

Comparison of Electric Vehicles and Hydrogen Fuel Cell Vehicles

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Abstract. In recent years, as carbon emissions continue to rise and the extent of global warming becomes wider, new energy vehicles have gradually grown into people's attention. Electric vehicles and hydrogen fuel cell vehicles with zero tailpipe emission become the solution. This paper describes the structural features and safety design of both HFCVs and EVs, and compares the carbon emissions, charging infrastructure, energy efficiency, and safety differences between them. The results show that EVs and HFCVs are better than traditional vehicles in terms of carbon emissions and safety, and EVs have more obvious emission reductions. EVs are developing faster than hydrogen energy vehicles in terms of charging infrastructure. HFCV's efficiency is lower than that of EV. Regarding safety, both of them are better than traditional vehicles, but EVs are more likely to heat up and catch fire due to battery structure problems. Based on the current research, this paper believes that the EV technology and supporting facilities are more complete, the cost is lower, and the carbon emission reduction is more effective. After the reform of energy grid composition in the future and more investment into new energy vehicles development, EVs' future is promising. This paper also hopes that a better way of hydrogen energy production is invented in the future, so as to accelerate the development of hydrogen energy vehicles.

Keywords: Fuel cell, New energy, Electric vehicle, Hydrogen.

1. Introduction

As a result of technological advances around the world and increased awareness of environmental protection, the demand for energy has begun to change. Humans are seeking new clean energy sources more than the original fossil energy sources. In addition to that global warming has become one of the most serious environmental problems of the time. It is widely acknowledged that CO₂ takes a large part of the anthropogenic emissions of greenhouse gases (GHGs). About 14% of the total global CO₂ emission is contributed by the transportation sector [1]. All major countries of the world target to control the emissions of the transportation sector by moving from the petrol-powered engine to engines powered by cleaner energy. Nowadays, hydrogen-powered cars and electric cars are two of the most popular new energy vehicles in the world. In the future, these two new energy vehicles are likely to replace the traditional gasoline and diesel internal combustion vehicles as the most popular mode of private transportation.

The popularity of electric and hydrogen fuel cell vehicles has increased the importance of research in this area. There has been a large amount of literature discussing research related to electric and hydrogen-powered vehicles. Most of the research has focused on the fundamentals of these two new energy vehicles, energy efficiency, environmental factors, and their economic benefits. This article summarizes the principles of both vehicles and their safety concerns. Comparison has been done to discover the advantages and disadvantages of both vehicles. Identifying aspects of each that still need further exploration and research. Many problems were found to be unsolved in the study. In order to balance the advantages and disadvantages of the two new energy vehicles, many hybrid energy vehicles have emerged in recent years. It is hoped that this article will help to further understand,

develop or integrate the two technologies in order to promote the further development of new energy vehicles by summarizing the basic knowledge of the two vehicles.

The main purpose of this paper is to introduce the working principle of electric vehicles and hydrogen fuel cell vehicles, the safety risks and to compare the current status of the two vehicles. First of all, this paper introduces the overall structure of electric vehicles. The choice of positive and negative lithium batteries commonly used in electric vehicles and the common safety hazards that electric vehicles may face in different environments. Secondly the article introduces the working principle of hydrogen fuel cell vehicles which use hydrogen as an energy source and its safety factors. Finally, a comparison is made between four aspects: charging experience and convenience, environmental impact, safety and efficiency of energy use, and the advantages and disadvantages of each of the two new energy vehicles are summarized as a basis for determining the future improvement direction of electric vehicles and hydrogen fuel cell vehicles.

2. Electric vehicles

2.1. Structure

A high voltage system is taken as an example to introduced the internal structure of the electric vehicles. The distribution of the components of a high-voltage system is shown in figure 1. The role of each component is described below. The battery packages with a normal voltage of 360V are arranged on the bottom of the electric car and it takes over the largest volume among the components.

The traction battery pack store the electric power which is mainly came from charging. Some EVs regenerate power during deceleration. The electric power is released as flows of direct current and the high voltage DC flows is converted into low voltage DC by DC/DC inverter. The low voltage DC is supplied to the motor and to control the torque and the speed of the motor with the help of a power electronics controller. The electric power is transferred to the mechanical power as the propelling force to drive the vehicle's wheels by the electric traction motor. The motor for some EVs also works to regenerate the electric power from the braking force during deceleration and transmit the electric power to the battery. The commercial power sources provide electric power as flows of AC. The charger port enables the vehicle to connect to the commercial power source and the onboard charger would converting AC from the external power source to DC for charging the batteries. The thermal system protects the components by maintaining proper operating temperature. The transmission drives the wheels by mechanical power produced by an electric traction motor. Besides, the auxiliary battery is isolated from the other batter pack with provides power to run vehicle accessories. Some EVs contain a vehicle control module (VCM) and the service disconnect switch (SDSW). The vehicle integration is controlled by the VCM. The SDSW works to protect people during maintenance or rescue. It enables the high-voltage circuit to be cut for needs.

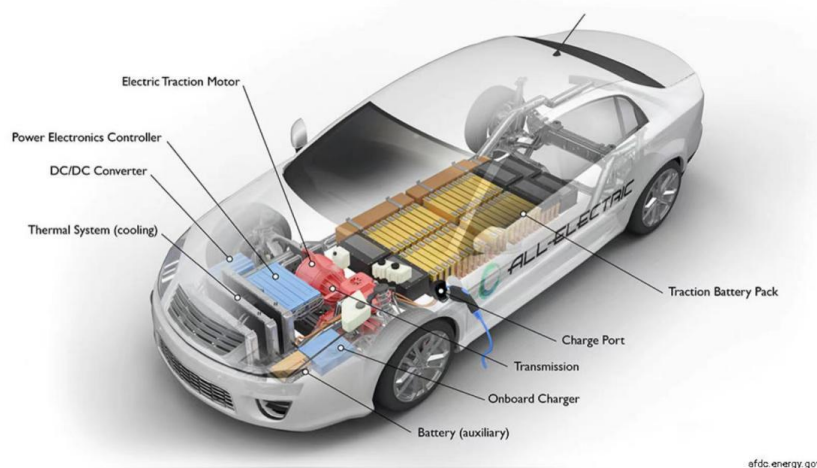


Figure 1. Internal structure of an electric vehicle [2]

2.1.1 Protection system

To protect passengers from the potential electric shock in the crush, the high voltage components are placed outside the passenger compartment and it is placed under the front and rear seats. The zone body structure as shown in figure 2 protects the battery pack from collision. Two crash impact zone is designed to absorb impact force from the front and back. The high-strength cabin protects both sides of the mid-piece of the vehicle. Most of the side impact energy is absorbed by floors across the members. The deformation of the framework due to the collision may cause damage to the battery pack. To prevent those damage, the impact energy is transferred to the floors across members by separating it from the whole body sill. Besides, a high-strength battery frame is set around the battery pack for further protection.

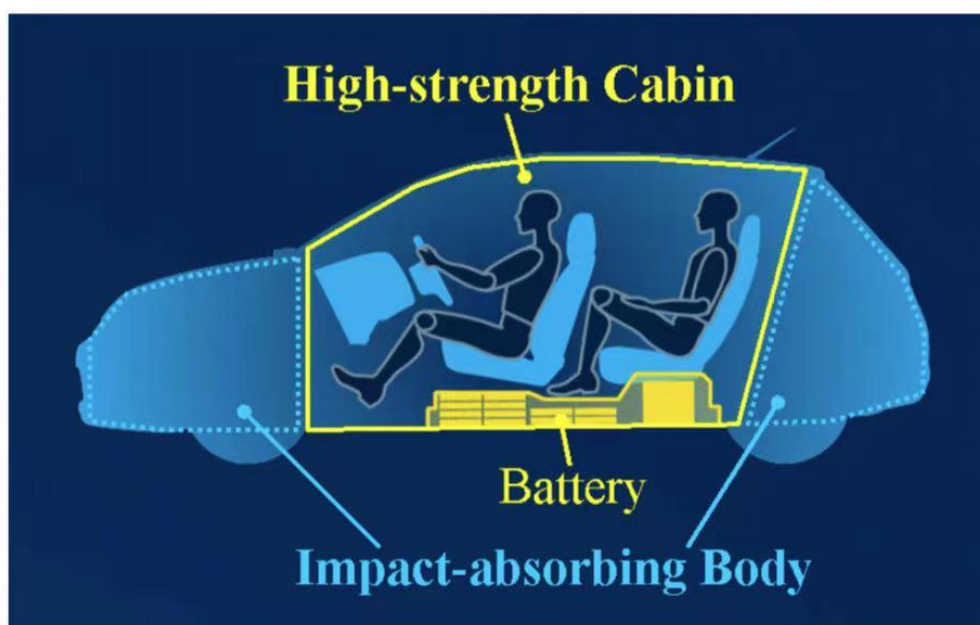


Figure 2. Side view of an electric car [3]

2.2. Lithium-ion batteries

The lithium-ion batteries is the most preferred battery used in the electric vehicle industry because of its high energy density and power density. For instance, it would maintain its performance under wide temperature range. It has higher energy density and power density. The lithium batteries consist of separators and electrodes which the lithium-ion between anode and cathode [4].

2.2.1 Cathode

Three kinds of cathode materials are most commonly used in the electric vehicle industry. LFP, LMO and LiMO_2 where M represents Ni, Co, Mn and Al. LFP has the highest thermal stability, long and low cost. The strong covalent bond between P and O in PO_4^{3-} octahedral structure enables it to have a stable performance under 350°C . However, the volume energy density and the theoretical specific capacity of the LFP is low. LMO has better manufacturing properties. However, it has low energy density and poor cycling stability due to the dissolution of Mn by temperature during charging/discharging. The electrochemical properties and thermal stability of pure LiNiO_2 are poor so the performance of the cell is enhanced by replacing Ni with Mn, Co or Al to form a lattice structure [4].

2.2.2 Anode

The materials used as anode in lithium-ion batteries can be classified to three types. The advantages and disadvantages are summarized in table 1. (I) carbon based material such as graphite and lithium titanium oxide; (II) Conversion reaction anode; (III) Alloying type materials.

Table 1. Advantages and disadvantages of four common types of Lithium-ion battery [4].

Materials	Advantage	Disadvantage
Graphite	Low cost, High electrical conductivity, Low potential plateau	Low volume expansion
LTO	High rate charge/discharge, long lifespan	High lithiation/ delithiation plateau, low specific capacity
MX (M=transition metal and X=O, F, H)	High specific capacity	Poor electronic capacity, low rate performance
IV and V group and its oxides, sulfides or phosphates	High discharge capacity	Poor lifespan and serious pulverization

2.3. Safety issues

The safety issues of lithium-ion batteries related on both materials and cell level [4]. The fundamental reason for the unsafety factors is the exothermic reactions happened inside batteries. In general, these exothermic reactions include: (I) excessive lithium removal from the anode leads to irreversible changes in the anode structure, oxygen release and organic solvent oxidation; (II) lithium dendrites formed on the anode react with the electrolyte, generating large amounts of gas and heat, and the lithium dendrites grow and further penetrate the diaphragm, leading to an internal short circuit; (III) PE-based diaphragms melt when the temperature rises above 130 °C; (IV) Due to the low flash point and low boiling point of carbonate organic solvents, the electrolyte is easy to decompose at high temperature (> 200°C) and high pressure (about 4.6V), which generates a lot of heat.

Electric vehicles containing a large number of batteries connected in series and parallel. Those circuit works together to form a high energy and power battery system to run an electric vehicle. The battery system of the electric vehicle may faced to varies triggering condition such as car crash, overcharge, overdischarge, water soak and so on. Lithium-ion batteries are sensitive to temperature and voltage. Both high and low temperature would cause fault. As shown in the Figure 3, if the temperature continues to rise, it may be dangerous due to the decomposition of the solid electrolyte interface (SEI) and electrode materials and continue to exacerbate the side reactions. On the other hand, low temperatures can lead to lithium plating of the negative electrode and poor multiplicative performance which may cause serious problem such as circuit shortage. Overcharging causes the positive material to collapse and intensifies the side reactions, thus generating a lot of heat, thus heat, thus rapidly increasing the temperature. According to the data, overcharging is one of the main causes of electric vehicle failure. And over-discharge occurs when the battery is over-discharged causing the voltage of the battery to fall below the minimum voltage. Over-discharge will reduce the performance of the lithium battery and can lead to serious safety problems such as internal short circuit.

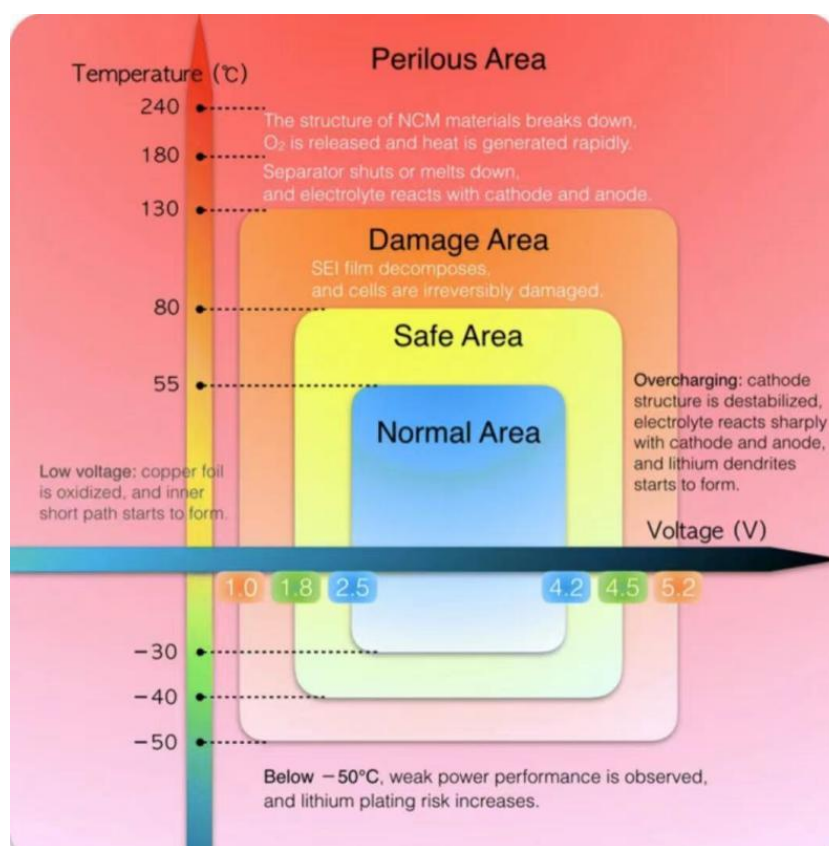
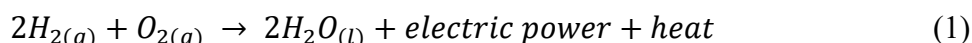


Figure 3. The behaviors of Lithium ion batteries under different temperature and voltage [1].

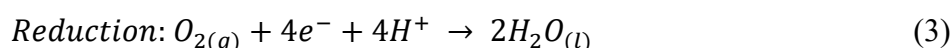
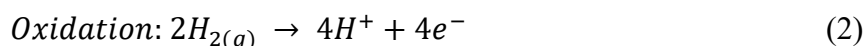
3. Hydrogen Fuel Cell Vehicles (HFCV)

3.1. Structure of hydrogen fuel cells (HFC)

A fuel cell produces electricity by mixing fuel with air (oxygen). In reverse to a typical electrolysis reaction, the energy produced by HFC comes from the energy released from the reaction between hydrogen and oxygen that produces water. The basic chemical reaction in an HFC is shown in equation 1:



Similar to any other cell, fuel cells contain basic cell structure including a cathode, where the reduction reaction happens, an anode, where the oxidation reaction happens, an electrolyte to maintain the balance between two sides of the cell, and an external circuit, where the generated energy can be used to power vehicles. In the hydrogen fuel cell, hydrogen is oxidized into hydrogen protons and electrons at anode. The generated electrons pass through external circuit and the current is used for power purposes. Then, the oxygen is reduced into oxygen ions at cathode. The oxidation and reduction equations are shown in equation 2 and 3.



There are several types of HFC, but the main reaction is the same. The only difference is the electrolyte used in the cell. According to the operating temperature, purity requirement of the fuel, cost of cell, byproducts of the reaction, etc., the cells are used in different fields. The Alkaline fuel cell is used in space for its stability and possible byproducts of pure water. The Phosphoric acid fuel cell is used in large power plants or on-site stationary applications for its low fuel purity requirement. Proton exchange membrane fuel cell (PEMFC) is often used in hydrogen-powered vehicles because

of its moderate operating temperature and high output power. The major feature comparison of all 5 types of cells is given in Table 2.

Table 2. Types of fuel cells and their properties.

Types of fuel cell	Alkaline fuel cell (AFC)	Molten carbonate fuel cell (MCFC)	Phosphoric acid fuel cell (PAFC)	Proton exchange membrane fuel cell (PEMFC)	Solid oxide fuel cell (SOFC)
Electrolyte	KOH	LiCO ₃	H ₃ PO ₄	Nafion	Y ₂ O ₃ /ZrO ₂
Free moving ions	OH ⁻	CO ₃ ²⁻	H ⁺	H ⁺	O ₂ ⁻
Operating temperature	<120-250°C	650°C	160-220°C	<100°C	800-1000°C
Reactant	Highly purified H ₂	H ₂ /CH ₄	H ₂	H ₂	H ₂ /CH ₄
Oxidizer	O ₂	O ₂	O ₂	O ₂	O ₂
Electric efficiency	70%	50-60%	40-45%	<40%	50-60%

3.2. Proton exchange membrane fuel cell (PEMFC)

In a PEMFC cell, the electrolyte is hydrogen proton that is produced in oxidation reaction from the anode. Input fuel, hydrogen, catalyzed by platinum, is oxidized into hydrogen proton and electrons at anode. The proton is then passed through a proton exchange membrane between anode and cathode. After that, the proton is combined with electrons and air. There is no tailpipe emission for PEMFC because only pure water is produced. The electrons generated at the anode are used in external circuit. Figure 4 illustrates the structure of PEMFC.

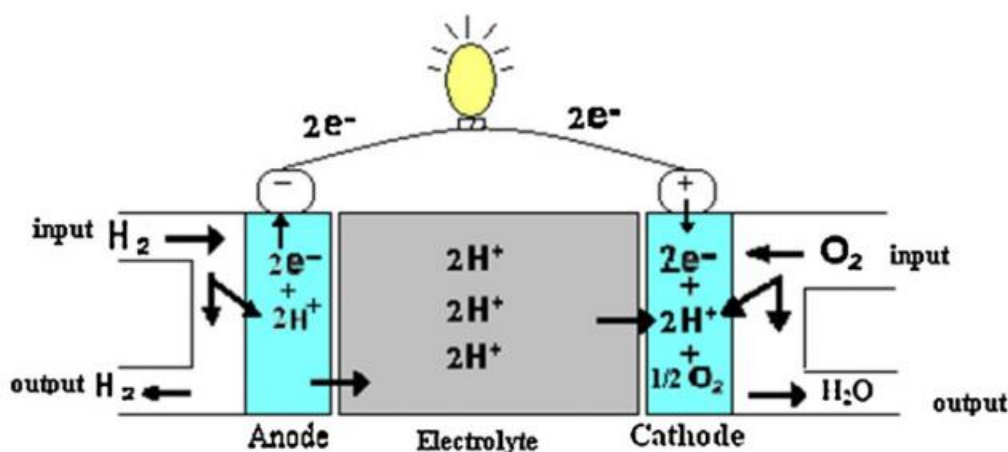


Figure 4. Proton exchange membrane fuel cell (PEMFC) [5]

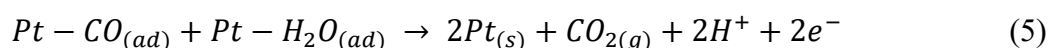
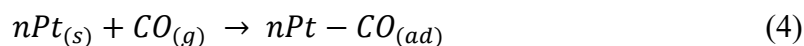
PEMFC has membrane electrode assembly (MEA). Inside the assembly, there is one porous layer, two catalyst layers, and most importantly, a proton exchange membrane [6]. Platinum or other new catalyst material (most recent development alternatives to reduce the use of noble metals) are used in the catalyst layer, to speed up the reaction rate of reduction and oxidation. The porous gas diffusion layer helps to balance the pressure between anode and cathode, allowing the cell to consume fuel uniformly. It also transfers the heat and creates enough mechanical strength to hold the expansion of proton exchange membrane. The proton exchange membrane is used to allow hydrogen protons to pass through from anode to cathode and prevent electrons to go through, keeping electrons to go through the external circuit, where the energy is used.

PEMFC is suitable for transportation use because of its moderate operating temperature. PEMFC requires an operating temperature between 60 to 100°C, only a bit higher than the environmental

temperature. It is also lightweight with no solid or liquid electrolyte inside, no additional weight is given to the vehicle. Besides, it is cheap to produce compared to other types of hydrogen fuel cells and has a longer lifetime.

The efficiency of PEMFC depends solely on temperature. According to the collision theory, the chemical reaction rate (efficiency) increases as temperature increases. However, PEMFC cannot operate at a temperature over 100°C, because the membrane only functions under wet condition. Electrical efficiency is around 40% and the output power can reach 250kW, similar to the one generated by internal combustion engines (around 500kW).

One key limitation of PEMFC is its possible carbon monoxide contamination, which lowers the efficiency. The catalyst platinum reacts with carbon monoxide and will form a layer covering the catalyst layer. The available surface for hydrogen redox reaction is reduced as carbon monoxide keeps accumulating on the surface. The surface is covered by carbon monoxide through equation 4, while the carbon monoxide is removed through oxidation (equation 5). The three reactions compete with each other and affect efficiency, depending on conditions [7].



3.3. Hydrogen Fuel Cell Vehicles Safety

Hydrogen is often thought to be a highly explosive and possible bomb material. In fact, hydrogen fuel cell vehicles (HFCVs) are much safer than people thought. Indeed, hydrogen is highly explosive. Hydrogen can explode when hydrogen to air ratio is with the range of 4% to 75%. The range is greater than most of the other fuels. Moreover, hydrogen has low ignition energy of 0.017MJ, suggesting possible ignition and explosion if handled carelessly [8].

However, every coin has two sides. The same properties suggest a perfect fuel alternative. The low boiling point and high latent heat of combustion give hydrogen unique advantages of being a clean fuel if safety measures are carefully prepared. Recent researches have proved HFCVs' safety. First of all, there is no severe accident that is caused by hydrogen leak from the tank. Hydrogen, the lightest gas in nature, vaporize quickly under room temperature and pressure and floats up above the air, reducing possible fire hazard. Secondly, recent HFCVs have onboard sensors that monitor the leakage of hydrogen, the imbalance between consumption and flow out rate, and the internal temperature and pressure of the tank. If any unsafe scenario happens, the valve will be automatically shut off, protecting drivers' safety. As a result, HFCVs' safety are guaranteed.

4. Comparison

4.1. Eco-friendly

Global warming has become a serious issue around the world. Because of the constant emission of greenhouse gases, the global temperature has risen by 0.08° Celsius per decade and the rate of warming has doubled since 1981 [9]. New energy vehicles, are expected to lower the emission extent and control the rising temperature. Carbon dioxide is one of the most significant factors of global warming. EVs and HFCVs with zero tailpipe emissions seem to be so pleasant, compared to conventional cars that burn gasoline and emit carbon monoxide, hydrocarbons, and nitrogen oxides. However, zero-emission is nonsense for both EVs and HFCVs. Emission can come from the generation of fuels.

For EVs, emissions come from the production of electricity. Research shown that natural gas and coal, which pollutes greenhouse gases, accounts for 60.1% of electricity source in America, a well-developed country [10]. 4,000 pounds of carbon dioxide are polluted annually per electric vehicle. This indicates that all-electric cars are produced about 33 % of carbon dioxide compared to conventional cars. Although 4,000 pounds is much less than 12,000 pounds produced by gasoline

cars, it is still far more than zero emission. In other countries relies mostly on non-renewable energy sources, EVs produce even more emissions than conventional vehicles.

For HFCVs, emissions come from the production of hydrogen. Right now, there are 3 major methods to produce hydrogen [11]. One is called steam methane reforming process (SMR), by converting methane (natural gas) into carbon dioxide and water vapor. The other two are electrolysis of water and direct source of methane from landfills and sewage. At present, over 95% of the hydrogen is produced through SMR, a high carbon process. According to Praxair, one of the biggest hydrogen fuel production companies, a total of 21.9 metric tons of carbon dioxide is produced per million cubic feet of hydrogen in practical. This is equivalent to 9.3kg of CO₂ emission per 1 kg of hydrogen [12]. At the same time, when producing 1 gallon of gasoline (3.78 liters), 9.1kg of CO₂ is produced. Assuming an HFCV consumes 0.55kg of hydrogen per 100 kilometers, around 5.15 kg of CO₂ is produced per 100 kilometers. At the same time, assuming 0.5 liters of gasoline per 100 kilometers for conventional cars [13], around 12 kg of CO₂ is produced per 100 km. This indicates that HFCV is produced only half of the CO₂ compared to conventional cars.

By comparing the data, EVs produce fewer greenhouse gases emission than HFCVs at present technology, but far more than zero-emission due to the production of fuels. HFCV produced half of CO₂, while EVs only produced 33% of CO₂, compared to gasoline cars. EVs' performances in reducing carbon emissions are around 30% better than HFCVs. Overall, they are both more eco-friendly than ICVs.

4.2. Charging Infrastructure

The associated refueling facilities are still in a early stages. Therefore, there is a huge difference in the number of the electric charging station and hydrogen refueling station. For example, according to a statistics from January 13, 2022, there are 46,290 public charging stations and 113,558 private charging outlets to support the electric vehicles in the US [14]. There are about 43 hydrogen refueling station available in the US and all of them are mostly concentrated in California. Figure 5 and figure 6 are collected from the alternative fuel data center capture the distribution of the electric charging stations and hydrogen refueling station in most of North America. It clearly shows the huge disparity in the number of charging stations between the two types of stations. The number of both types of charging stations is bound to increase in the future, but so far, electric vehicles have a definite advantage in terms of charging convenience.

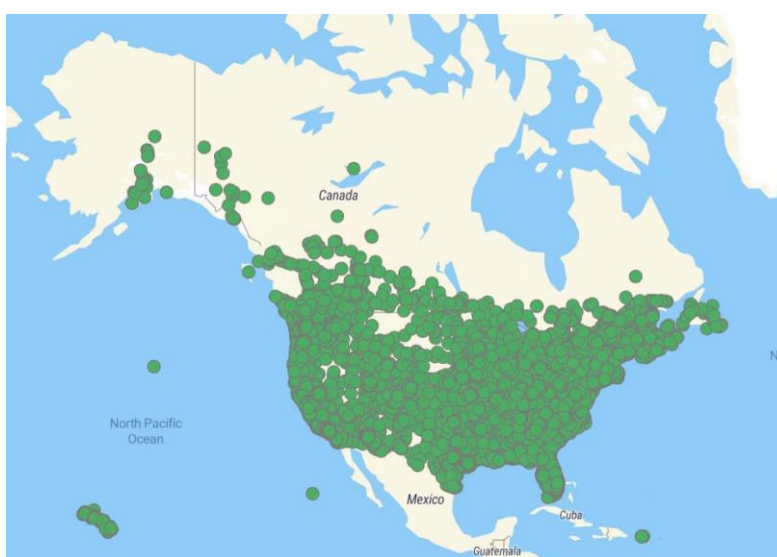


Figure 5. Distribution of electric charging station [15].



Figure 6. Distribution of hydrogen refueling station [16].

The charging time of an electric vehicle depends on the battery capacity and charging efficiency. Most current electric vehicles require between half an hour and twelve hours to recharge. Hydrogen cars are charged in a similar way to conventional cars, simply by filling the tank through a designated hydrogen dispenser at a public refueling station. Only five minutes or less is needed for it to complete the process. In this aspect of charging time, electric cars have a big disadvantage.

4.3. Energy efficiency

The efficiency of energy usage of the electrical motor is much higher than that of the internal combustion engine vehicles. The internal combustion motor is very low tank-to-wheel efficiencies with only 10% to 25% can be used to propel the car and the other 75% to 90% of energy is lost as heat [17]. The efficiency of the electrical motor is up to 90% which is significantly high compared to that of an internal combustion motor. However, to investigate the overall energy efficiency of internal combustion and electrical motor, further research on the well-to-wheel (WTW) efficiency is taken. The well to wheel efficiency considered both well to tank efficiency and tank to wheels efficiency. This investigation indicates the WTW efficiency of hydrogen powered internal combustion vehicles ranged from 6.8% to 29.2% depends on the hydrogen production and transformation routes [18]. The WTW efficiency of electric vehicles depends highly on the power sources used to charge the batteries. The electric vehicles powered by fossil fuels-powered plants have the WTW efficiency ranging from 12% to 22% which have a similar performance to the hydrogen-powered vehicles. However, the overall energy efficiency is significantly improved by powering the electric vehicles with renewable energy sources and the WTW efficiency is ranged between 39% and 72% [19].

4.4. Safety comparison

Safety issue is also a concern when people talk about alternative fuel cars. Recent studies show that both electric vehicles and hydrogen fuel cell vehicles are safer than internal combustion vehicles (ICVs). In 2022, the Insurance Institute for Highway Safety (IIHS) tested the safety performance of several cars in the United States, including both ICVs and EVs. Surprisingly, most of the EVs' safety score exceeds that of the ICVs'. The Tesla Model 3 even attains a score that breaks the records of IIHS [20]. EVs can outweigh ICVs because, firstly, the gasoline fuel inside an ICV is already potentially dangerous. The vehicle itself is a small "time bomb" with fuel inside. Though battery pack is also combustible, it is not as volatile as liquid gasoline. Secondly, the lack of engine at the front of the car gives EV a better performance when doing front crash simulations. Moreover, the low center of gravity makes EVs low chance of rollovers.

Nevertheless, lithium-ion batteries suffer from thermal runaway. Lithium-ion battery pack is constructed of several individual cells. Once one of the cells is short-circuited, it will heat up and

affect other cells. If the heat is self-sustaining, the heat transforms into energy, and energy converts to heat again, the cell is experiencing a thermal runaway. At that moment, the battery can easily catch fire [21]. In real life, many cases of EV fires are caused by a short circuit inside the battery. Although there is a protection system to control the temperature of individual cells, it is still not guaranteed that the system will work 100% during accidents.

For HFCVs, they are also safer than ICVs. As said in previous section, hydrogen is the lightest gas in the atmosphere and will quickly disperse in the air when the fuel leaks. Research done by the University of Miami in 2008 compares fire fuel leaks between hydrogen and gasoline vehicles. As shown in Figure 7, after three seconds of ignition, the flame produced by high-pressure hydrogen is injected directly above, while gasoline is heavier than air and ignites from the lower part of the car. By one minute, the hydrogen-fueled car only burns the leaked hydrogen, and the car has no major problem; while the gasoline car has already become a big fireball and completely burned out. In addition, the fuel tanks of hydrogen are designed to resist huge pressure from both inside and outside when an accident comes. Tanks made of carbon fibre can theoretically withstand pressure less than 10,000 psi (6 times atmospheric pressure) [22].

To conclude, it is certain that both EVs and HFCVs are safer than traditional gasoline vehicles. However, EVs suffer from thermal runaways and have more serious accidents than HFCVs.



Figure 7. Combustion comparison test of hydrogen fuel cell vehicle and gasoline vehicle [23].
(left: 3s; right: 1min)

5. Conclusion

As the transport sector accounts for a quarter of the emission, new energy vehicles have played an important role in energy saving and emission reduction, especially electric vehicles and hydrogen fuel cell vehicles. The entire article compares the differences between EVs and HFCVs in terms of carbon emissions, construction of charging facilities, driving experience and safety. The study found that the performance of EVs in energy saving and emission reduction is nearly 30% better than that of HFCVs. EVs' charging infrastructure is more complete than HFCVs'. In United States, there are over 15,000 charging points for EVs, but only 43 hydrogen gas stations. In respect to energy efficiency, HFCVs have efficiency less than 30%, while EVs have efficiency around 30% to 70%. EVs are better. In terms of safety, HFCVs are less likely to cause fires after an accident due to their volatile fuel and lightweight property of gas. EVs are prone to heat up and catch fire, causing serious accidents. But both have better safety than traditional cars. For now, the advantages of electric vehicles are more obvious. In the future, with the power reform, more infrastructure investment, and more low-carbon hydrogen production methods, such as the electrolysis of water to produce hydrogen, electric vehicles and hydrogen fuel cell vehicles have plenty of room for development.

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