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Review

Future of Electric and Hydrogen Cars and Trucks: An Overview

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Abstract: The negative consequences of toxic emissions from internal combustion engines, energy security, climate change, and energy costs have led to a growing demand for clean power sources in the automotive industry. The development of eco-friendly vehicle technologies, such as electric and hydrogen vehicles, has increased. This article investigates whether hydrogen vehicles will replace electric vehicles in the future. The results showed that fuel-cell cars are unlikely to compete with electric cars. This is due to the advancements in electric vehicles and charging infrastructure, which are becoming more cost-effective and efficient. Additionally, the technical progress in battery electric vehicles (BEVs) is expected to reduce the market share of fuel-cell electric vehicles (FCEVs) in passenger vehicles. However, significant investments have been made in hydrogen cars. Many ongoing investments seem to follow the sunk cost fallacy, where decision-makers continue to invest in an unprofitable project due to their already invested resources. Furthermore, even with megawatt charging, fuel-cell trucks cost more than battery-powered electric trucks. The use cases for fuel-cell electric trucks are also much more limited, as their running expenses are higher compared to electric cars. Hydrogen vehicles may be beneficial for heavy transport in remote areas. However, it remains to be seen if niche markets are large enough to support fuel-cell electric truck commercialization and economies of scale. In summary, we believe that hydrogen vehicles will not replace electric cars and trucks, at least before 2050.

Keywords: hydrogen cars and trucks; electric cars and trucks; future transportation

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1. Introduction

Because of the harmful implications of toxic emissions from internal combustion engines, there is an increasing demand for clean power sources in vehicle-related technology. The existing environmentally friendly automotive technology is evolving with time. For instance, biodiesel is an ecologically friendly, cleaner-burning alternative that may be utilized in diesel engines with minimal modification. Biodiesel reduces emissions of greenhouse gases by up to 86% [1,2]. Green hydrogen is a fuel that is produced with renewable energy rather than fossil fuels. It can provide sustainable energy for industry, transportation, and more, with water as a waste. Hydrogen energy is exceptionally adaptable since it may be utilized in gaseous or liquid form, converted to power or fuel, and produced in various methods. Approximately 70 million metric tons of hydrogen are generated annually for oil refining, ammonia production, steel manufacture, chemical and fertilizer production, food processing, metalworking, and other applications [3].

The misconception that 90% of all atoms in the cosmos are hydrogen atoms is incorrect. Recent research indicates that around 75% of baryonic matter in the cosmos is composed of hydrogen, with the other 25% primarily comprised of helium. This estimate is based on studies of the abundance of elements in stars and galaxies and observations of cosmic microwave background radiation. According to most research, hydrogen is the most abundant element in the universe, followed by helium. Exact percentages may vary somewhat depending on the technique of measurement performed, but most agree that hydrogen is the most abundant element in the universe. However, it is crucial to note that baryonic matter (consisting of protons, neutrons, and other subatomic particles) comprises just a minuscule portion of the universe's total matter. The remainder is thought to consist of poorly understood dark matter and dark energy, which are topics of continuing study and discussion [4]. Hydrogen is the most abundant element in the universe, yet it is often found as a component of compounds with other elements [5]. Atoms of hydrogen can unite to produce molecular hydrogen (H_2), the universe's most prevalent form of hydrogen. Hydrogen is also a component of several other molecules, including water (H_2O) and methane (CH_4) [6]. Despite its abundance, hydrogen atoms cannot be found alone. To obtain hydrogen, its atoms must be separated from other elements in water. Hydrogen production is achieved through the steam methane reforming process, which employs a catalyst to transform methane and high-temperature steam into hydrogen, carbon monoxide, and a negligible quantity of carbon dioxide [7], which generates the vast majority of hydrogen used today. In the next stage, carbon monoxide, steam, and the catalyst create further hydrogen and carbon dioxide. Finally, carbon dioxide and contaminants are eliminated, resulting in pure hydrogen.

There are generally three types of hydrogen: Grey hydrogen: This is the most common type of hydrogen produced today and is made by the process of steam methane reforming (SMR) or coal gasification. Grey hydrogen is produced from non-renewable sources of energy and emits greenhouse gases during its production. Blue hydrogen: This is also produced using the SMR or ATR process, but the carbon dioxide produced during the process is captured and stored, making it a cleaner form of hydrogen. Green hydrogen: This is produced through electrolysis, using renewable energy sources such as solar, wind, or hydropower to split water molecules into hydrogen and oxygen. It is considered the cleanest form of hydrogen as it produces no greenhouse gas emissions during its production.

Fossil fuels, such as propane, gasoline, and coal, can be transformed into hydrogen. This method of manufacturing hydrogen from fossil fuels produces grey hydrogen and contributes 830 million metric tons of CO_2 annually [8], similar to the yearly emissions of the UK and Indonesia combined. Steam Methane Reforming (SMR) or Auto Thermal Reforming (ATR) separates natural gas into hydrogen and carbon dioxide, producing blue hydrogen.

Another method for producing hydrogen is through water electrolysis, which produces oxygen as a by-product. The electrolysis process uses an electric current to separate water into hydrogen and oxygen through an electrolyzer. If the energy used in the process comes from renewable sources, such as solar or wind, the resulting hydrogen is known as "green hydrogen" and is considered environmentally friendly. The decreasing cost of renewable energy is driving growing interest in green hydrogen [6]. In recent years, the price of renewable energy has declined rapidly, making green hydrogen more economically viable. According to research by the International Renewable Energy Agency (IRENA) [9], the levelized cost of electricity (LCOE) for solar and wind generation has fallen by 89% and 70%, respectively, since 2009. The global weighted average levelized cost of electricity for solar power reduced by 85 percent between 2010 and 2020, according to a separate analysis by Bloomberg New Energy Finance (BNEF) [10]. In addition, the levelized cost of electricity for wind generation reduced by 49% during the same time period, according to the research. The declining cost of renewable energy, especially solar and wind power, has made the production of green hydrogen, which can be utilized as a clean fuel source in a variety of applications, more cost-effective. Recent interest in green hydrogen has been extensive. President Biden, the 46th president of the USA, has vowed to produce renewable energy-based green hydrogen at a lower cost than natural gas [11]. The United States Department of Energy will invest up to USD 100 million over five years (2022–2026) in hydrogen and fuel cell R&D [12]. This investment intends to expedite the adoption of hydrogen and fuel cell technologies in transportation and other applications [13,14]. This funding is part of the efforts of the Hydrogen and Fuel Cell Technologies Office (HFTO) to expedite the development and implementation of hydrogen and fuel cell technologies in the United States. The Hydrogen Fuel Technology Organization supports several research and development initiatives, such as fuel cell electric cars, hydrogen production, storage, and infrastructure.

Similar to the United States, the European Union has earmarked USD 430 billion to create 70 green hydrogen projects by 2030 in order to meet its Green Deal objectives [15]. This investment is intended to support the development of a green hydrogen economy and minimize the carbon footprint of the region. The cash will help various projects, including manufacturing renewable hydrogen and deploying fuel cell vehicles.

In addition, Chile, Germany, Japan, Australia, and Saudi Arabia are undertaking substantial green hydrogen investments. Chile, Germany, Japan, Australia, and Saudi Arabia are investing considerably in green hydrogen [16]. In order to attain 5 Gigawatts (GW) of electrolysis capacity by 2025, the Chilean government aims to invest USD 30 million in green hydrogen projects by 2022 [17]. Germany has spent EUR 9 billion to build a national strategy for producing 5 GW of green hydrogen by 2030 [18]. The Japanese government has invested 2 trillion (USD 18.5 billion) towards realizing its goal [19] of producing 300,000 tons of green hydrogen yearly by 2030. Australia has committed USD 370 million to hydrogen research and development to produce USD 2 per kilogram by 2030 [20]. Saudi Arabia has established a USD 5 billion green hydrogen effort to produce 650 tons of green hydrogen by 2025, intending to export it to Europe and Asia [21].

Given the difficulty of lowering emissions from some economic sectors, most analysts believe that green hydrogen will be vital to achieving the goals of the Paris Agreement. The Paris Agreement's main goal is to limit global warming to well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 degrees Celsius. This is to be achieved through a cooperation framework to enhance climate action, with countries submitting nationally determined contributions (NDCs) and regularly reporting on their progress. The Agreement also aims to strengthen countries' ability to deal with climate change's impacts and support them in their efforts.

The United States' top three contributions to global warming are transportation, power generation, and industry [22]. Green hydrogen is "critical" for attaining net-zero carbon emissions by 2050 and satisfying the objectives of the Paris Agreement, according to research by the International Energy Agency (IEA) [23]. The paper stresses the significance of green hydrogen in sectors that are difficult to decarbonize with electricity alone, such as heavy manufacturing, shipping, and aviation.

Another study by the Hydrogen Council, a worldwide coalition led by Chief Executive Officers (CEOs), also emphasizes the significance of hydrogen in reaching the goals of the Paris Agreement, suggesting that hydrogen may supply up to 18% of global energy consumption by 2050 and help cut yearly carbon emissions by six gigatons [24].

In addition, a report by the United Nations Development Programme (UNDP) highlights the potential of green hydrogen to reduce transportation, heating, and industrial emissions and urges further investment in the technology to fulfill climate goals [25].

Future hydrogen production will rely on several criteria, such as cost, efficiency, scalability, and environmental implications, making it impossible to foresee which techniques or technologies will emerge as important players. However, as the need for sustainable and low-emission technologies develops, electrolysis driven by renewable energy and biomass gasification will likely play a greater part in future hydrogen generation. Table 1 summarizes the present and expected cost per kilogram of hydrogen for each technique [23,26].

Note that the present and anticipated costs are estimates that may change based on location, size, and technological advances. The trend, however, is predicted to cut prices for all techniques, with renewable energy electrolysis and grid electricity electrolysis becoming more competitive as renewable energy costs decline. In addition, steam methane reforming and coal gasification may encounter difficulties in the future because of their large carbon emissions and the possible expense of carbon capture and storage.

Table 1. Predicted cost per kg of hydrogen for each method.

Hydrogen Production Method	Current Cost per kg	Predicted Cost per kg
Steam Methane Reforming (SMR)	USD 1.5–2.5	USD 1.0–USD 1.5
Coal Gasification	USD 2.0–3.5	USD 1.5–2.0
Electrolysis (Renewable Energy)	USD 2.5–7.0	USD 1.0–3.0
Biomass Gasification	USD 3.0–5.0	USD 2.0–3.0
Photoelectrochemical (PEC)	USD 20.0–30.0	USD 10.0–15.0

Improving energy efficiency, increasing the use of renewable energy, and transitioning to direct electrification can reduce greenhouse gas emissions from electricity generation and parts of the transportation sector. However, decarbonizing the remaining 15% or more of the economy, which encompasses industries such as aviation, shipping, long-distance transportation, and the production of concrete and steel, presents a challenge, as these sectors require high-density energy or intense heat. Green hydrogen may provide a solution to these needs [27].

Hydrogen offers a major advantage over batteries by using excess renewable energy and being able to be stored for a long duration. The major benefit of green hydrogen is its ability to be produced anywhere where water and energy are available to generate electricity or heat. Hydrogen has many applications, including being used in the industrial sector and stored in existing gas pipelines to power household appliances or being transformed into a zero-carbon shipping fuel, such as ammonia, to transport renewable energy. Hydrogen can power everything that requires energy, including electric vehicles, electronic equipment, and fuel cells. Additionally, unlike batteries, hydrogen fuel cells do not require recharging and do not degrade as long as hydrogen fuel is present.

The term "hydrogen vehicles" refers to a range of automobiles powered by hydrogen. These vehicles may utilize internal combustion engines, gas turbine engines, or hydrogen fuel cells as their propulsion systems. There are typically two types of hydrogen-powered engines: a traditional internal combustion engine that uses hydrogen gas instead of gasoline or natural gas and a fuel cell engine. Like petrol stations, hydrogen fuel stations are available for hydrogen vehicles. The hydrogen gas produced by steam methane reformation is kept in hydrogen filling stations. In addition, the construction of hydrogen-powered vehicles is challenging and costly. Hydrogen is flammable and deadly if not properly stored and handled.

Hydrogen can be compressed to different pressures depending on its intended use. For example, 350 and 700 bar are common compression pressures for hydrogen storage in fuel cell vehicles; 350 bar is suitable for shorter-range vehicles, while 700 bar is more suitable for longer-range vehicles as it allows for greater storage capacity in the same volume. Industrial applications may also use different pressure levels depending on their specific requirements. Hydrogen must be compressed to high pressure for road vehicles, typically to 700 bar. This requires energy and infrastructure to compress and transport the hydrogen, which adds to the cost of using it as a fuel. Most hydrogen currently produced worldwide is made from fossil fuels, primarily natural gas, in a process called steam methane reforming. This energy-intensive process produces carbon dioxide (CO_2) as a byproduct. The IEA states that steam methane reforming accounts for over 80% of global hydrogen production. Most of this hydrogen is used in industrial applications, such as ammonia production for fertilizers and refining petroleum. Renewable hydrogen production methods, such as water electrolysis powered by wind or solar energy, are available but more expensive than steam methane reforming. Renewable hydrogen production has been estimated to be two to three times more expensive than the hydrogen produced from natural gas. However, the cost of renewable hydrogen is expected to decrease in the coming years as the cost of renewable energy technologies continues to fall. While hydrogen has the potential to be a low-carbon alternative to fossil fuels, producing hydrogen requires significant amounts of energy and infrastructure, and most of the hydrogen produced today comes from fossil fuels, with associated CO_2 emissions.

On the other hand, electric automobiles are propelled by an electric motor powered by electrical energy, rather than an internal combustion engine and lack a petrol tank. Battery electric vehicles (BEVs) are a category of battery-powered electric cars that lack a fuel tank and an internal combustion engine. Other similar technologies include plug-in hybrid electric cars (PHEVs).

The key advantage of battery electric vehicles is that they rely on the already established electric grid infrastructure, allowing for any electrical outlet in the world to act as a charging station. In contrast, fuel-cell electric vehicles require the creation of new infrastructure from scratch. The main challenge in the widespread adoption of battery electric vehicles is the need for more conventional fast-charging stations, which is simpler than developing a complete hydrogen production, transportation, storage, and distribution system.

Battery electric vehicles (BEVs) rely solely on the battery for energy storage. In contrast, hydrogen fuel-cell electric vehicles (FCEVs) use both a fuel cell stack and a smaller battery for energy storage. The battery in an FCEV is typically much smaller than a BEV's. It is used primarily for power buffering during acceleration, other peak power demands, and regenerative braking. However, both vehicles face challenges related to their energy storage systems. BEVs face challenges related to the battery's limited range and the time required to recharge it, as well as the cost and weight of the battery. FCEVs face challenges related to the cost and complexity of the fuel cell stack and hydrogen storage and the limited availability of hydrogen refueling infrastructure.

A hydrogen fuel cell consists of an anode and a cathode, separated by an electrolyte. Hydrogen gas is supplied to the anode, where it undergoes a chemical reaction that separates the electrons from the hydrogen atoms, leaving positively charged hydrogen ions (protons). The electrons flow through an external circuit, producing an electric current that can be used to power a device or recharge a battery. Meanwhile, at the cathode, oxygen from the air reacts with the hydrogen ions and the electrons that have flowed through the external circuit, producing water vapor and heat as byproducts. The water vapor is typically expelled from the fuel cell as exhaust. Figure 1 is a simple schematic diagram to help illustrate this process:

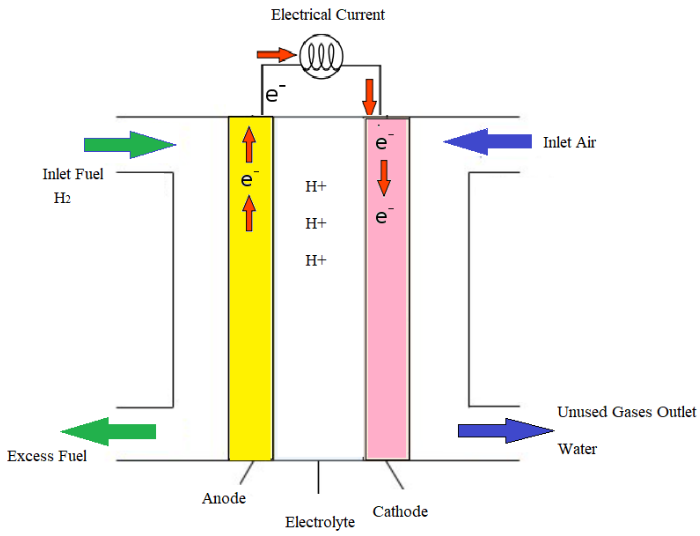

Figure 1. Schematic diagram of a fuel cell working principle.

The electrolyte membrane is a crucial component of the fuel cell, as it must be able to conduct protons while blocking electrons and preventing gas crossover between the anode and cathode. Different types of electrolyte membranes can be used depending on the specific application and requirements of the fuel cell. The cathode uses hydrogen as a propulsion source, and the fuel cell is more energy-efficient than a conventional internal combustion engine, with a 2–3-times-higher efficiency [28]. In addition, refueling a fuel-cell electric car often takes less than four minutes.

Hydrogen is a colorless, odorless, and flammable gas. Like many other fuels, it can ignite and burn if it comes into contact with an ignition source, such as a spark, heat, or flame. Hydrogen has a wide flammable range and can ignite at as low concentrations in air (hydrogen can ignite in air at concentrations as low as 4% by volume and can continue to burn up to concentrations of 75% by volume). Handling hydrogen safely requires proper training, procedures, and equipment. Some of the safety risks associated with hydrogen include:

- Fire and explosion: Hydrogen has low ignition energy and can easily ignite and burn if it comes into contact with a spark or heat source. This can lead to fire and explosion hazards.
- Asphyxiation: Hydrogen gas is lighter than air and can displace oxygen in poorly ventilated or confined spaces. This can lead to asphyxiation if proper precautions are not taken.
- Toxicity: Hydrogen gas is not toxic, but some of the impurities in hydrogen, such as ammonia and hydrogen sulfide, can be toxic and pose health risks.
- Leakages: Hydrogen can leak from storage tanks, pipelines, and other equipment. If not detected and controlled, hydrogen leakage can pose fire and explosion hazards and asphyxiation risks.

Safety measures, such as proper ventilation, gas detection systems, and training for handling hydrogen, are essential to mitigate these risks. Hydrogen can be safely handled and used as fuel but requires proper handling and precautions.

This is evident in hydrogen-powered automobiles, where the fuel cell serves as a source of electricity for the electric motor. In a fuel cell, the cathode is responsible for sucking in oxygen, mixing it with electrons and protons from the anode to generate water, and releasing energy to power the electric motor [28]. Despite being highly flammable, hydrogen burns in moderate amounts, similarly to other fuels. Its lightweight nature, being approximately 57 times lighter than gasoline fumes, can quickly spread into the surroundings, making it relatively safer in the event of a fire [29].

Hydrogen is a light gas with a low volumetric density, meaning that it takes up more space than other fuels with the same amount of energy. This makes hydrogen transportation challenging, especially for long distances, because it requires large and expensive storage tanks or pipelines. Hydrogen can be compressed to increase its volumetric density to overcome this issue, but this requires energy and specialized equipment. Alternatively, it can be liquefied, which reduces its volume and allows for easier transportation and storage. However, this also requires energy and specialized equipment, as well as maintaining the low temperature required for liquid hydrogen (−253 °C) [30].

Hydrogen may cause steel pipes and welds to become brittle and shatter; hence, natural gas pipelines occasionally transfer a small quantity of hydrogen. When blended with natural gas in a less than 5-to-10-percent ratio, hydrogen can be safely transported through the existing natural gas infrastructure. However, to transport pure hydrogen, the existing natural gas pipelines would have to undergo significant modifications to prevent metal brittleness, or new dedicated hydrogen pipelines would have to be built [31]. Platinum is used in fuel cells, which will increase their cost. The high cost of fuel cells has hindered fuel cell progress [32]. Ongoing research seeks to improve the performance of fuel cells and to develop more cost-effective and practical materials. It has been difficult for fuel cell electric vehicles to store sufficient hydrogen—five to thirteen kilograms of compressed hydrogen gas—to enable the typical 300-mile driving range [33]. The main challenge of green hydrogen is its cost. At present, green hydrogen is three times more expensive than natural gas in the United States. This higher cost is due to the high expense of electrolysis, which is the process used to produce green hydrogen.

Nevertheless, as production increases, electrolyzer prices are expected to decrease. Currently, gray hydrogen is priced at around EUR 1.50 per kilogram, blue hydrogen at between EUR 2 and EUR 3 per kilogram, and green hydrogen between EUR 3.50 and EUR

6 per kilogram [34]. By 2030, the hydrogen economy in the United States might create USD 140 billion and sustain 700,000 jobs [35].

Hydrogen feasibility studies have been performed; for instance, it was proven feasible by Jordan [36]. The role of hydrogen in the manufacturing, transportation, and synthetic aviation fuel industries is crucial. However, the widespread adoption of hydrogen technology for sustainable road transportation is unlikely to occur anytime soon. Our focus should be on the growth of battery electric passenger and freight vehicles. As of 2016, there were only 25,000 hydrogen fuel cell vehicles on the road, with 2 models available for purchase and only 540 hydrogen filling stations globally. In contrast, the number of battery electric and plug-in hybrid vehicles is rapidly growing, with an estimated 15 million vehicles on the road and over 350 models currently available worldwide [18]. Currently, nearly all automakers provide such vehicles for sale [37].

Moreover, while the majority of drivers of battery electric vehicles (BEVs) currently charge at home, there were approximately 1.3 million public charging points in operation in 2020, a quarter of which were fast chargers (at least 22 kW), and more than 1000 public chargers of up to 300 kW are now available in Europe. When battery electric vehicles had restricted ranges of less than 150 km and charging took a few hours, long-distance travel was a crucial and substantial market sector for fuel-cell vehicles. The increased energy density of compressed hydrogen and the ability to recharge within a few minutes make fuel-cell cars excellent for regular long-distance travel compared to battery electric vehicles. Nevertheless, battery electric cars currently have a real-world range of more than 400 km, and the newest versions employ 800 V batteries that can be charged for 200 km in roughly 15 min [37].

The trucking industry powered by hydrogen fuel is not as advanced as the battery-powered sector, with about 30,000 battery electric vehicles globally available, primarily in China. On the other hand, fuel-cell electric trucks are still in test trials and not yet commercially available. In contrast, over 150 battery electric truck models for medium and heavy freight have already been introduced. The current challenge for battery electric vehicles is long-distance logistics (with an average of 100,000 km per year) and transporting heavy cargo, which results in high energy consumption per kilometer. This is where hydrogen trucks are often discussed as a potential solution. Nevertheless, the goal of having 100,000 fuel-cell trucks on European roads by 2030, set by several truck manufacturers and fuel-cell and infrastructure suppliers, appears unlikely in light of their statements that the earliest commercial production of fuel-cell electric trucks will commence in 2027. By then, second-generation battery electric vehicles will be commercially available and in operation [37].

Long-distance trucking of more than 500 km per day presents a difficulty for battery electric solutions; however, European laws compel truck drivers to take a 45 min rest after driving for more than 4.5 h. In 4.5 h, a large vehicle could travel around 400 km. Consequently, feasible battery ranges of around 450 km would be sufficient if high-power quick charging was generally accessible for battery electric vehicles. For a big vehicle to charge 400 km in 45 min, the average charging power required is around 800 kW. The current specification for fast charging enables up to 350 kW. Despite this, a new megawatt charging system standard is now being developed, allowing for over 2 MW charging. Specifications are anticipated, and a final standard will be established by 2023. Truck manufacturers in Europe are lobbying to construct a megawatt charging network, and prospective locations for fast chargers have been suggested. A draft European infrastructure plan suggests that high-power charges are required every 50 km along the leading highway network [37].

2. Electric vs. Hydrogen Automobile

The future of electric and hydrogen cars and trucks is likely influenced by several factors, including technological advancements, cost considerations, and government policies and regulations. Battery electric vehicles (BEVs) are powered by electricity stored in a battery and are becoming increasingly popular due to their high efficiency, low emissions, and relatively low operating costs. Advancements in battery technology, such as increased energy density and faster charging times, will likely make BEVs more practical and attractive to consumers. Fuel-cell electric vehicles (FCEVs) are powered by hydrogen and produce only water as a byproduct, making them a clean and efficient alternative to traditional gasoline-powered vehicles. The future of FCEVs will depend on advancements in hydrogen production and distribution technology and the cost of hydrogen fuel. As the technology becomes more mature and hydrogen production and distribution become more efficient, the cost of FCEVs will likely decrease, making them more affordable and practical for consumers.

Regarding government policies and regulations, both BEVs and FCEVs are likely to benefit from policies aimed at reducing greenhouse gas emissions and promoting the use of clean vehicles. Governments may offer incentives, such as tax credits or subsidies, to encourage the purchase of clean vehicles, which can help to drive the market for electric and hydrogen vehicles.

The automotive industry has not reached a consensus on the best approach to reducing vehicle emissions. While many car manufacturers are focusing on battery electric vehicles, a few, such as Toyota, Hyundai, and General Motors, are still pursuing hydrogen fuel cell technology, which can offer zero-emission driving but is less efficient than battery electric vehicles. The public's response to fuel-cell electric vehicles has been lackluster, largely due to the lack of infrastructure and overall lower efficiency than electric cars. Charging electric cars overnight at the driver's home is possible, but this is not the case for hydrogen fuel cell vehicles. A recent study [38] has cast doubt on the feasibility of fuel-cell electric cars on the market for commercial trucks, even if they still have a chance.

The charging infrastructure for BEVs is rapidly expanding, with many cities investing in public charging networks. However, the production of BEV batteries still requires significant amounts of energy, much of which comes from fossil fuels. Additionally, there are concerns about the limited availability of certain metals in producing BEV batteries [39,40]. As for the future of these two technologies, the increasing demand for clean transportation and the rapid development of charging infrastructure indicate that BEVs will likely play a significant role in the future of personal transportation. However, hydrogen FCVs may also have a place in specific niche markets, such as long-haul trucking, where their more extended driving range and faster refueling times may be advantageous [41].

Comparison between Fuel-Cell Electric Vehicles (FCEVs) and Battery Electric Vehicles (BEVs)

The car industry has disputed FCEVs vs. BEVs. Toyota, Hyundai, and GM have made FCEVs practicable. Most automakers prefer BEVs. Zero-emission FCEVs are less efficient than BEVs. Infrastructure hinders FCEV adoption. FCEVs, unlike BEVs, require fuelling stations. BEVs are more energy-efficient than FCEVs. FCs are being developed for hydrogen-powered EVs [42]. This makes sustainable transportation simpler. A BEV's onboard battery pack powers several battery cell configurations. BEVs are cheaper and greener, but their lithium-ion batteries only hold 1% of the energy in gasoline or diesel [43]. Battery electric powertrains are likely in smaller, lighter cars. Battery power limits vehicle range [44,45]. The cost of electric vehicles (EVs) is influenced by factors such as battery technology, power pricing, government incentives, and regulations. The advancements in battery technology can reduce the cost of EVs, and improved battery efficiency can further decrease their prices. Energy prices also affect the cost of operating EVs; if electricity prices decrease, EVs become cheaper to run, but if power prices increase, the expenses also increase. Government subsidies and regulations can impact EV prices, and tax credits and other incentives may reduce operating costs. However, the implementation of cleaner electricity rules may increase EV running expenses. The cost of EVs will continue to decrease as technology evolves and becomes widely adopted. In addition, research suggests that the cost of producing green hydrogen may decrease by up to 85 percent by 2050, making it more competitive with fossil fuels [46]. According to a second study by the

Hydrogen Council, the cost of hydrogen fuel cell systems might drop by 50 percent by 2030, bringing the price of hydrogen vehicles in line with battery electric vehicles (BEVs) [47]. However, it should be highlighted that there are still obstacles to overcome in terms of the cost of producing and storing hydrogen, as well as the development of the infrastructure required to sustain a hydrogen economy [48]. In contrast, battery prices have decreased considerably in recent years, and this trend is anticipated to continue. According to research by Bloomberg New Energy Finance, the cost of lithium-ion batteries might decrease by an additional 52 percent by 2030, while their energy density could grow by 42 percent [49].

It is important to note that the relative prices of hydrogen and batteries may vary based on the particular application and local conditions. Hydrogen may be more cost-effective for heavy-duty and long-distance transportation, whilst batteries may be better suited for short-range and urban applications [50]. BEVs and FCEVs are two forms of zero-emission cars that potentially considerably reduce greenhouse gas emissions from the transportation sector. FCEVs utilize hydrogen fuel and a fuel cell to create energy for the electric motor, whereas BEVs use rechargeable lithium-ion batteries to store electricity and power an electric motor. The comparison of costs between the two types of cars is contingent upon a number of variables, including the price of batteries, hydrogen, and the availability of charging or refueling infrastructure [51].

Due to the high cost of fuel cell technology and the restricted availability of hydrogen filling facilities, BEVs are typically less costly than FCEVs. As manufacturing quantities rise and technology improves, however, the cost of fuel cell technology is likely to fall over time. In addition, it is anticipated that the cost of hydrogen will fall as production grows and as additional renewable sources of hydrogen become accessible. One research estimates that by 2030, the price of hydrogen might fall to between USD 1.40 and USD 2.60 per kilogram, making it more competitive with gasoline per mile. On the other hand, technical developments and economies of scale in production are anticipated to reduce the price of batteries over time. Nonetheless, the restricted range and recharging time of BEVs remain significant impediments to their widespread adoption.

FCEVs, on the other hand, have a longer range and can be refueled more rapidly, making them more suited for long-distance travel [52]. BEVs and FCEVs have the potential to considerably cut greenhouse gas emissions from the transportation sector. Nevertheless, their cost competitiveness is contingent on a number of factors, including the price of batteries and hydrogen, as well as the availability of charging and refueling infrastructure. Refueling a hydrogen fuel cell vehicle still takes longer than refueling a conventional gasoline vehicle, typically around 5 to 10 min. The advantage over a battery electric vehicle is the longer driving range between refueling stops. Additionally, the statement explains that hydrogen fuel cells offer higher energy density than battery packs, but this advantage comes with added costs and technical challenges. The use of fuel cell technology in electric vehicles has the potential to overcome issues such as range anxiety, as these vehicles have longer ranges and quicker charging times compared to battery electric vehicles. This advantage could potentially outweigh the disadvantages of producing, storing, and distributing hydrogen fuel. However, it is important to note that there are still challenges to be addressed in the widespread adoption of fuel cell technology, including the high cost of production and the need for an extensive refueling infrastructure [53,54]. In addition, financial benefits are associated with using FCEVs because it is estimated that the cost of charging or discharging a lithium-ion battery is approximately USD 130/kW in terms of power output. This presents an opportunity for consumers to save money [55–60].

On the other hand, the cost of hydrogen storage tanks in compressed form and fuel cell stacks are estimated at approximately USD 15 per kilowatt-hour and USD 53 per kilowatt, respectively. In addition, it is anticipated that the price of hydrogen will be decreased to USD 8 per kilogram, which is comparable to USD 0.24 per kilowatt-hour [61]. Even though the technology and the prices of refueling are competitive with those of BEVs, the cost of acquiring FCEVs is typically still expensive, and the infrastructure for refueling is not less despread. Regarding performance, FCEVs, typically utilized for traveling longer distances, generally perform better than BEVs.

If all goes according to plan, the price of hydrogen fuel at the pump might drop from EUR 9.50 per kg to as low as EUR 1.5 per kg in the year 2050. FCEVs would have a fighting chance against BEVs if they had a price point of EUR 2.5 per kilogram. However, the success of this pricing would be contingent on a high degree of subsidy and market take-up. Fuel-cell electric vehicles (FCEVs) would only succeed if the costs of similar completely electric vehicles increased. In the most pessimistic scenario, the price of hydrogen fuel in 2050 would barely decrease, reaching EUR 8.50 per kg [60].

Based on historical data on electrolyzer investment expenses, Wright's Law, also known as the learning curve, suggests a learning rate of around 18% [62–64]. However, low and high estimates of 12 to 20% have been used by others [36]. The historical learning rate for different types of technology likewise varies significantly from one instance to the next. For instance, the learning rate for lead batteries is about 4%, but the learning rate for portable lithium-ion batteries is believed to be 30% [65]. Because of the learning curve effect, the cost of lithium-ion (Li-ion) battery cells drops by 28% for every cumulative doubling of the number of units manufactured [66].

Assuming both BEVs and FCEVs are powered entirely by renewable energy sources, the overall energy efficiency (i.e., the amount of energy converted into useful work) for BEVs is around 77%, while FCEVs have an efficiency of around 33%. However, the statement also highlights that FCEVs are less energy-efficient than BEVs, meaning that more energy is lost during the conversion process from the fuel source to the energy used to power the vehicle. This means that even if both types of vehicles are powered entirely by renewable sources, FCEVs would require more energy to achieve the same driving range as BEVs, making them potentially more expensive to operate [67]. This significant difference in overall energy efficiency will create a massive challenge for future hydrogen cars. In addition, the cost of FCEVs is much higher than BEVs, and their prices are dropping faster than FCEVs. The energy content of hydrogen is around 33.6 kWh, and the overall energy efficiency is almost half the BEVs; the running cost for FCEVs will compete with the BEVs when the cost of hydrogen is below USD 1.5/kWh. Figure 2 illustrates the cost of useful energy in USD/kWh used to move the BEVs and FCEVs, assuming the cost of electricity is USD 0.1/kWh and the overall energy efficiency for BEVs and FCEVs is 77% and 33%, respectively.

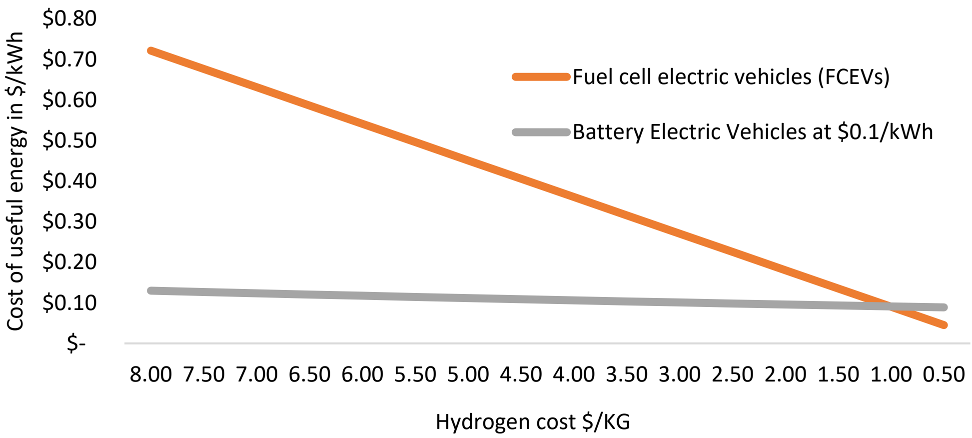

Figure 2. The cost of useful energy in USD/kWh used to move the BEVs and FCEVs [60–75].

The preceding number is consistent with the following investigations. A study undertook a cost analysis of BEVs and FCEVs in Europe and determined that FCEVs had a greater cost of useable energy than BEVs. The FCEVs had a usable energy cost of between USD 1.6 and 2.1/kWh, whereas the BEV cost was between USD 0.70 and 0.90/kWh [68]. Another study analyzed the cost of BEVs and FCEVs in the United States and concluded that the FCEVs had a greater cost of useable energy than the BEVs. The FCEV had an energy cost of USD 1.7–2.3/kWh, whereas the BEV had an energy cost of USD 1.0–1.3/kWh [69].

Research comparing the cost of usable energy for a BEV with an FCEV in China determined that the FCEV had a lower cost of useful energy. The FCEVs had an energy cost of USD 0.69 to 0.75/kWh, whereas the BEVs had an energy cost of USD 0.77 to 0.84/kWh [70]. A cost comparison of BEVs and FCEVs in Japan revealed that the FCEVs' cost of useful energy was more than that of the BEV. The FCEVs had an energy cost of between USD 1.6 and 2.4/kWh, whereas the BEV cost between USD 1 and 1.5/kWh [71]. One research compared the USD/kWh cost of useful energy for propelling battery electric vehicles (BEVs) versus fuel-cell electric cars (FCEVs). The study indicated that the cost of useful energy for FCEVs was always more than for BEVs due to the additional expenses of manufacturing and transporting hydrogen fuel [72].

Considering the cost of hydrogen production and transport infrastructure, another research assessed the future cost of hydrogen fuel-cell cars in comparison to battery electric vehicles. The study concluded that although the initial cost of FCEVs is now greater than that of BEVs, it is anticipated to fall with time and finally become equivalent. Even as renewable energy becomes more prevalent, the cost of manufacturing and distributing hydrogen for FCEVs is projected to remain greater than the cost of electricity [73].

According to Bloomberg New Energy Finance, assuming these prices continue to decline, green hydrogen may be generated for USD 0.70 to USD 1.60 per kilogram in most of the world by 2050, a price comparable to that of natural gas [74]. However, even with this optimistic scenario, it is hard to compete with the prices for electricity from renewable energy as it is currently less than USD 0.005/kWh, and it is predicted to fall even further. Hydrogen cars will not compete with electric cars.

Recent studies on the cost of useful energy for BEVs and FCEVs. For example, a 2020 study by the IEA found that the cost of useful energy for BEVs had declined in recent years, with costs ranging from USD 0.03/kWh to USD 0.12/kWh, depending on the efficiency of the vehicle and the cost of electricity. The IEA also found that the cost of useful energy for FCEVs was typically higher than for BEVs, ranging from USD 0.06/kWh to USD 0.20/kWh, depending on the efficiency of the vehicle and the cost of hydrogen fuel [75]. These estimates are based on average costs and may vary depending on specific circumstances, such as regional differences in electricity or hydrogen fuel prices.

The electric car market has grown rapidly in recent years, driven by increasing consumer demand for clean transportation and government incentives. Major automakers, including Tesla, Nissan, and Chevrolet, have launched electric car models with increasing range and capabilities, making electric cars more practical for everyday use. The charging infrastructure for electric cars is also expanding, with many cities investing in public charging networks and private companies installing chargers in various locations, such as shopping centers and parking lots. This growing infrastructure, combined with the rapid decrease in battery technology costs due to the learning curve, has made electric cars increasingly affordable and competitive with traditional gasoline-powered vehicles [76].

In contrast, the hydrogen fuel cell vehicle (FCV) market is still in its early stages, with limited infrastructure and high production costs. Despite this, some countries, such as Japan and Germany, have made significant investments in hydrogen fuel cell technology and infrastructure and are working to promote the adoption of FCVs. The high cost of hydrogen fuel cell technology is a significant barrier to market penetration, but some experts believe that the cost will decrease over time as production volume increases. Hydrogen FCVs have a more extended driving range than battery electric vehicles (BEVs) and can be refueled in minutes, similar to gasoline vehicles. This makes them a potential option for specific niche markets, such as long-haul trucking, where their more extended driving range and faster refueling times may be advantageous [77,78].

The electric car market is expected to play a significant role in the future of personal transportation, driven by increasing consumer demand and the rapid decrease in battery technology costs. The hydrogen fuel cell vehicle market is still in its early stages. However, it may have a place in specific niche markets as hydrogen fuel cell technology costs decrease over time.

The future of trucking is still uncertain, with battery electric vehicles (BEVs) and hydrogen fuel-cell vehicles (FCVs) being explored as options. BEVs have the advantage of being powered by batteries that are becoming increasingly efficient and affordable. Many sizeable commercial truck makers have started developing electric truck models with extended ranges suitable for long-haul transportation. However, hydrogen FCVs also have the potential to play a role in the future of trucking, particularly for long-haul operations. FCVs have a more extended driving range than BEVs, and the hydrogen fuel can be refueled in minutes, similar to gasoline vehicles. This makes them a potential option for specific niche markets, such as long-haul trucking, where their more extended driving range and faster refueling times may be advantageous. The future of trucking will likely involve a mix of both BEVs and FCVs, depending on the specific needs of the operations. BEVs will likely be used for shorter hauls, while FCVs may be better suited for longer-haul operations.

The need for environmentally friendly power sources in technologies connected to automobiles is continuously growing due to the damaging effects of toxic emissions produced by internal combustion engines. The technologies that are now available for environmentally friendly automobiles continue to advance. This article will discuss electric and hydrogen vehicles and their many different variants. It will also compare electric and hydrogen vehicles and address whether they will ultimately replace electric automobiles. It seems doubtful that fuel cell vehicles will be able to compete with the economies of scale offered by battery automobiles. The price of electric cars and the charging infrastructure's performance are expected to continue falling while improving. FCEVs will decrease their market share in the automotive passenger sector as BEVs continue to make technological strides forward. Since we have already invested significant money into hydrogen-powered vehicles, many current investments adhere to the sunk cost fallacy.

FCEVs are significantly more expensive than BEVs, whose costs are falling more rapidly. The energy content of hydrogen is approximately 33.6 kWh, and the overall energy efficiency is almost half that of BEVs; the running cost for FCEVs will begin to compete with BEVs when the cost of hydrogen falls below USD 1.5/kWh, assuming the cost of electricity from renewable energy sources is approximately USD 0.1/kWh; however, if the cost of electricity is USD 0.05/kWh, hydrogen cars will not be able to compete with electric cars.

The learning curve concept refers to the decrease in the cost of production for a particular technology over time as more units are produced, and the technology becomes more mature. This can have a significant impact on the market penetration of technology.

In the case of electric cars, the learning curve is already well underway, with the cost of battery technology decreasing rapidly as the production volume of electric cars increases. This, combined with the development of charging infrastructure, has made electric cars increasingly competitive with traditional gasoline-powered vehicles. As a result, many automakers are investing heavily in electric vehicle technology and predicting that electric cars will play a significant role in the future of personal transportation. In contrast, the hydrogen fuel-cell vehicle (FCV) market is still in its early stages, with limited infrastructure and high production costs. However, some experts believe that the cost of hydrogen FCV technology will decrease as production volume increases and that hydrogen FCVs may become competitive with BEVs in specific niche markets where their more extended driving range and faster refueling times are advantageous. Electric cars are currently more competitive in the market due to the rapid decrease in battery technology costs and the growing charging infrastructure.

It is unclear how the ongoing conflict between Ukraine and Russia will impact the use of hydrogen technology. Wars and conflicts can negatively impact economies and technological development, diverting resources and attention away from technological advancement and deployment. However, it is also possible that the conflict could lead to increased investment in hydrogen technology to reduce dependence on fossil fuels and improve energy security. It is important to note that hydrogen technology deployment is a complex issue influenced by many factors, including technological developments, government policies, and economic considerations. While the conflict in Ukraine and

Russia may have some impact, it is likely just one of many factors that will influence future hydrogen technology use.

The recent cost increase can be attributed to Europe's over-dependence on fossil fuels in general and Russian gas in particular. A significant increase in renewable energy sources would be the most effective solution to this problem. This is the only proper way that Europe can ensure its energy supply in an environment that is becoming increasingly unstable geopolitically. It would not only bring down power costs in the medium and long term, but it would also bring down electricity prices in the short term.

3. Conclusions

Fuel-cell electric vehicles (FCEVs), sometimes called passenger cars, no longer play as significant a role in the passenger transportation sector as they previously did due to technological improvements. Many present investments in hydrogen automobiles appear to be directed by the sunk cost fallacy, which claims that we have already spent a substantial amount of money creating this technology. However, because economies of scale are already in place for batteries and electric vehicles, and charging infrastructure will get cheaper and better soon, it is doubtful that fuel cell cars will be able to compete.

The cost of owning a fuel-cell truck would be higher than that of a battery-powered car that can be charged at a high capacity. Moreover, truck operational expenses are more critical than cars, making a case for fuel-cell electric vehicles even weaker. Despite this, hydrogen-powered vehicles may be advantageous for transporting heavy loads in sparsely populated areas. The challenge lies in determining whether these specialized markets are large enough to drive the commercialization and cost-effectiveness of fuel-cell electric trucks and the required supporting infrastructure. By 2030, carbon-neutral biofuels or renewable synthetic fuels may be an option for powering such applications, depending on the market demand for these niche areas. Such vehicles will never be able to compete in the market for low-carbon road transportation until truck manufacturers begin mass-producing fuel cell trucks as soon as feasible to reduce production costs. Politicians and business leaders need to decide as soon as possible if the market for fuel-cell electric trucks is big enough to justify more research and development into hydrogen technology or if it is time to give up and focus on other possibilities.

The need for clean power sources in vehicle technology is increasing due to the negative consequences of toxic emissions from internal combustion engines. Electric and hydrogen vehicles are the two leading eco-friendly automobile technologies being developed. This article investigated whether hydrogen vehicles will replace electric vehicles. The results showed that fuel-cell cars are unlikely to compete with electric cars due to the cost reductions and performance improvements in electric vehicles and charging infrastructure. However, hydrogen vehicles may be helpful for heavy transport in remote areas, yet the market for fuel-cell electric trucks is limited, and their use cases are much more limited compared to battery-powered electric trucks. In conclusion, hydrogen vehicles will not replace electric vehicles before 2050.

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