), which are less prone to CO_2 poisoning than liquid-electrolyte AFCs. On the other hand, AMFCs continue to lag behind PEMFCs, and CO_2 still impacts performance and durability. Tolerance to carbon dioxide, membrane durability and conductivity, higher temperature operation, water management, power density, and anode electrocatalysis are among the challenges faced by AMFCs.

4.2.2. Polymer Electrolyte Membrane Fuel Cell (PEMFC)

Proton exchange membrane (PEM) fuel cells are distinguished from other fuel cells by their low weight, volume, and high power density [110]. They employ porous carbon electrodes with a platinum or platinum alloy catalyst in conjunction with a solid polymer as the electrolyte. PEM fuel cells run solely on hydrogen, water, and oxygen from the air. Pure hydrogen is usually fed into the cells via reformers or storage tanks. Lower operating temperatures, about 80 °C (176°F), provide faster startup times and increased durability. The process of separating the protons and electrons in hydrogen necessitates the use of a noble-metal catalyst, usually platinum, which raises the cost of the system. Because the platinum catalyst is susceptible to carbon monoxide poisoning, reducing carbon monoxide in the fuel gas requires the use of an extra reactor. PEM fuel cells find their main use in stationery and transportation settings, especially in automobiles, buses, and heavy-duty trucks.

4.2.3. Molten Carbonate Fuel Cell (MCFC)

Molten carbonate fuel cells, or MCFCs, are being developed for a variety of uses in coal- and natural gas-fired power plants [110]. The electrolyte used in these high-temperature fuel cells is a molten mixture of carbonate salt suspended within a porous ceramic matrix of lithium aluminum oxide, which is inert by nature. They run at high temperatures of roughly 650 °C and non-precious metals can be employed as catalysts at the electrodes, which lowers expenses. Additionally, MCFCs are more efficient; when combined with a turbine, their efficiencies can approach 65%. Fuel efficiency can exceed 85% when waste heat is collected and put to use. MCFCs may produce hydrogen from fuels like natural gas and biogas without the need for an external reformer, in contrast to alkaline, phosphoric acid, and PEM fuel cells. Methane and other light hydrocarbons can be converted into hydrogen through internal reforming, which lowers expenses. The main drawback of the present MCFC technology is that high temperatures and a corrosive electrolyte speed up component corrosion and breakdown, reducing the cell life. Researchers are looking at materials that can withstand corrosion and fuel cell architectures that can quadruple the cell life without sacrificing efficiency.

4.2.4. Phosphoric Acid Fuel Cell (PAFC)

The electrolyte in phosphoric acid fuel cells (PAFCs) is liquid phosphoric acid, which is encapsulated in a silicon carbide matrix bound with Teflon [110]. The porous carbon electrodes in PAFCs are coated with a platinum catalyst. The earliest type of contemporary fuel cells are phosphoric acid fuel cells (PAFCs), which are utilized in some large vehicles like city buses and for stationary power generation. When fossil fuels are converted into hydrogen, they may withstand impurities better than PEM cells, which are quickly poisoned by carbon monoxide. When used for cogeneration of heat and electricity, PAFCs have an efficiency of over 85%; however, their efficiency for producing electricity alone ranges from 37% to 42%. They are usually huge and heavy, and they are also less powerful than other fuel cells. The greater loadings of pricey platinum catalysts in PAFCs than in other fuel cell types contribute to their increased cost. All things considered, PAFCs are a reliable and affordable substitute for conventional fuel cells.

4.2.5. Solid Oxide Fuel Cell (SOFC)

A strong, non-porous ceramic substance is used as the electrolyte in solid oxide fuel cells (SOFCs), a form of fuel cell that converts fuel into energy [110]. In co-generation applications, they can reach 85% fuel consumption efficiencies, and their efficiency is about 60%. Operating at temperatures as high as 1000 °C (1830 °F), SOFCs may reform fuels internally and require fewer precious-metal catalysts. They may use coal gasses, biogas, and natural gas, since they are the most sulfur-resistant fuel cell type. They can withstand higher sulfur concentrations than other cell types and are not carbon monoxide poisoned. On the other hand, there are drawbacks to high-temperature operation, including sluggish startup and substantial heat-shielding. The creation of low-cost materials with great durability is a major technical problem, since high operating temperatures also impose strict durability requirements on materials. Researchers are looking into the possibility of using less expensive, lower-temperature SOFCs that operate below 700 °C and have fewer durability issues.

4.2.6. Direct Methanol Fuel Cells

Hydrogen is the fuel used in most fuel cells; it can be produced internally or supplied directly. Water and pure methanol are delivered directly to the fuel cell anode in direct methanol fuel cells (DMFCs) to provide energy [110]. Because methanol has a higher energy density than hydrogen but a lower one than gasoline or diesel fuel, DMFCs have less fuel storage issues. Because methanol is a liquid, it is simpler to transport and distribute to the general public. DMFCs are frequently utilized in portable fuel cell devices, such as laptops and cell phones. We are still developing functions in this lower temperature range.

4.2.7. Reversible Fuel Cells

Like other fuel cells, reversible fuel cells use hydrogen and oxygen to produce electricity [110]. As by-products, they also produce heat and water. However, using a process known as electrolysis, reversible fuel cell devices may also divide water into oxygen and hydrogen fuel using electricity from sun, wind, or other sources. Reversible fuel cells are capable of producing electricity when required, but they may also store excess energy in the form of hydrogen when high power output from other sources occurs (for example, when strong winds result in an excess of wind power being available). Technologies utilizing intermittent renewable energy sources may benefit greatly from this energy storage capacity. Table 6 lists the basic electro-chemical reactions in different types of fuel cells.

4.2.8. Fuel Cell Application for Electric Vehicles

The fuel cell operates based on the electrolysis process. The electrolysis process occurs between the two electrodes of the fuel cells. The anode and cathode are the two electrodes that conduct two electrochemical processes. Protons and electrons are extracted from hydrogen in the anode. Protons go across a membrane to reach the cathode, while electrons travel via an external electric circuit. Current is the term for the flow of electrons. Water is created when protons and electrons interact with the oxygen that is supplied from the cathode. The water is the by-product of a fuel cell.

Due to its ease of use and high energy density, the polymer electrolyte membrane (PEM) fuel cell is a popular option for automotive applications [111]. It is composed of an electrolyte membrane that is positioned between a positive and negative electrode, with oxygen going to the cathode and hydrogen going to the anode. In the fuel cell catalyst, the hydrogen molecules undergo an electrochemical reaction that splits them into protons and electrons. Materials including polytetrafluoroethylene, graphite NCK 194, platinum, and carbon cloth are used for the membrane, flow channel plate, catalyst, and gas diffusion layer [111]. The basic electrochemical reactions that occur across the anode and cathode electrodes are shown in Figure 13.

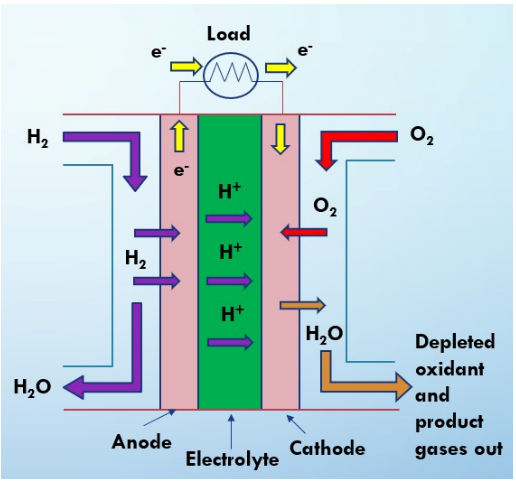

Figure 13. Electrochemical reaction mechanism of a fuel cell. Reprinted from Ref. [112].

4.3. Key Components and Technological Features

Fuel cell electric vehicles, or FCEVs for short, are a subset of electric vehicles that rely less on batteries and more on fuel cells to produce power internally. The main parts and advanced features of fuel cell electric vehicles are as follows.

Fuel cell stack: The fuel cell stack is the major component of a fuel cell electric vehicle. It is made up of several separate fuel cells that use an electrochemical mechanism to turn hydrogen and oxygen into energy. The proton exchange membrane fuel cell (PEMFC) is most used for automobile applications [109].

Storage tanks for hydrogen: High-pressure tanks are used by FCEVs to store hydrogen, the fuel for the fuel cell. To maintain the vehicle's range and general performance, the hydrogen must be stored in a safe and effective manner. Vehicles usually employ hydrogen pressure tanks operating at 700 bar, with a storage capacity varying between 4.4 kg and

6.33 kg [113]. These tanks are made using type IV manufacturing techniques that include wet-winding and polymer liners (HDPE, PA6, etc.) [113].

Battery (auxiliary): In an electric drive vehicle, the low-voltage auxiliary battery provides electricity to start the car before the traction battery is engaged and it also powers vehicle accessories [114].

Battery pack: The electric traction motor receives extra power from this high-voltage battery, which also stores energy produced by regenerative braking. A high-performance Li-ion battery pack with a capacity of 1.5–2 kWh [115].

DC/DC converter: This device converts the higher-voltage DC power from the traction battery pack to the lower-voltage DC power needed to run the vehicle accessories and recharge the auxiliary battery. A unidirectional non-isolated step-up converter fulfils the requirements of the DC/DC convertor for fuel cell vehicles [116].

Power electronics controller (FCEV): This unit manages the flow of electrical energy delivered by the fuel cell and the traction battery, controlling the speed of the electric traction motor and the torque it produces.

Electric traction motor (FCEV): Using power from the fuel cell and the traction battery pack, this motor drives the vehicle's wheels. Some vehicles use motor generators that perform both the drive and regeneration functions. A motor with power in the range of 100–160 kW is used in most of the fuel cell electric vehicles [11].

Transmission (electric): The electric traction motor's mechanical power is transferred to the wheels through the transmission [114].

Hydrogen fueling system: A specific infrastructure for hydrogen fueling is needed for FCEVs. The vehicle's storage tanks are filled with compressed hydrogen from hydrogen fueling stations. High-pressure dispensing is used in the procedure to guarantee effective refueling.

Thermal management system: There is a temperature range in which fuel cells perform best. By keeping the fuel cell stack's working temperature at the proper level, a thermal management system helps avoid overheating or inefficient performance. Furthermore, the system keeps the power electronics, electric motor, and other parts within their recommended working temperature range. The liquid cooling is better for developing an effective integrated thermal management system in fuel cell vehicles and the heat pump is best option for providing air-conditioning [117]. The inner assembly design for a fuel cell electric vehicle is shown in Figure 14.

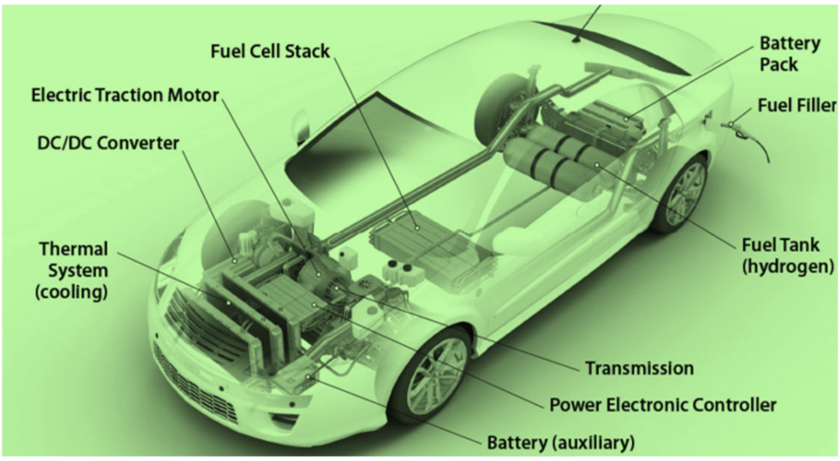

Figure 14. Technical components of a fuel cell electric vehicle. Reprinted from Refs. [109,118].

4.4. Commercial Fuel Cell Electric Vehicles

There are various commercial vehicle models available on the market from various manufacturers. Table 7 lists out some of the commercial fuel cell electric vehicles and their specifications.

Table 7. Fuel cell vehicles by various companies and their specifications [119].

Company Name	Fuel Cell Vehicle Model	Tank Capacity (kg)	Electric Motor	Range (km)	Carbon Emissions (g/km)
Toyota	MIRAI 2016 Sedan 	5.6	135.33 kW	650	0
	MIRAI II 2021 Sedan 	5.6	135.33 kW	650	0
Hyundai	NEXO 2018 SUV 	6.33	120 kW	756	0
	ix35 2012 SUV 	5.64	100 kW	594	0
Honda	Clarity Fuel Cell 2008 Saloon 	5.0	130 kW	589	0
Mercedes-Benz FCEV with Li-ion battery	GLC F-CELL 2018 SUV 	4.4	155 kW	478	0
Citroen	e-Jumpy Hydrogen 2019 Transporter 	4.4	100 kW	400	0
PEUGEOT	e-Expert Hydrogen 2019 Transporter 	4.4	100 kW	400	0
Opel	Vivaro e-HYDROGEN 2021 Transporter 	4.4	100 kW	400	0

4.5. Pros and Cons of Fuel Cell Electric Vehicles

Fuel cell electric vehicles offer advantages such as zero emissions and long ranges, but they face challenges related to the infrastructure, cost, and competition from other electric vehicle technologies. The success of FCEVs depends on overcoming these challenges through technological advancements, increased investment, and supportive government policies. Table 8 lists the positives and limitations of a fuel cell electric vehicle.

Table 8. Pros and cons of fuel cell electric vehicles [113–118].

Pros	Cons
Zero tailpipe emissions	Limited refuel infrastructure
Higher energy density than other conventional fuels	Storage of hydrogen
Renewable fuel such as H_2 can be generated using solar wind power	Production cost of hydrogen
Long range of journey	Production cost of the vehicle
Short refueling time	Highly flammable
Noise-free working of motor	Cost of cathode/anode materials

5. Vehicle-Integrated Photovoltaics (Solar-Powered Vehicles)

The integration of photovoltaic systems in vehicles can help to decrease transportation-related emissions and support the global effort to mitigate the effects of climate change. A lot of renewable energy had been introduced throughout the years and photovoltaic technology had proven that it is one of many steps in chasing the sustainability of energy sources [120].

5.1. History and Development

- The concept of solar-powered vehicles has been around for decades, with early experiments dating back to the 1950s. However, significant development began in the 1980s and 1990s.
- The World Solar Challenge, a solar car race across Australia, has played a crucial role in driving innovation and promoting solar-powered vehicle development since its inception in 1987.
- Over the years, advancements in photovoltaic technology, energy storage, and vehicle design have contributed to the evolution of solar-powered vehicles. The use of VIPVs has been gaining traction in recent years to reduce the environmental impact of transportation.
- Through transportation, industry players also started to introduce and produce battery electric vehicles (BEVs) as a way to support the movement to save the world from catastrophic climate failure. Figure 15 shows the model of a solar vehicle named as Lightyear One.

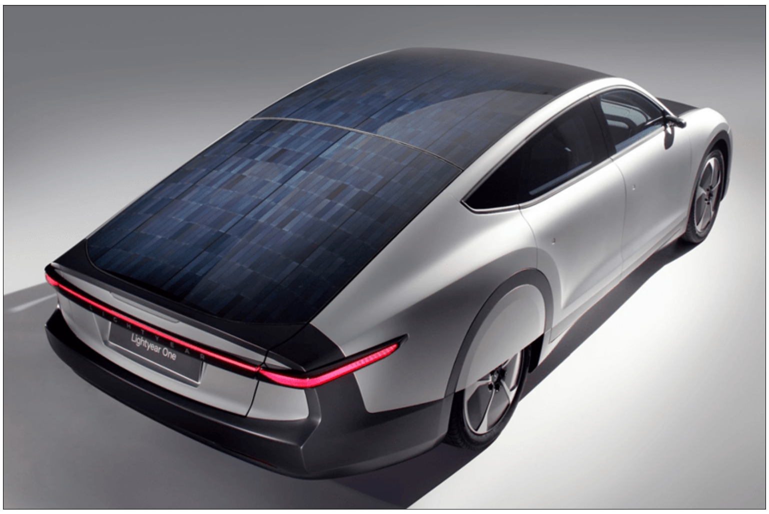

Figure 15. Photograph of a vehicle-integrated photovoltaics (VIPV). Reprinted from Ref. [121].

5.2. Working Principles of Solar-Powered Vehicle (Vehicle-Integrated Photovoltaics)

The use of photovoltaic (PV) windows has been gaining attention as a potential solution for achieving energy efficiency in buildings. PV windows are specially designed windows that have integrated photovoltaic cells, which convert sunlight into electricity. This means that PV windows cannot only provide natural lighting but also generate electricity. Solar automobiles require solar arrays, which use photovoltaic cells (PV cells) to convert sunlight into electrical power. PV cells turn sunlight directly into electricity, as opposed to solar thermal energy, which converts sunlight into heat that can be used in buildings or converted into electricity later [122]. When sunlight (photons) hits PV cells, it excites the electrons and allows them to flow, which creates an electric current. PV cells are made from semiconductor materials such as silicon and alloys of indium, gallium, and nitrogen. Crystalline silicon, which has an efficiency rate of 15–25%, is the most common material. The rooftop is often where solar panels for solar cars are installed because it receives the greatest sunshine there. The photovoltaic cells of solar panels are comprised of silicon, a mixture of gallium and indium alloys. These materials have a built-in retention ability that allows them to absorb solar light energy. The energy is subsequently released as free-moving electrons into specially designed storage areas. In actuality, we refer to this storage area as batteries. They are composed of distinctive materials, including nickel-cadmium, lithium-ion, and others. These batteries can transform free electrons into useable energy to power the car's motor. These batteries are special in that we can continue to use them to power an automobile. We can do this by recharging them with solar energy. On a single full charge, solar-powered vehicles may go 60 to 90 km. Integrated photovoltaics in an electric vehicle as shown above is an emerging technology that can extend the range of electric vehicles, and as the costs of photovoltaics (PVs), batteries, and electric vehicles are likely to keep falling, the technologies can jointly play a key role in deep decarbonization [123].

5.3. Technological Features of Solar Vehicles

5.3.1. Key Components

Figure 16 shows the key components of a solar vehicle, which comprises of a solar PV panel, motor, motor power controller, the battery pack and the cockpit.

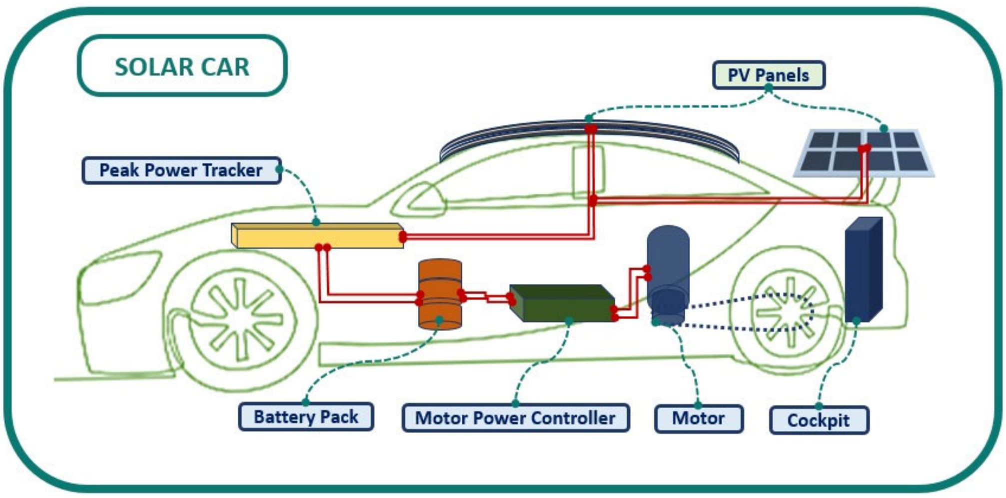

Figure 16. Technical components of a solar vehicle.

- Photovoltaic Cells: Solar panels mounted on the vehicle's surface to capture sunlight. Also known as solar panels, lined with thousands of photovoltaic cells that convert the solar energy into usable electricity.
- Energy Storage: High-capacity batteries to store and manage the generated solar energy. Stores the energy required to run the motor and controller.

- Power Trackers: Assists in directing the solar energy generated toward the storage battery. They also serve as a stopper to avoid overcharging the batteries.
- Electric Motor: Drives the vehicle using the stored solar energy. Converts the electric energy into mechanical energy that helps in moving the wheels.
- Power Management System: Controls the distribution and usage of solar-generated electricity.
- Lightweight Material Chassis: Many solar vehicles use lightweight materials to enhance efficiency and maximize the vehicle's range.
- Navigational Device: Steering or remote control helps in navigating the solar car in the desired direction. The outer framework on which the entire structure of the car sits upon.
- Wheel: Helps in maneuvering the direction and speed of movement of the vehicle
- Speed Controller: Aids in keeping track of the vehicle's speed and controlling the engine and wheels accordingly.

5.3.2. Performance Based on Climate, Design and Emission Aspects of the VIPV

Solar irradiance is a major factor in the design of vehicle-integrated photovoltaics (VIPVs). Studies have shown that the performance of vehicle-integrated photovoltaic (VIPV) systems can vary significantly depending on the climate zone, with variations in the solar irradiance, temperature, and humidity all having an impact on the system's efficiency. The performance of VIPV systems is affected by different climate zones, which can lead to reduced power production and driving range. It varies across different climate zones, making it difficult to design a single system that can be used in all locations. This poses a challenge for engineers and designers who need to create systems that are tailored to the specific climate zone they are working in. As such, it is important to understand how solar irradiance affects the design of VIPV systems so that they can be optimized for each location. This poses a challenge for those looking to use VIPV systems in different climates, as they must consider how their system will perform in each climate zone. A VIPV system has the potential to revolutionize the way we power our vehicles. VIPVs' problem is that they are using solar cells as a range extender or for auxiliary usage rather than fully powering the vehicle. This means that the vehicle is not able to take full advantage of the solar energy available and is not able to reach its full potential. This issue needs to be addressed in order to make sure that VIPV run to its full potential. A study assessed the relationship of six different climatic conditions with one passenger vehicle and a small commercial vehicle. This study concluded that in the best climatic conditions, the researcher discovered that the average annual solar range of a photovoltaic electric vehicle (PVEV) with 454 Wp VIPV can equal around 35% of the yearly mileage of a car [123]. This figure can be as low as 12% in unfavorable weather conditions. The advantages are lesser, between 9 and 23%, for a delivery van with a 649 Wp VIPV, in part because of the 51% higher yearly mileage compared to driving a vehicle. An investigation investigated the solar irradiance that can be collected on a car roof for VIPVs. This study was conducted in a tropical climate zone with a dense urbanization of tall buildings that were not affected by the four seasons [124].

Figure 17 shows different possible PV technologies integrated and the potential integration sites for solar cells on the vehicle. This study indicates that in tropical zones, the humidity, cloud presence and multiple orientations of buildings resulted in much lower performance compared to sunny days. Thus, the researcher concluded that VIPV users plan the drive to reduce shading and before urbanization, the orientation of the buildings must not produce high shading in the path of the sun.

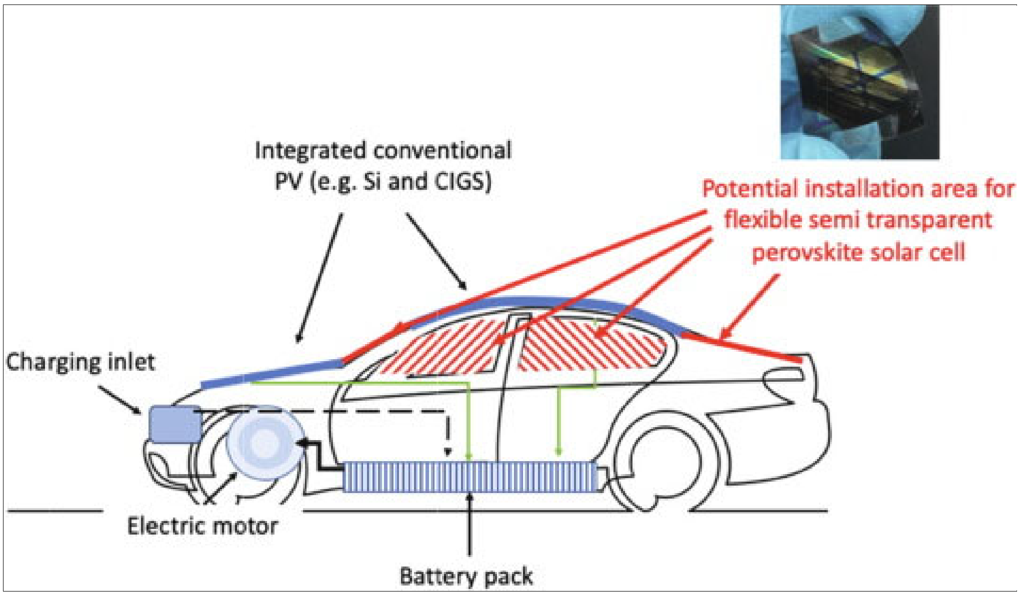

Figure 17. Integration points and types of PV panels for solar vehicles. Reprinted with permission from Ref. [125]. Copyright 2024 Elsevier.

Solar electric vehicles (EVs) have been seen as a solution to reduce emissions from transportation. However, there are still debates about the actual emissions reduction by EVs, as it depends on the source of electricity, as shown in Figure 18, and the comparison with conventional vehicles. In research by R. Álvarez Fernández [126], the author highlighted the importance of considering the grid mix of the region when evaluating the emissions of EVs. The study found that EVs in regions with high coal-based electricity generation might not significantly reduce greenhouse gas emissions compared to conventional vehicles. In another study by A. Hoekstra [127], the author suggested that battery EVs have a larger potential to reduce emissions than previously estimated. The authors of [128] reviewed the effects of electric mobility on emissions, air pollutants, and human health. The study found that EVs have a positive impact on reducing greenhouse gas emissions and air pollutants compared to conventional vehicles, but it also points out the importance of considering the source of the electricity. Next, in another study by J. Xing et al. [129], the authors studied the impact of EVs on the transportation sector and the replacement of conventional vehicles.

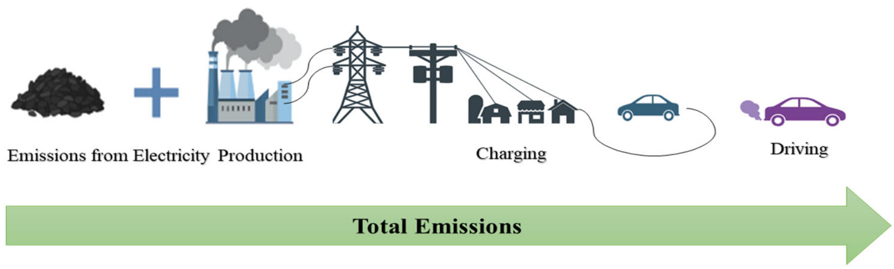

Figure 18. Emissions during the operation of an electric Vehicle [130].

Research has shown that the integration of photovoltaics into vehicles can lead to a reduction in emissions from transportation by reducing the need for fossil fuels and increasing the use of renewable energy. This is achieved by using the power generated by the photovoltaics to either directly power the vehicle or to charge the battery of an electric vehicle. This can lead to a reduction in emissions from the tailpipe, as well as emissions from the power generation needed to charge the vehicle.

In 2020, a study by Susskind et al. [120] examined the potential for decarbonization in Malaysia and found that the widespread adoption of electric vehicles (EVs) and renewable energy sources, including VIPVs, could play a significant role in reducing emissions in the country. The study also found that the integration of photovoltaics into vehicles could lead to a reduction in emissions from power generation, as the power generated by the photovoltaics could be used to charge the EVs, reducing the need for power generated from fossil fuels. Another 2020 study by Kobashi et al. [131] found that the combination of photovoltaics and EVs has the potential for deep decarbonization of power systems in Kyoto, Japan. The study found that the integration of photovoltaics into vehicles could lead to a reduction in emissions from power generation and transportation, as the power generated by the photovoltaics could be used to charge the EVs and to power the vehicles directly. The possible emissions from the various stages of solar vehicle operation are shown in Figure 18.

VIPV technology has the potential to significantly reduce the dependence on fossil fuels and increase the energy efficiency of vehicles. However, several challenges need to be overcome for its widespread implementation, such as the need for more efficient and flexible PV modules and new design and integration methods. Studies have also highlighted the potential of this technology to reduce greenhouse gas emissions and increase the driving range of electric vehicles. Research has shown that vehicle-integrated photovoltaics have the potential to reduce emissions from transportation. The integration of photovoltaics into vehicles can lead to a reduction in emissions from the tailpipe, as well as emissions from power generation. The implementation of VIPVs, in combination with the use of electric vehicles and renewable energy sources, can play a significant role in decarbonization efforts. However, more accurate testing methods are needed to better understand the real-world emissions of vehicles and the potential impact of VIPVs on emissions reduction.

5.4. Commercial Status of the Solar Vehicles

Lightyear 0

The Lightyear 0, as in Figure 19 (formerly Lightyear One), is a solar-powered vehicle. The Lightyear 0 electric vehicle is now being manufactured by the Dutch solar EV startup at Valmet Automotive's factory in Uusikaupunki, Finland. The Lightyear Company was founded in September 2016 and now employs more than 500 employees. Lightyear takes pride in being the first automaker to produce an electric car that uses sunlight as its primary source of electricity. To get to this point and ultimately enter the market with new technology, the startup spent six years building its own technologies. The Lightyear 0 is merely the first stage in the company's plan to change the mobility industry, as its name implies. By 2025, the business hopes to introduce a solar-powered electric vehicle (EV) with a substantially smaller battery. Lightyear hopes to enable users to bypass the charging grid and travel more sustainably for the time being by developing an effective vehicle with a smaller battery capacity of 60 kWh. Much like the One, the 0 wears a strip of photovoltaic cells from its snoot to its boot. According to Lightyear, there are a full 5 square meters of solar array atop the 0, which equates to 54 square feet, a figure that carries over from the prototype. The tapered tadpole body shape is the same, though it appears Lightyear made some minor concessions to regulatory demands with the 0, enlarging its headlight binnacles and reshaping some aspects of the fog lights and taillights. Lightyear focused hard on the aerodynamics, largely because there is a relatively small 60 kWh battery pack backing up the 0's solar array.

Figure 19. Lightyear 0 and One car design. Reprinted from Ref. [121].

Lightyear 0 has curves, soft lines and organic shapes, which enable the car to slip through the air, minimizing the energy lost through air resistance. A good (low) drag coefficient means a more economical car that consumes less energy and, as a result, drives further. Lightyear 0 has a record of <0.19 drag coefficient, making it the most aerodynamic family car on the market. Every element of Lightyear 0′s design minimizes energy usage and stretches each joule as far as it can go. It slips through the air like silk, attaining a record-breaking drag coefficient (Cd) of 0.175. The grill shutter reduces air resistance and therefore energy consumption by up to 6.6%, its closed rims by 3.5% and its rear wheel covers by 1.9% through reducing the effect of turbulence caused by the wheels on the drag of the car. Not a detail has been overlooked, right down to the car's length. If it were just 15 cm shorter, energy consumption would increase by 3%.

Aerodynamics—Cd value 0.175;
Energy use—10.5 kWh/100 km;
*Tested at highway speeds of 100 km/h (62 miles).

Unlike traditional EVs, the body of Lightyear 0, as in Figure 20, does not depend on sockets and cables alone. Lightyear 0′s integrated solar technology greatly reduces the need for plug-charging. It charges wherever there is daylight, whether parked or on the move. With a peak solar charging speed of 1.05 kW, it can yield up to 70 km (depending on habits, location and season) of free, clean range per day. With an infinite power source like that on the roof, it can drive for months without charging.

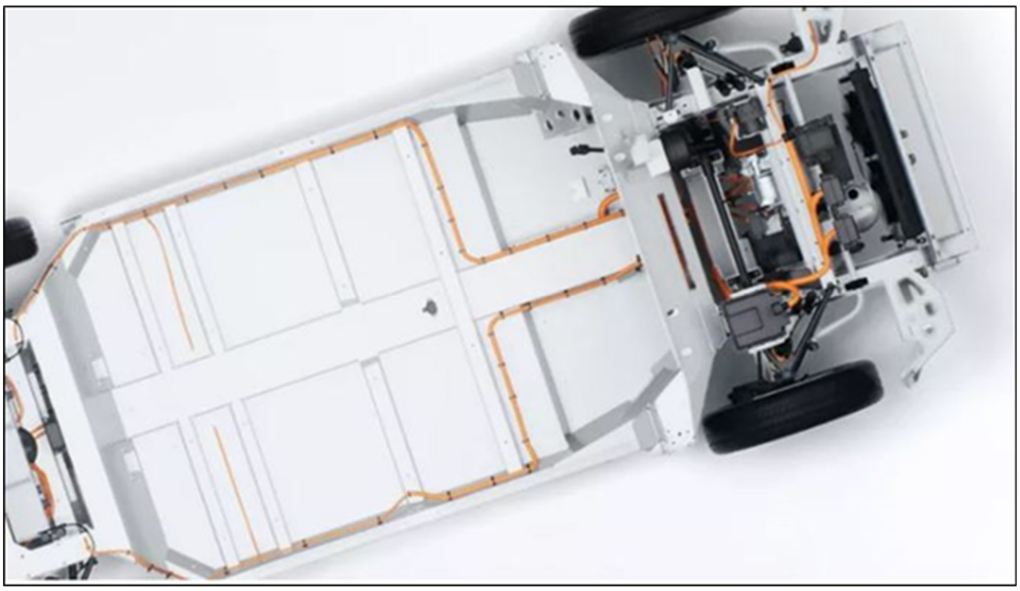

Figure 20. Body of Lightyear 0. Reprinted from Ref. [121].

Lightyear 0's body has a balanced, symmetrical, and streamlined design that utilizes lighter building materials that maintain rigorous safety standard, like aluminum and reclaimed carbon fiber. Despite being over five-meters long, its total weight is just 1575 kg. Reclaimed carbon that will otherwise go to waste forms its outer body panels.

- While solar-powered cars for daily commuting are still in the experimental stage, solar technology has found applications in certain commercial vehicles.
- Solar panels are being integrated into electric buses, trucks, and even some electric bicycles to extend their range and reduce reliance on external charging.
- Public transportation and delivery vehicles in urban areas are potential candidates for solar integration due to their frequent stops and starts, providing opportunities for solar recharging.

5.5. Pros and Cons of Solar Vehicles

The best thing about solar cars is their ability to constantly recharge their batteries, even while they are sitting still and parked in direct sunlight. This effectively eliminates the running costs associated with the vehicle [132]. However, the disadvantages are the price of the solar panel is expensive, making the solar vehicle itself expensive. The solar panel also does not reach its maximum utilization yet and hence is less efficient. In addition, solar vehicles are weather-dependent, which means that there are limited optimal operating hours in a day. Solar-powered cars present an opportunity for reducing the electricity demand from the grid for electric cars. They may also reduce the necessary battery capacity needed for a specific vehicle range. This could contribute to reducing greenhouse gas emissions from both electricity generation and battery manufacturing. A smaller battery capacity also limits the amount of raw materials needed in the battery. However, manufacturing of the PV cells may in turn generate some additional greenhouse gas emissions and increase the requirements for other scarce materials. Furthermore, the geographical location of the car influences the amount of electricity generated by the PV cells as well as the energy use per km driven. Finally, the car use patterns will also affect the electricity that can be generated by the PV cells.

Pros:

- Renewable Energy: Solar power is a clean and renewable energy source, reducing dependence on non-renewable resources.
- Extended Range: Solar integration can extend the range of electric vehicles, especially in sunny regions.
- Low Operating Costs: Once installed, solar panels have minimal operating costs and can reduce the overall cost of vehicle ownership.

Cons:

- Limited Efficiency: Current solar technology has limitations in terms of its efficiency, especially on compact vehicles with limited surface area for solar panels.
- Weather-Dependence: Solar power generation is dependent on sunlight, making it less effective during cloudy or night-time conditions.
- Initial Cost: The integration of solar technology can increase the initial cost of the vehicle, although this may be offset by lower operating costs over time.

6. Comparative Analysis of Sustainability Aspects of Various Green Vehicles

Table 9 compares different types of vehicles based on the source of fuel, like bio fuels, solar panels, fuel cell and battery, on various aspects.

Table 9. Comparison of vehicles on various aspects.

	Parameters	Bio Fuels	Solar	Fuel Cell	Electrical
Technical	Power Supply Core Components	Engine	Solar Cell Battery and Motor	Fuel Cell and Electric Motor	Battery and Electric Motor
	Fuel	Bio-Derived Fuels	Sunlight	Hydrogen	Electricity
	Mileage/Range	Very High	Low	High	Moderate
	Possible Hazards	Fuel Flammability	Battery Explosion	Hydrogen Flammability	Battery explosion
	Infrastructure	Established	Not Needed	Low	Moderate
	Hybridization Possibility	Yes	No	No	Yes
Economical	Initial Cost	Low	Very High	High	Moderate
	Running Cost	High	Nil	Moderate	Low
Environmental	Tailpipe Emissions	Depends on Fuels	zero	Zero (Water Vapor)	Zero
Social	Social Perception	Moderate	Low	Low	High
Policy	Government Policy Support	Yes	No	No	Yes
Market trend	Commercial Status	Commercial Blending is Available	Lightyear	Honda, Toyota, Mercedes, Hyundai	More Companies

6.1. Biofuel Vehicles

6.1.1. Technical Aspects

Compatibility: Discuss the compatibility of biofuels with existing vehicle engines and infrastructure, including considerations for engine modifications or adjustments to accommodate different fuel compositions.

Performance: Evaluate the performance characteristics of biofuel-powered vehicles in terms of the power output, fuel efficiency, and emissions compared to traditional gasoline or diesel vehicles.

Fuel Blends: Explore the feasibility and benefits of blending biofuels with conventional fossil fuels to reduce greenhouse gas emissions and enhance engine performance.

Engine Durability: Assess the long-term effects of biofuels on engine components, including wear and corrosion, and potential measures to mitigate any adverse impacts.

6.1.2. Economical Aspects

Cost-Competitiveness: Analyze the cost-competitiveness of biofuels compared to traditional petroleum-based fuels, considering factors such as production costs, feedstock availability, and government subsidies or incentives.

Supply Chain Economics: Discuss the economic implications of establishing a sustainable biofuel supply chain, including feedstock cultivation, processing, distribution, and retail infrastructure.

Job Creation: Explore the potential for job creation and economic development associated with the biofuel industry, including opportunities in agriculture, biofuel production, and related sectors.

6.1.3. Environmental Aspects

Greenhouse Gas Reduction: Highlight the environmental benefits of biofuels in reducing greenhouse gas emissions compared to fossil fuels, particularly when produced from renewable feedstocks such as agricultural residues or algae.

Land-Use Impact: Address concerns about the potential competition between biofuel feedstock production and food crops, as well as the importance of sustainable land management practices to minimize environmental impacts.

Biodiversity Conservation: Discuss the importance of preserving biodiversity and ecosystem integrity when cultivating biofuel feedstocks, emphasizing the need for sustainable land-use practices and biodiversity safeguards.

6.1.4. Social Aspects

Rural Development: Explore the potential for biofuel production to stimulate rural economies and provide alternative sources of income for farmers and agricultural communities.

Energy Access: Discuss how the production and distribution of biofuels can contribute to improving energy access and energy security in remote or underserved regions, reducing reliance on imported fossil fuels.

Consumer Awareness: Address the importance of consumer education and awareness campaigns to promote the adoption of biofuels and support sustainable practices in the transportation sector.

6.1.5. Policy Aspects

Renewable Fuel Standards: Evaluate the effectiveness of government mandates and incentives, such as renewable fuel standards (RFS) or biofuel-blending mandates, in promoting the use of biofuels and reducing dependence on fossil fuels.

Subsidies and Incentives: Discuss the role of government subsidies, tax credits, and other financial incentives in supporting biofuel production, distribution, and consumption, and their impact on market competitiveness.

Sustainability Certification: Highlight the importance of sustainability certification schemes and regulatory frameworks to ensure that biofuel production meets environmental, social, and economic criteria, such as the Roundtable on Sustainable Biomaterials (RSB) or the European Union's Renewable Energy Directive (RED).

6.1.6. Challenges and Opportunities

Feedstock Availability: Address challenges related to the availability and sustainability of biofuel feedstocks, including competition with food production, land-use constraints, and the development of advanced feedstock cultivation techniques.

Technological Innovation: Discuss opportunities for technological innovation in biofuel production processes, such as advanced bio-refining techniques, genetic engineering of feedstock crops, and the development of microbial fermentation pathways.

Market Acceptance: Explore challenges related to market acceptance and consumer perceptions of biofuels, including concerns about fuel compatibility, performance, and availability, and strategies to overcome these barriers through education and awareness campaigns.

These discussion points provide a comprehensive overview of the technical, economic, environmental, social, and policy aspects, and the challenges and opportunities, associated with biofuel-powered vehicles, highlighting both their potential benefits and the need for sustainable practices and policy support for widespread adoption.

6.2. Electric Vehicles

6.2.1. Technical Aspects

Battery Technology: Discuss advancements in battery technology, such as lithium-ion batteries, solid-state batteries, and their impact on EV performance, range, and charging times.

Motor Efficiency: Explore the efficiency of electric motors compared to internal-combustion engines, highlighting the simplicity, reliability, and torque characteristics of electric drivetrains.

Charging Infrastructure: Assess the development of charging infrastructure, including the availability of fast-charging stations, home-charging solutions, and emerging wireless charging technologies.

Vehicle Design: Examine how EV design differs from traditional vehicles, focusing on aerodynamics, lightweight materials, and regenerative braking systems.

6.2.2. Economical Aspects

Total Cost of Ownership (TCO): Analyze the TCO of EVs compared to internal-combustion vehicles, factoring in the purchase price, fuel/energy costs, maintenance, and potential incentives.

Market Trends: Discuss the growth trajectory of the EV market, including declining battery costs, economies of scale in production, and the potential for EVs to reach price parity with conventional vehicles.

Job Creation: Explore the economic implications of transitioning to EVs, including the creation of new jobs in manufacturing, battery production, and the renewable energy sector.

6.2.3. Environmental Aspects

Emissions Reduction: Highlight the environmental benefits of EVs in reducing greenhouse gas emissions and air pollution, particularly in urban areas with high traffic congestion.

Lifecycle Analysis: Consider the environmental impact of EVs throughout their lifecycle, including manufacturing, operation, and end-of-life recycling of batteries and vehicle components.

Renewable Energy Integration: Discuss the synergy between EV adoption and the expansion of renewable energy sources, such as solar and wind, to power-charging infrastructure.

6.2.4. Social Aspects

Equity and Access: Address the importance of ensuring equitable access to EVs and charging infrastructure across socio-economic groups, including initiatives to support underserved communities.

Public Health: Discuss the health benefits of reducing air pollution from transportation sources through the widespread adoption of EVs, leading to improvements in respiratory health and quality of life.

Consumer Adoption: Examine consumer perceptions and attitudes toward EVs, including range anxiety, charging convenience, and the role of education and awareness campaigns.

6.2.5. Policy Aspects

Government Incentives: Evaluate the effectiveness of policies such as purchase incentives, tax credits, and subsidies aimed at promoting EV adoption and accelerating market penetration.

Regulatory Framework: Discuss regulations related to vehicle emissions standards, fuel economy targets, and zero-emission vehicle mandates that influence the adoption and manufacturing of EVs.

Infrastructure Investment: Highlight the role of government investment in building charging infrastructure, public transit electrification, and research and development in EV technology.

6.2.6. Challenges and Opportunities

Range Anxiety: Address concerns about EV range limitations and the need for continued advancements in battery technology to increase the energy density and reduce the charging times.

Grid Integration: Explore challenges and opportunities associated with integrating EVs into the electricity grid, including managing the charging demand, grid stability, and smart charging solutions.

Industry Transformation: Discuss how the shift toward electric mobility presents opportunities for traditional automakers, startups, and technology companies to innovate and capture market share in a rapidly evolving landscape.

These discussion points provide a comprehensive overview of the multifaceted aspects of electric vehicles, highlighting both their potential benefits and the challenges that need to be addressed for widespread adoption.

6.3. Fuel Cell Vehicles

6.3.1. Technical Aspects

Advanced technical components of power fuel cell vehicles (FCVs). The fuel cell stack, which uses proton exchange membrane technology, is crucial to their operation. In high-pressure tanks, hydrogen performs electrochemical processes to produce electricity, which powers electric motors. Auxiliary systems provide optimal fuel cell operation while power electronics govern energy flow. During deceleration, efficient regenerative braking collects and stores energy. Technical aspects include the durability, hydrogen storage, and addressing infrastructure difficulties. FCVs have zero tailpipe emissions, underscoring their potential significance in sustainable transportation as researchers work to improve efficiency, lower costs, and advance the technology landscape.

6.3.2. Economical Aspects

The adoption of fuel cell vehicles (FCVs) is heavily reliant on economic factors. High production costs, particularly for platinum-based fuel cell stacks, pose problems. The prices of producing hydrogen and establishing a large refueling infrastructure are significant economic barriers. Economies of scale and current research are aimed at reducing these expenses. Total cost of ownership (TCO) studies that take into account lower operating costs and a longer lifespan may improve FCVs' competitiveness. Government incentives, supportive regulations, and improvements in green hydrogen production are all important in increasing the economic feasibility of FCVs and promoting their position in sustainable and cost-effective transportation options.

6.3.3. Environmental Aspects

Fuel cell vehicles (FCVs) offer promising environmental advantages. FCVs contribute to cleaner air and better urban air quality by emitting only water vapor and heat. Their reliance on hydrogen paves the way for a low-carbon future, particularly when produced via renewable techniques such as electrolysis. Green hydrogen production has the potential to significantly lower the overall lifecycle emissions of FCVs, therefore aligning with climate goals. However, obstacles include the use of scarce resources in the construction of fuel cells and potential water usage issues. End-of-life considerations and efficient recycling procedures are crucial for waste reduction. FCVs are a more environmentally friendly alternative than standard internal-combustion engines, providing a path to more sustainable transportation. Regardless of the advances, further research, green hydrogen infrastructure development, and measures to address material problems are required to maximize the positive environmental impact of fuel cell vehicles on a worldwide scale.

6.3.4. Social Aspects

The social aspects of fuel cell vehicles (FCVs) include a wide range of concerns. Their zero-emission profile improves public health by lowering air pollution, which benefits communities near highways. The widespread use of FCVs could create job possibilities, notably in the manufacturing and maintenance industries, thereby promoting economic growth. However, the current high costs of FCVs may limit their accessibility, thus creating a transportation equity divide. As communities embrace hydrogen infrastructure development, social acceptance and awareness are critical. In order to promote a sustainable and equitable future in the field of transportation, it is critical to ensure inclusivity in the transition to FCVs, as well as to address public attitudes and concerns.

6.3.5. Policy Aspects

The policy elements of fuel cell vehicles (FCVs) are critical to their adoption and success. Incentives, subsidies, and supportive laws from governments are critical in promoting the development of FCV technology and infrastructure. Policies addressing hydrogen production, distribution, and infrastructures for refueling are critical to overcome obstacles. To establish common laws and encourage a consistent approach, global collaboration is required. Policymakers must stimulate R&D and commercialization, so establishing a favorable environment for industrial investment. Balancing the promotion of FCVs and other green technologies is critical for complete and effective policies that foster widespread adoption of environmentally friendly transportation options.

6.3.6. Challenges and Opportunities

Challenges:

High manufacturing costs: The production of fuel cell vehicles (FCVs) necessitates the use of expensive materials, such as platinum in the fuel cell stack, which results in high manufacturing costs. Reduced prices are critical for the broad adoption of FCVs.

Hydrogen production and infrastructure: A fundamental difficulty is the lack of extensive hydrogen infrastructure. To support the rise of FCVs, a dependable and wide network of hydrogen production and refueling stations is required.

Competing technologies: FCVs face competition from battery electric vehicles (BEVs) and other alternative technologies. The growing popularity of FCVs, as well as developments in battery technology, might affect consumer decisions and effect the FCV market share.

Limited vehicle models: When compared to traditional automobiles, the number of FCV models offered to consumers is currently limited. Increasing the number of available models may attract a larger consumer base.

Opportunities:

Emissions reduction: FCVs provide a road to zero-emission transportation, considerably contributing to efforts to reduce greenhouse gas emissions and battle climate change.

Renewable hydrogen production: The ability to generate hydrogen using renewable energy sources such as wind or solar power is a sustainable and environmentally beneficial technique that reduces the carbon footprint of FCVs.

Energy independence: Hydrogen may be created from a variety of sources, reducing reliance on fossil fuels and fostering energy independence. Energy security and resilience are improved as a result of this diversification.

Research and development: Continuous research and development efforts create chances for technological breakthroughs, resulting in more efficient fuel cells, lower production costs, and improving overall performance.

Government incentives: Government policies, subsidies, and incentives can encourage the use of FCVs. Consumer financial incentives and investment in hydrogen infrastructure can help to drive market expansion.

Collaboration and standardization: Global collaboration across sectors and governments can promote the standardization of technology, laws, and infrastructure, hence creating a more favorable climate for the expansion of FCVs.

Improved urban air quality: FCVs help to improve urban air quality by reducing tailpipe emissions and resolving health concerns connected with traditional internal-combustion engines.

Diverse applications: FCVs are not only used in passenger vehicles; they can also be used in buses, lorries, and even stationary power generation, making them a versatile and scalable option.

To establish fuel cell vehicles as a sustainable and viable alternative in the broader transportation scene, ongoing innovation, investment, and collaboration across sectors are required.

6.4. Solar Vehicles

6.4.1. Technical Aspects

Solar vehicles harness energy directly from the sun, showcasing high efficiency in converting solar power into vehicle motion. Solar vehicles demonstrate impressive energy efficiency, relying on clean and renewable solar power. Its energy consumption per mile/kilometer is remarkably lower, translating to an eco-friendly mode of transport. Technical performance, which plays a significant role in these vehicles, includes solar radiation, temperature, and shading. Crystalline silicon, CIS, CdTe and thin film are widely available solar technologies. It is important to note that the choice of solar PV technology for vehicle integration depends on factors such as the efficiency, weight, flexibility, and the specific design requirements of the vehicle. In order to be beautiful, reduce wind resistance, and improve the comfort of the driving experience, the design is mostly a streamline or spindle type. Monocrystalline silicon flexible solar panels (21% conversion efficiency) with good bending resistance, heat dissipation, weather resistance, corrosion resistance, durability and flexibility are more suitable for integration on the curved surface of the vehicle. Also, thin film solar cells' flexibility makes them suitable for curved or irregular surfaces on vehicles, such as roofs and windows. It provides design flexibility for vehicle manufacturers. Advances in solar panel efficiency, energy storage systems, and electric propulsion technologies can significantly improve the feasibility and performance of solar vehicles. However, challenges remain, such as optimizing solar panel integration for maximum efficiency and addressing the limitations of energy storage. To optimize the energy transfer from a photovoltaic (PV) system to a vehicle, it is essential to implement prolonged and low-power charging methods. This approach enables the effective utilization of the peak production hours for the photovoltaic cells. Nevertheless, the incorporation of an energy storage system becomes imperative to ensure a continuous and reliable energy supply. The significance of photovoltaic materials, the manufacturing techniques employed for PV cells and modules, as well as the electric and electronic equipment utilized for converting, distributing, monitoring, and storing solar energy cannot be overstated in this context.

6.4.2. Economical Aspects

While the initial cost of solar vehicles may be high, the long-term economic benefits include reduced operating costs due to lower fuel expenses and minimal maintenance requirements. The potential for job creation in the renewable energy and electric vehicle sectors is another economic advantage. Governments and industries must collaborate to invest in research, development, and infrastructure to make solar vehicles more economically viable and accessible.

6.4.3. Environmental Aspects

Solar vehicles contribute to a cleaner environment by producing zero emissions during operation. By reducing reliance on fossil fuels, solar vehicles play a crucial role in mitigating air pollution and combating climate change. However, the environmental impact of manufacturing solar panels and batteries must be considered, emphasizing the importance of sustainable production practices.

6.4.4. Social Aspects

The adoption of solar vehicles can positively impact society by promoting sustainable transportation and reducing air pollution in urban areas. Moreover, the integration of solar charging infrastructure can empower communities to harness renewable energy locally. Accessibility and affordability, however, remain key social challenges, necessitating inclusive policies to ensure widespread adoption and benefits for diverse socio-economic groups.

6.4.5. Policy Aspects

Governments play a pivotal role in shaping the future of solar vehicles through supportive policies. Incentives such as tax credits, subsidies, and infrastructure development are crucial for encouraging both consumers and industries to embrace solar transportation. Robust regulations must also be established to ensure the safety, reliability, and standardization of solar vehicle technologies.

6.4.6. Challenges and Opportunities

Opportunities of Solar Vehicles

Opportunities lie in advancements in energy storage technologies, improved solar efficiency, and the creation of smart grids that can optimize solar energy usage.

Environmental Benefits: Solar vehicles are a game-changer in the fight against climate change. They produce zero tailpipe emissions, significantly reducing greenhouse gas emissions and air pollution. By using clean, renewable energy from the sun, they contribute to a cleaner and healthier environment.

Economic Benefits: Solar vehicles can save their owners a substantial amount of money in the long run. With lower fuel costs (since sunlight is free), they offer a cost-effective alternative to traditional vehicles. Additionally, solar-powered homes can use the excess energy generated by the vehicle to power the household or sell it back to the grid, potentially leading to energy cost savings.

Energy Security: Solar vehicles reduce our dependence on fossil fuels, enhancing energy security. With solar power as a primary energy source, countries can become less vulnerable to oil price fluctuations and supply disruptions.

Challenges and Limitations

Challenges to the widespread adoption of solar vehicles include limitations in energy storage, intermittent sunlight availability, and the need for a comprehensive charging infrastructure. Overcoming these challenges requires continued research, development, and international collaboration. While solar vehicles hold immense promise, they face several challenges and limitations:

Limited Energy Capture: Solar panels have a limited surface area, which means they can only capture a finite amount of sunlight. This limits the range of solar vehicles, especially during cloudy or night-time conditions.

Energy Storage Limitations: Solar vehicles require efficient energy storage solutions to operate when the sun is not shining. Current battery technology can be limiting in terms of the capacity and weight.

Cost and Affordability: Solar vehicles, particularly cars, can be expensive due to the cost of high-efficiency solar panels and advanced battery systems. Mass production and technological advancements are needed to make them more affordable.

Technological Hurdles: Advancements in solar cell efficiency and energy storage are essential to make solar vehicles more practical and widespread.

6.5. Insights into CO_2 Emissions from Various Vehicles

The definitive CO_2 emissions value for each vehicle type is not straightforward, as emissions vary significantly depending on several factors and may require detailed analysis based on specific scenarios and assumptions.

Fuel source and production: CO_2 emissions from a biofuel vehicle depend on the feedstock (e.g., corn, sugarcane) and its production methods. Sustainable practices can minimize emissions, but values can range from 30% less to equal or even higher than gasoline depending on the specific biofuel and its life cycle.

Vehicle size and efficiency: Larger, less efficient vehicles emit more CO_2 per kilometer, regardless of the fuel type.

Location and grid mix: The electricity mix used for production and operation significantly impacts electric and fuel cell vehicles' emissions. Regions with high renewable energy penetration lead to lower emissions overall.

Manufacturing practices: The CO_2 emissions during the manufacturing phase of vehicles can vary depending on factors such as the type of biofuel used, type of engine, production of hydrogen fuel, the efficiency of production processes, for solar panels, batteries, electric motors and other components and the materials used in the vehicle construction/assembly. The carbon intensity of the electricity used in manufacturing processes also influences emissions. Sustainable manufacturing practices, including using recycled materials and energy-efficient processes, can reduce CO_2 emissions across all vehicle types

Usage phase: The CO_2 emissions during the usage phase of vehicles largely depend on the carbon intensity of the fuel, source of electricity for charging, and auxiliary energy requirements. Charging with electricity from renewable sources can significantly reduce CO_2 emissions compared to charging with electricity from fossil fuels.

End-of-life processes: The CO_2 emissions during the end-of-life phase of vehicles can vary depending on the efficiency of recycling the vehicle components, solar panel, batteries, and fuel cell materials. Recycling materials and using sustainable disposal methods minimize emissions in the final phase

Considering these factors, a general overview of the CO_2 emissions ranges for each vehicle type is provided below [133–135]. The specific values can vary greatly.

- Biofuel: 30–150% of gasoline vehicles' emissions (depending on the feedstock and production)
- Electric vehicle: 30–300 g CO_2/km (depending on the grid mix and manufacturing)
- Solar vehicle: 20–120 g CO_2/km (manufacturing-focused emissions)
- Fuel cell vehicle: 0–200 g CO_2/km (depending on the hydrogen source)

When comparing vehicles, detailed life-cycle assessments, emission data for fuels, and individual circumstances have to be considered for accurate assessment. Additionally, efforts to reduce emissions from each phase of the vehicle life cycle, such as through renewable energy adoption, efficiency improvements, and recycling initiatives, are essential for mitigating the environmental impact of transportation.

7. Conclusions

- Electric vehicles (EVs) currently offer the greatest potential for significant CO_2 emission reductions, boasting life-cycle emissions 50–80% lower than gasoline vehicles, even when accounting for grid mix variations. The adoption of sustainable vehicles contributes significantly to achieving carbon neutrality and net-zero emissions, promoting a cleaner and greener transportation landscape. The widespread adoption of EVs could lead to economic benefits through reduced fuel dependence, lower maintenance costs, and new job creation in the clean energy sector.
- The comparative analysis revealed that electric vehicles and solar vehicles currently stand out as the more feasible and sustainable options, while fully biofuel vehicles and fuel cell vehicles face challenges that need to be addressed.
- This analysis reveals the strengths and weaknesses of each technology:
    - ❖ BPVs: Offer reduced greenhouse gas emissions, but concerns exist regarding feedstock sustainability and land use.
    - ❖ FCVs: Produce minimal emissions at the tailpipe, but require clean hydrogen infrastructure and face cost challenges.
    - ❖ EVs: Boast significant emission reductions, but rely on grid decarbonization and face challenges with charging infrastructure and battery cost.
    - ❖ SVs: Present the potential for zero emissions with limited environmental impact, but require further development to address the range limitations and weather dependence.
- Several challenges, like biofuel scarcity, increased weight, faster wear of car tires, range anxiety for EVs, infrastructure constraints for FCVs, and the intermittency of solar power for solar vehicles, need to be addressed.
- Early studies suggest solar vehicles could achieve even lower emissions in sunny regions, though further research is needed. The performance of solar-powered vehicles

is influenced by the solar radiation, temperature, and shading. Solar-powered vehicles will be viable with the integration of hybrid backup systems to overcome challenges associated with seasonal variations and reduced sunlight availability. Evaluating the local climate is crucial for integrating photovoltaics into electric vehicles, leading to successful solar-powered transportation solutions. This ensures optimal functioning in various regions.

- Research and Development: R&D efforts should focus on addressing various technical challenges to foster widespread sustainable mobility. This includes advancements in battery technology, reduce charging time, minimize battery degradation, develop lightweight solar panels, improve solar panel efficiency, improving charging infrastructure, hydrogen production methods and disposal practices to enhance the viability of green vehicles.
- Industry stakeholders: Industry stakeholders should invest in the expansion of solar charging infrastructure, hydrogen refueling infrastructure, and efficient recycling to support the growth of electric and solar vehicles. This includes the development of charging stations, battery-swapping facilities, and grid integration technologies to enhance reliability and accessibility.
- Role of Policymakers: Policymakers should prioritize measures such as tax incentives, tax credits, tax rebates, and subsidies to promote the purchase and use of electric and solar vehicles. Additionally, regulatory measures can be implemented to promote the development of solar charging infrastructure for biofuels and fuel cells. Introduce carbon pricing mechanisms to incentivize the transition away from fossil fuel-powered vehicles. Large-scale renewable energy deployment is critical to overcoming barriers to adoption and facilitating the transition toward a more sustainable transportation system.
- Collaboration between governments, industry, academia, and non-profit organizations is essential for driving innovation and knowledge-sharing in the field of sustainable mobility. This includes collaborative research projects, technology demonstration programs, and information-sharing platforms to facilitate the exchange of best practices and lessons learned.
- Limitations of the study: This study is subject to the availability of current data and may be influenced by rapid technological advancements and evolving policies. Future research should address these limitations for a comprehensive understanding of sustainable mobility.

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