

Electrification of Transport: Advantages and Prospects

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Abstract. Electrification has become the main mode of new energy transportation. This paper compared electric vehicles with internal combustion and hydrogen fuel cell vehicles. Less environmental pollution, higher efficiency of power system, and lower cost were the most favourable attributes of electric vehicles. In addition, comparing Li-ion and other batteries, the greatest energy density, the lowest self-discharge rate, and the longest cycle life made Li-ion the most suitable choice for electric vehicles. However, the Li-ion battery in electric vehicles still has some limitations. The 400 km driving range limits electric vehicles in urban and developed areas. It also made traditional fossil fuel vehicles the best choice for people with long-range travel needs. Under low temperatures, the capacity decline and polarization effects of Li-ion batteries made electric vehicles unable to meet the needs of use in extreme environments. A higher energy density and a wider range of working temperatures are needed to advance further in transportation.

Keywords: Renewable energy, electric vehicle, electrification, lithium-ion battery, transportation.

1. Introduction

The long history of industrialization in Europe had brought convenience to people's daily travel, but it also resulted in a serious environmental problem. As a product of industrialization, until 2021, there were 246.3 million cars on the road across Europe, with 11.8 years on average old [1]. Accordingly, most European cars were traditional internal combustion (IC) engines powered by fossil fuel. The exhaust IC engine cars produce the main source of nitrogen oxides (NO_x) and greenhouse gases, which lead to significant air pollution and global warming. Also, manufacturing and oil extraction caused serious heavy metals pollution in the air. As shown in Figure 1, most of the urban population in Europe was exposed to concentrated air pollutants, which caused about 400,000 premature adults died attributed to air pollution each year [2, 3].

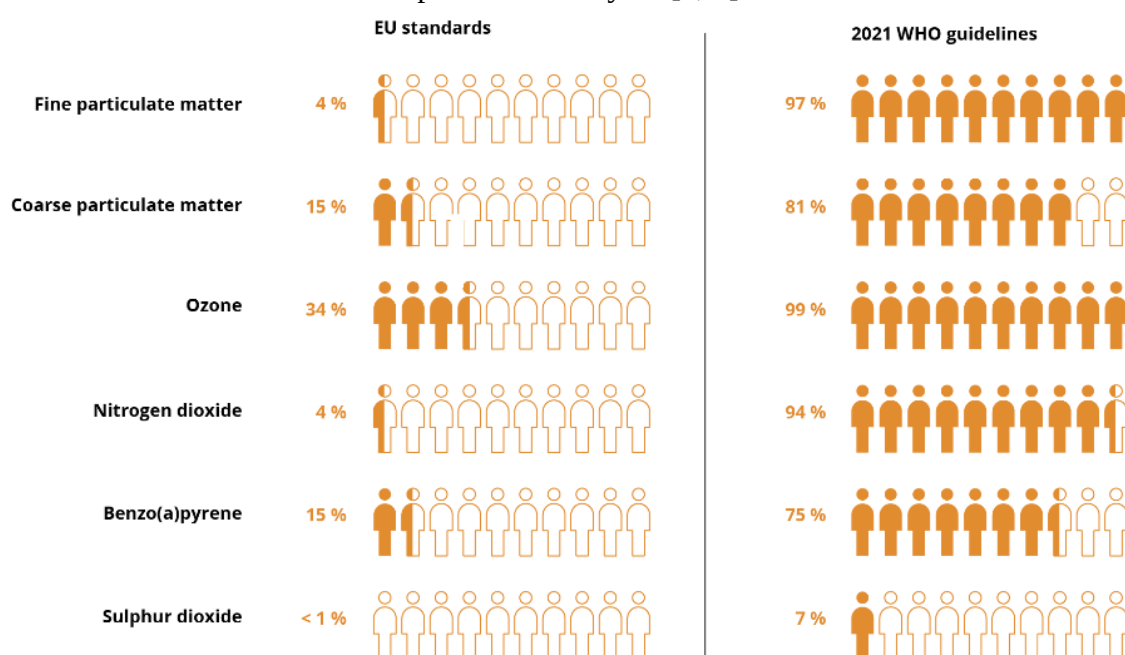


Figure 1. The proportion of urban residents affected by air pollutants in 2021 under EU standards and WHO guidelines [2].

To reduce air pollution, the European Union has already promoted some policies to limit the air pollutants emissions from exhaust and manufacturing. The trend of main air pollutants and GDP from 2005 to 2019 (Figure 2) showed us that European countries had already found a balance between economic development and pollution emissions in the past decade. However, to further increase the air quality in Europe, the most efficient way was to reduce the exhaust gas that the huge amount of IC engine vehicles produced and the oil extraction, which led to the development of new energy in the transportation area.

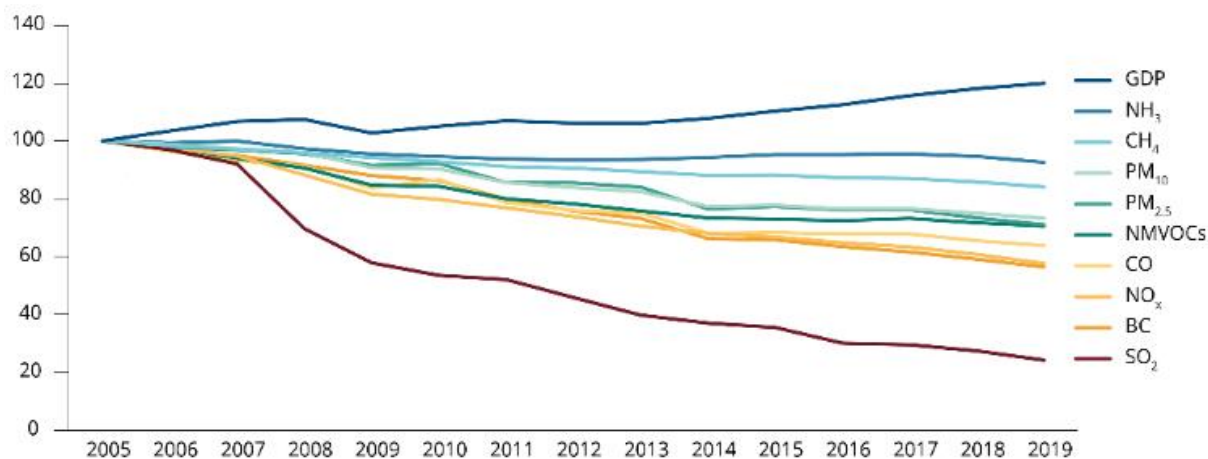


Figure 2. The total emission trend of main air pollutants with the trend of GDP development between 2005 to 2019 [4].

Nowadays, with the development of new energy technology, people pay increased attention to the application of electricity. In transport, the application of electricity provided two main directions of new energy transportation: fuel cell electric (hydrogen-powered) vehicles and electricity-powered vehicles. Although electric and fuel cell electric vehicles significantly reduced environmental emissions compared to traditional internal combustion engines, electric vehicles had a wider range of applications than fuel-cell electric vehicles. This paper will discuss the reasons for the electrification of transport and the increased popularity of electric vehicles in terms of environmental pollution, power system, costs and the development of renewable energy technology, as well as provide an outlook on the future development and application of electric vehicles.

2. Differences in working mechanism between electric and traditional vehicles

2.1. Internal combustion engine

The IC engine vehicles burnt fuel to generate forces to push pistons did work. The produced power was transferred by the connecting rod to the crankshaft and finally became kinetic energy and drove the vehicles (Figure 3). However, due to heat loss (for example, heat in the exhaust), only 12% to 30% of energy in gasoline is transferred to power at wheels, which causes a very low conversion efficiency [5].

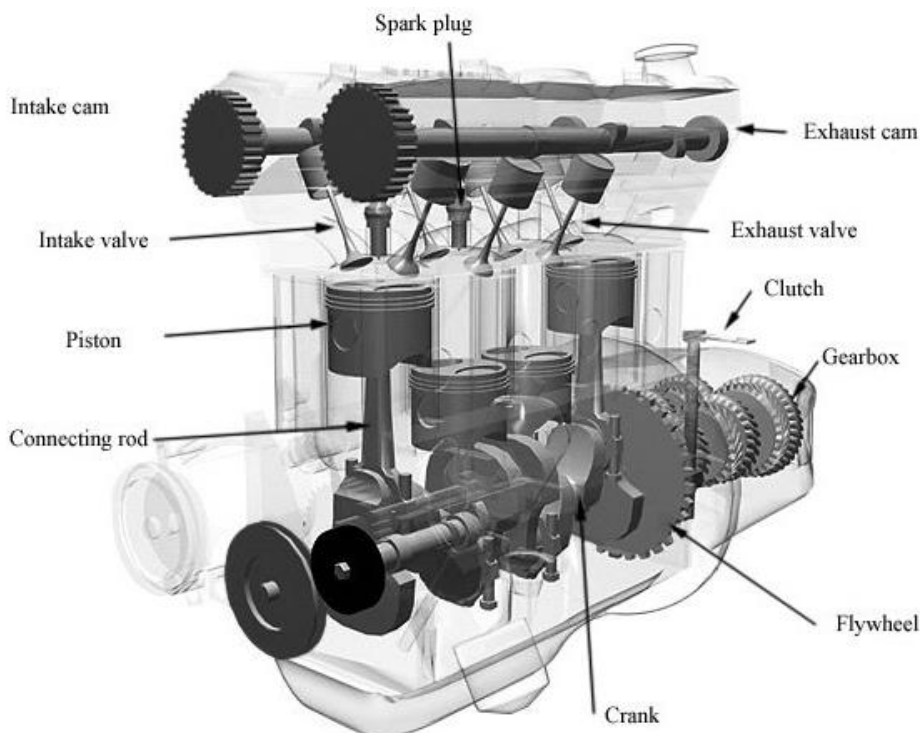


Figure 3. The structure of an internal combustion engine [6].

2.2. Li-ion battery and motor

In the power system of electric vehicles, the batteries drove an electric traction motor directly to convert electrical energy into kinetic energy (Figure 4) with no exhaust gas, which meant a much lower energy loss (15% to 20%) than the IC engine. EVs also had regenerative braking to reuse energy usually lost in braking, which led to an over 87% of total efficiency [7].

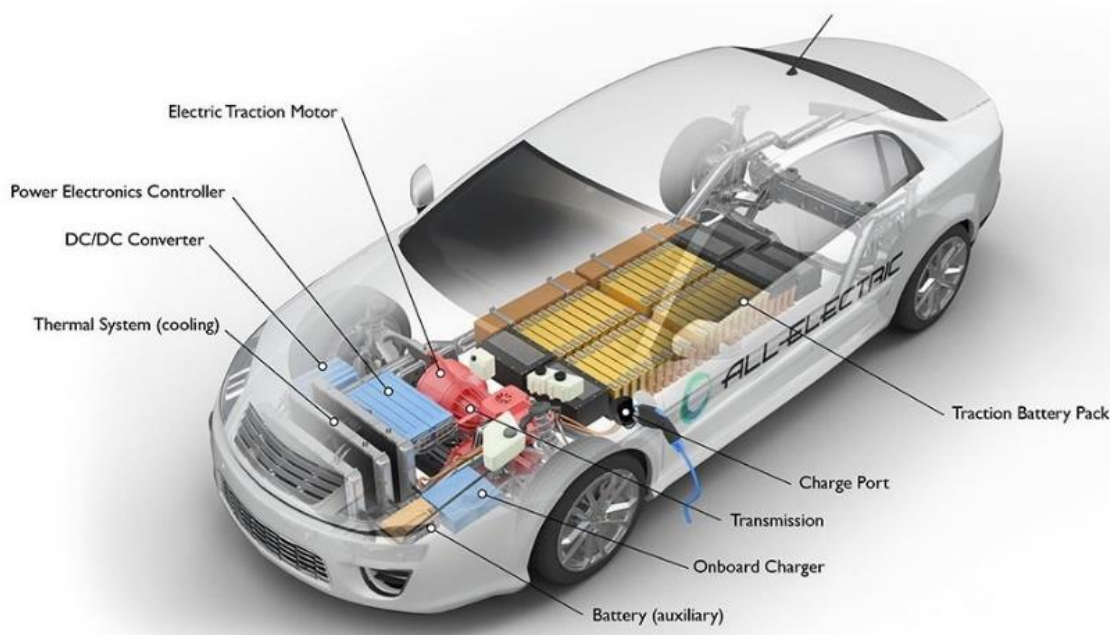


Figure 4. The basic structure of electric vehicles [8].

2.3. Fuel cell and motor

The catalyst (expensive metals like Pt) in the fuel cell's anode for hydrogen-powered vehicles facilitated the oxygen reduction reaction by converting hydrogen gas into hydrogen protons and electrons. The electrons flowed through the circuit to the cathode and produced electricity to drive

the motor. Finally, the electrons in the cathode are combined with hydrogen protons passing through the proton exchange membrane to produce hydrogen electrons, which are combined with oxygen and finally produce water (Figure 5). The reaction equations for the facilitation of oxygen in the fuel cell are shown below in equations (1) and (2).

Reaction in Anode:



Overall Reaction Equation:

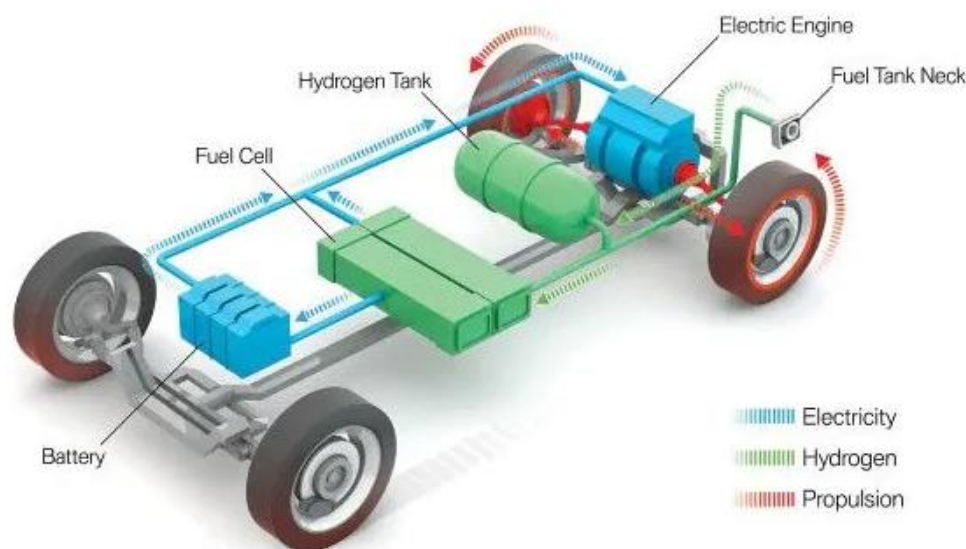


Figure 5. The basic structure of fuel cell (hydrogen-powered) vehicles [9].

3. Driving factors of transport electrification

3.1. Environmental improvement

For internal combustion engine vehicles, air pollutants are often produced by fuel combustion, especially when the engine has just started and has not reached operating temperature. Generally, most modern vehicle engines were designed to suit different conditions [10]. However, when the engine completely cooled and restarted the engine, due to the very low speed, there was still not enough air intake in the cylinder of the engine, which resulted in the air-to-fuel mass ratio (AFR) being lower than the ideal combustion ratio (about 14.7:1). The rich air to fuel mass ratio mixture in cylinder lead to incomplete combustion of gasoline fuel and higher emission of hydrocarbons (HC) and carbon monoxide (CO) [11]. Also, the cold engine made more heat conduction and less gas expansion. The catalyst also was inefficient in this situation. In this case, the emission of pollutants would increase further. Apart from this, HC is also produced through the volatilization of gasoline, which pollutes the environment.

On the other hand, electric vehicles are powered by electricity directly, renewable energy that can be obtained through nature sources (like hydropower, solar, and wind; Figure 6) with no pollution. Although about 30% of electricity was produced by burning coal, which would cause environmental pollution, it was still much less than oil extraction and related processing.

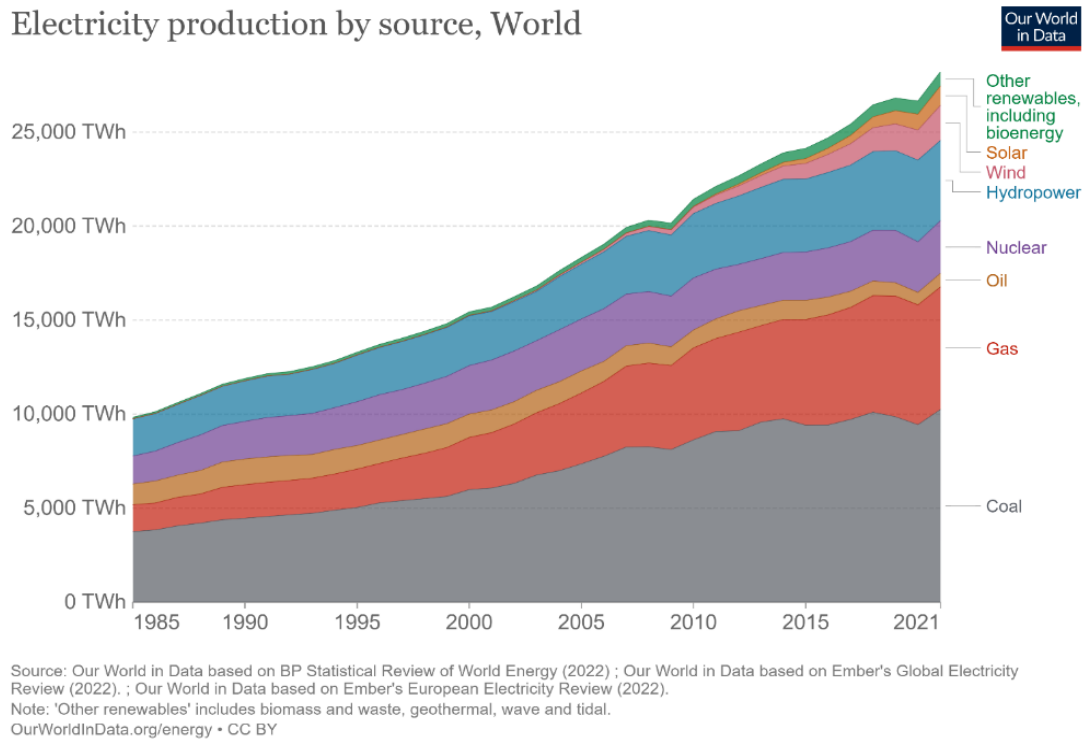


Figure 6. The electricity production by source worldwide (1985 - 2021) [12].

The power source of hydrogen-powered vehicles was the electricity produced by the fuel cell stack. Since only water was produced from the combination of hydrogen protons (H^+) and oxygen (O_2), hydrogen-powered vehicles were much more environmentally friendly than internal combustion engines. However, hydrogen extraction (combining high-temperature steam with natural gas) would produce pollution. The combination between hydrogen protons and oxygen in the cathode is shown below in equation (3).



3.2. Engine optimization

By comparing two power output graphs in Figure 7, two different torque trends at low speeds could be observed. Since the AFR in the cylinder of the IC engine was lower than the stoichiometric air-fuel ratio at low engine speed, the rich mixture could not completely burn. This made the temperature in the cylinder low so that the air expansion was less so that a smaller force was applied on the crankshaft, finally leading to a lower torque at low speed. In this "preparing phase", the increasing temperature increased the torque at low speed while the engine speed increased.

On the other hand, because the motor was activated by electricity directly, there were only on and off statuses for electric traction motors in electricity-powered vehicles. No "preparing phase" at low speed for electricity-powered vehicles made the trend of torque for EVs and hydrogen-powered vehicles similar in that the maximum torque could appear at zero speed and kept stable until a high RPM (about 5500 for BMW i4 in Figure 7) is reached.

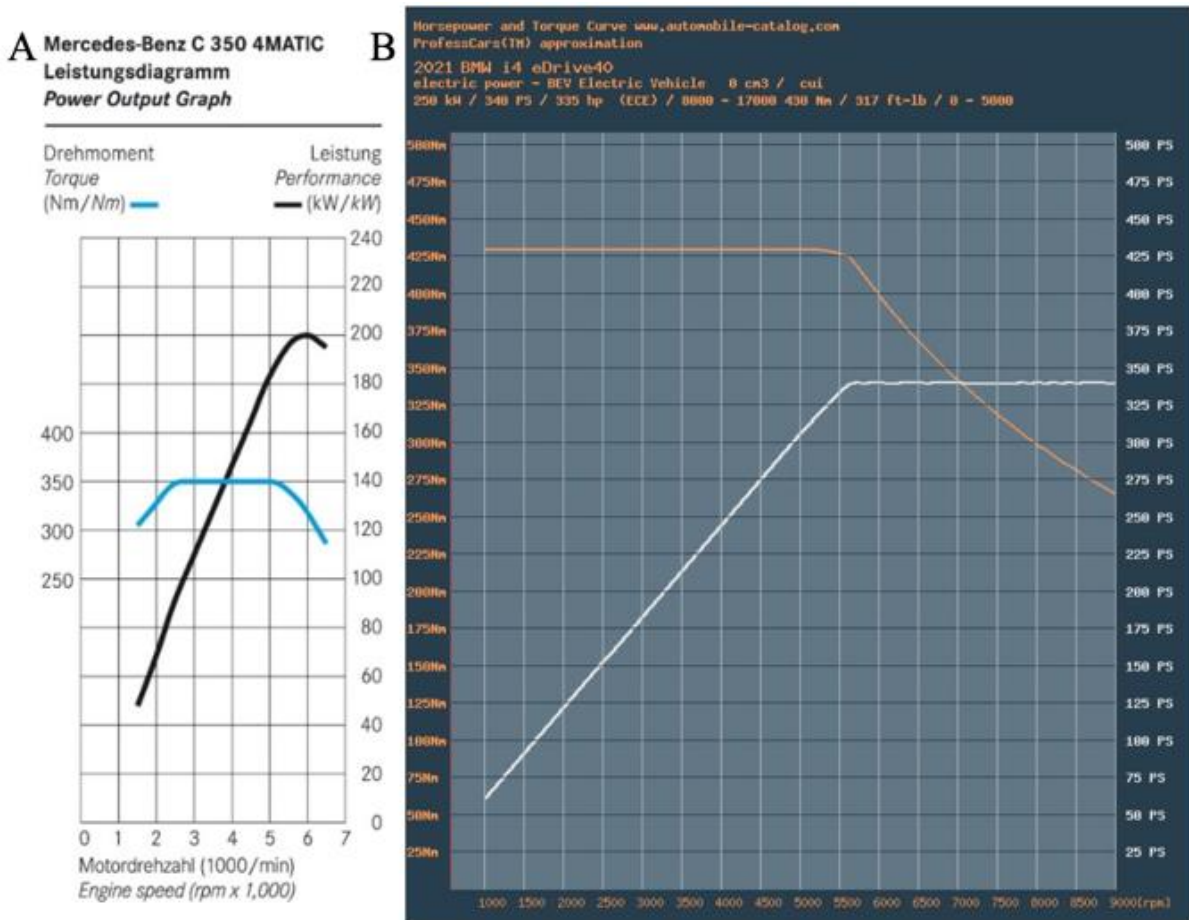


Figure 7. (A) The power output graph of Mercedes-Benz C350 4MATIC (IC engine) [13]. (B) The power output graph of BMW i4 eDrive40 (electric motor) [14].

In this situation, if an internal combustion vehicle faced an uphill while driving, the sudden decrease in speed would lead to a lower engine speed and a lower torque. The lower torque would further decrease the engine speed and eventually cause the car's stall. So, for the early engines, due to the lack of technology in control and structure, it was impossible to output the maximum torque under all speeds, so only some most used intervals are considered 2000 to 3000 for the gasoline engine. Since the engine speed while climbing was about 3500 to 5000, so the early engines set maximum torque in this range and ensured the torque in the range between 2000 to 3000 was as large as possible. With the application of a gearbox and the engine control module (ECM) control, the engine's maximum torque has become an interval rather than a point. In this case, since the characteristic of the motor is that the lower speed, the higher torque, the power system of electric vehicles and fuel cell vehicles was more suitable to be the power source from a dynamic point of view.

3.3. Cost reduction

Nowadays, many national governments have issued relevant preferential policies to push the development of new energy cars. In China, depending on car prices, the government subsidizes up to 10 thousand yuan when people buy a new energy car [15]. Also, the new energy cars were exemption from the purchase tax, which was about 10% of the whole price of a car [16]. Due to this situation, the new energy cars had a price advantage when choosing between a similar class IC engine car and an electric car. However, for hydrogen-powered cars, although subsidy policies are also applied to them, rooted in the inability to discover a catalyst that could outperform expensive metals to facilitate the oxygen reduction reaction, which leads to the expensive price of fuel cells and so hydrogen-powered cars can be five times more expensive than internal combustion engine vehicles [17]. So, hydrogen-powered vehicles did not have the price advantage.

Also, electric vehicles had a cost advantage when recharging. Before selling petrol to customers, three steps are required: extraction, refining, and transportation. These processes' high labor and transportation costs made the total cost high. Also, the tax (about 15%) made the selling price much higher. The huge cost during these processes led to the price of petrol today in China reaching about 9 yuan per liter. To fully refuel a 66 L tank of an internal combustion car would cost about 600 yuan and allow a car to drive about 1000km. This meant the traditional cars cost 0.6 yuan for each kilometer.

On the other hand, electricity prices had a significant drop since electricity could be easily obtained from natural sources (like solar and hydropower) and with the rapid development of renewable energy technology. Between 2010 to 2020, the price of cost of electricity from solar power fell by 85%, and the cost of onshore and offshore wind energy dropped by 56% and 48%, separately [18]. Moreover, natural resource power generation means less labor and transportation costs, which finally decreases the price of electricity for recharging decreased to 0.125 yuan per kilometer, and fully charging for EV cars cost about 50 yuan and allows cars to drive for about 400 km.

Furthermore, due to the different structures of vehicles, electric cars have fewer components (for example, gearbox) than IC engine cars. The fewer components and the simpler structure made electric vehicles easier to maintain. The maintenance cost for electric cars was lower with the related mature manufacturing industry.

3.4. Battery technology development

Today's battery in electric vehicles normally is a Li-ion battery which uses lithium ions as the anode. Since Sony bought Li-ion batteries in commercial areas, Li-ion batteries have had a significant development during the last decades. Li-ion was the most suitable for EVs compared with other materials due to the higher energy density (Figure 8) and the lower self-discharge rate [19]. The smaller size and lighter weight battery in EVs provided about 400 km driving range with a larger space than IC engine cars. Also, as shown in Table 1, the more cycle life and the shorter charge time gave Li-ion batteries more advantages in long-term use and people's daily need. Nevertheless, the Li-ion battery was safer than the highly combustible and concentrated hydrogen in fuel cell vehicles, allowing EVs to be widely used.

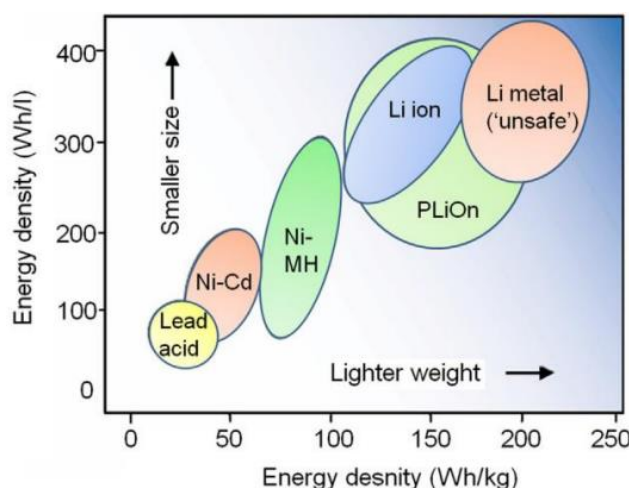


Figure 8. The contrast between diverse battery materials [19].

Table 1. Comparison between various battery materials [19].

Specifications	Lead Acid	NiCd	NiMH	Li-ion		
				Cobalt	Manganese	Phosphate
Specific Energy Density (Wh/kg)	30-50	45-80	60-120	150-190	100-135	90-120
Cycle Life (80% discharge)	200-300	1000	300-500	500-1000	500-1000	1000-2000
Fast Charge Time	8-16 h	1 h typical	2-4 h	2-4 h	1 h or less	1 h or less
Self-discharge/ month (room temp.)	5%	20%	30%	< 10%		
Charge Temperature (°C)	-20 to 50	0 to 45		0 to 45		
Discharge Temperature (°C)	-20 to 50	-20 to 65		-20 to 60		
Maintenance Requirement	3-6 months Topping charge	30-60 days Discharge	60-90 days Discharge	Not Required		
Safety Requirements	Thermally stable	Thermally stable fuse protection common		Protection circuit mandatory		
Toxicity	Very high	Very high	Low	Low		
In Use Since	The late 1800s	1950	1990	1991	1996	1999

4. Current limitations and future developments

Nowadays, although the technology of new energy vehicles has already met people's daily needs, some limitations still hinder the development of new energy. The first and most important limitation is the material. Since Sony introduced the Li-ion battery on the market in 1991, developing materials made by Li-ion batteries have had a huge advancement. However, the energy density of Li-ion batteries was still very low compared to other materials (Figure 9), which made electric vehicles limited to a single city, and people with long-distance needs would still choose gasoline-powered vehicles. The Li-air battery could increase energy density (theoretically output up to about 2000 kWh/kg), but the technology was still not mature [17]. Hydrogen-powered vehicles also face this problem. Although hydrogen had a super high energy density (much higher than gasoline), it was not easy to store large volumes of concentrated hydrogen fuel in civilian vehicles, which made the driving range of hydrogen-powered cars slightly bigger than electric vehicles (about 500 km). Also, the inability to find a better material than expensive metals as the catalyst led to the price of a hydrogen car being five times as expensive as a same-class IC engine.

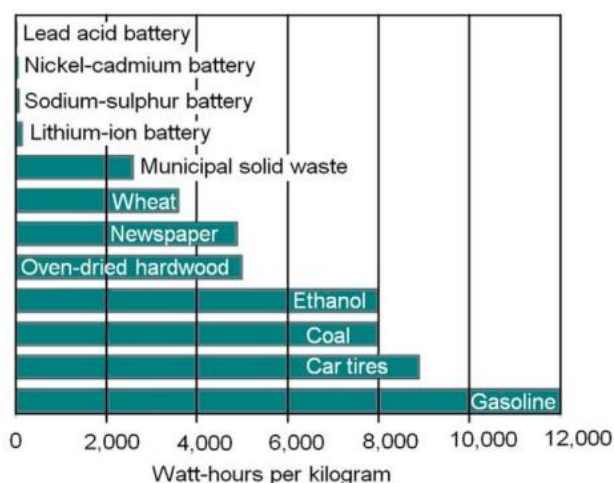


Figure 9. Comparison of energy density between different materials [19].

The normal working temperature for commercial Li-ion batteries was -20°C to 60°C . If Li-ion is applied in aerospace or used in an extreme environment on Earth, the temperature could be much lower than the suitable temperature. In this situation, the capacity reduction and polarization effects were more significant (Fig. 10), which would cause a shorter driving range and service life.

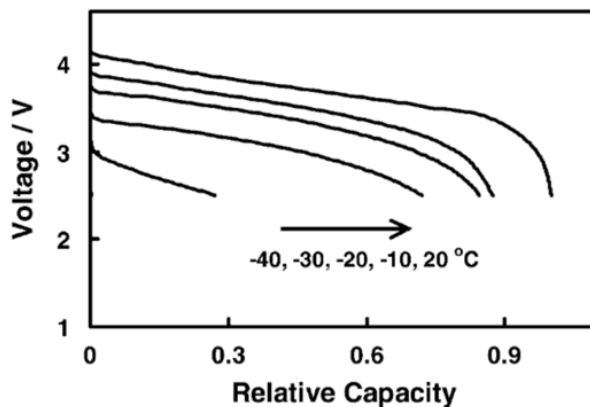


Figure 10. Li-ion battery discharge curves at various temperatures [20].

Since the total impedance (R_b , R_{sl} , and R_{ct}) would also impact the Li-ion battery's cycling performance. By comparing R_b , R_{sl} , and R_{ct} under different temperatures (Figure 11), R_b and R_{sl} had a similar trend with electrolytes, but R_{ct} significantly differed when the temperature dropped to around -10°C . The Li-ion battery performed poorly at low temperatures because of the super high R_{ct} attributed to the slow kinetics of electrode reactions [20].

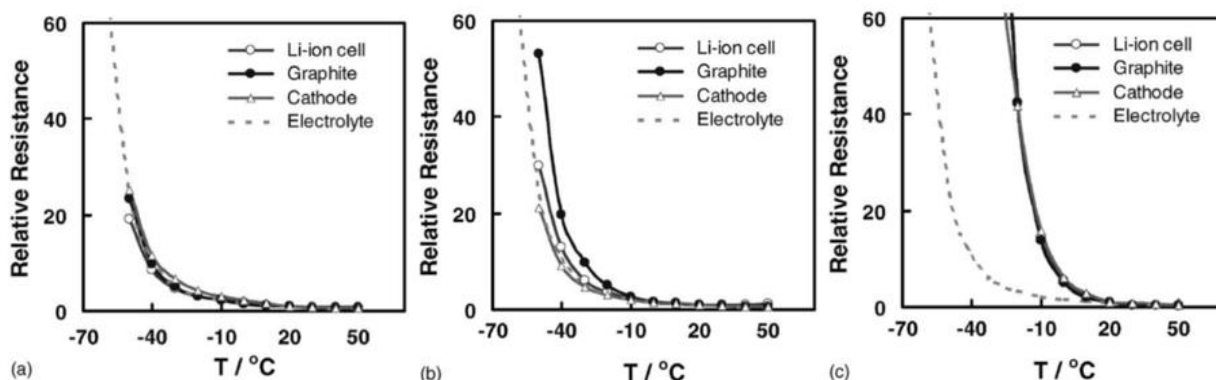


Figure 11. Comparison of the relative resistance of three different of battery at various temperatures. The electrolytic conductivity ratio was used to calculate the relative resistance of the electrolyte and represented by the dotted curve. (a) R_b , (b) R_{sl} and (c) R_{ct} [20].

5. Conclusion

In conclusion, through the battery technology development, EV batteries already had a good performance to support them becoming a method of transportation for people's daily needs. By comparing the EV cars with traditional internal combustion engine cars and hydrogen fuel cell cars, electric vehicles and fuel cell vehicles caused much less pollution than internal combustion vehicles from manufacturing to daily use, which meant the new energy transportation was necessary and efficient to reduce the air pollution and other heavy metals pollution. Also, electric and fuel cell vehicles use the motor to drive the car, which provides a higher conversion efficiency and a better performance under low engine speed, so electricity-powered vehicles are more suitable for energy saving. In addition, electric vehicles had a lower cost than internal combustion engine vehicles due to the related policies and the lower energy cost. In the comparison between EV and fuel cell vehicles, although the higher energy density of hydrogen made fuel cell vehicles have a larger driving range, the expensive cost of material (catalyst) in fuel cells and the safety risk made electric vehicles more

suitable for the large-scale development of transportation electrification. These advantages advanced electric vehicles as the mainstream in new energy transport. On the other hand, EV vehicles still had some limitations in capacity and battery stability, which limited EV vehicles in city areas and their application in more extreme environments. By overcoming these limitations, electric vehicles could have further development as a long-distance travel option and electrification could be widely applied in aerospace.

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