Research on Hydrogen Energy and Fuel Cell Vehicle Roadmap in Various Countries

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Abstract. This paper studied the roadmap of the hydrogen energy and fuel cell vehicle (FCV) industry in the US, Japan and the EU, and summarized the development goals, promotion paths and development plans of the hydrogen energy industry in developed countries. On this basis, the development prospect of hydrogen energy and FCV industry in China is further analysed based on resource endowment and current situation of FCV industry in China. Finally, by comparing the development plans and characteristics of hydrogen energy and FCV industry in various countries, the deficiencies of hydrogen energy and FCV industry in China are found, and suggestions are put forward for the development of hydrogen energy and FCV industry in China.

1. Introduction
With the increase of global vehicle ownership, the accelerated consumption of fossil energy and the aggravation of environmental pollution have become a worldwide problem. For this reason, various countries have conducted a lot of research around the transformation and upgrading of automotive power. Electric vehicles (EVs), hybrid electric vehicles (HEVs), fuel cell vehicles (FCVs), etc. have undergone research and development in the past decades and have become the main direction of automotive power transformation. The reason why hydrogen energy is considered to be the transformation direction of automotive power is that hydrogen energy and electric energy have many similar characteristics such as zero pollution and high efficiency in the process of use. Besides, FCVs have the advantages of long driving range and short refuelling time, which is complementary to EVs [1].

Due to the increasingly prominent role of hydrogen energy in the world energy revolution, many developed countries have issued hydrogen energy roadmaps or action plans [2]. As an important application field of hydrogen energy, the R&D and promotion of FCVs have received strong support from governments of various countries. After years of development, its technical route has gradually matured, and the development of commercialization has continued to accelerate in recent years, which has great reference significance for China. This paper studies the roadmap of hydrogen energy and FCVs in developed countries such as Japan, the US and the EU, analyses the strategies and competitive advantages of various countries, and makes recommendations for the development of China’s FCV industry.

2. Hydrogen and FCV roadmap in developed countries

2.1. US
After two oil crises, the US put forward the “energy independence” strategy in the 1970s, and started research on hydrogen energy. In order to realize the vision of hydrogen energy development, the U.S. Department of Energy (DOE) released the National Hydrogen Energy Roadmap in 2002 to encourage...
companies, research institutions and industry organizations to study the hydrogen energy industry. Since then, the Bush administration has issued important documents to support the development of hydrogen energy. The hydrogen and fuel cell R&D budget reached its peak during the Bush administration. During the Obama and Trump administrations, the US government’s enthusiasm for hydrogen energy weakened, so hydrogen and fuel cells R&D budget has been reduced, but still remains at about $150 million a year [3-5].

Figure 1. DOE Hydrogen & Fuel Cells Budget History.

Under the long-term high investment of the US government, the US has maintained a world-leading position in hydrogen energy and fuel cell technology, forming a complete industrial chain and a representative enterprise with core technologies [6]. However, due to the inconsistent attitudes of previous governments on hydrogen energy, the continuity of related policies is relatively poor, and the commercialization of hydrogen energy and fuel cell technology is relatively slow [7-8]. Against the background of the acceleration of the global commercialization of hydrogen and FCVs and the maturity of technology, the Fuel Cell and Hydrogen Energy Association (FCHEA) released *Road Map to a US Hydrogen Economy* in 2019, calling on the US government to promote the development of the hydrogen economy.

| Table 1. Road Map to a US Hydrogen Economy. |
|--------------------------------------------|
| **Policy**                                 |
| 2020-2022                                  |
| Dependable, technology-neutral decarbonization goals |
| Public incentives                          |
| Hydrogen codes and safety standards        |
| Workforce development programs             |
| 2023-2025                                  |
| Policy incentives to transition from direct support to scalable market-based mechanisms |
| Implementation of decarbonization policy   |
| 2026-2030                                  |
| Transition of policy incentives in fast-following markets from direct support to scalable market-based mechanisms |
| Applications to broaden beyond transport   |
| 2030 and beyond                            |
| Reduced/no direct policy support in certain applications when reaching cost parity |
| Robust hydrogen code at federal level      |

| **Hydrogen industry**                      |
| 2020-2022                                  |
| First dedicated hydrogen production for mobility |
| Mid-scale SMR/ATR + CCUS                   |
| Mid-scale electrolyser plants (10—50 MW)   |
| 2023-2025                                  |
| First large-scale electrolyser plants (50 MW+) |
| First large scale SMR/ATR + CCUS           |
| 2026-2030                                  |
| Development of electrolytic hydrogen production with dedicated renewables and nuclear |
| 2030 and beyond                            |
| Expanding use of hydrogen, enabling further cost reduction and performance improvement |
The roadmap proposes to promote industrial development through the cooperation of government, industry and scientific research institutions. The government’s work mainly includes investment, policy formulation, and legislative supervision. Based on the existing technology, the government should continue to encourage technological research and development to ensure the safety of hydrogen use and improve product performance. At the same time, the development of the hydrogen energy industry requires large-scale hydrogen production facilities, storage and transportation facilities, and refuelling infrastructures. The construction of these facilities requires government investment. In order to increase public acceptance, it is recommended that the US government promote the development of the hydrogen energy industry including policies, regulations, technology, and infrastructure. In terms of policies and regulations, establish direct incentive policies to accelerate the early market commercialization process, improve standards and regulations, and strengthen industry supervision to ensure the healthy development of the industry. At the same time, introduce technology-neutral decarbonization goals to expand the use of hydrogen. With the continuous expansion of the market size, policy incentives transition from direct support to scalable market-based mechanisms. In terms of technology, it is necessary to develop advanced hydrogen production technologies to gradually achieve “zero emissions” in hydrogen production; develop hydrogen energy storage and transportation technologies to reduce the cost of hydrogen use; enterprises and scientific research institutions should develop advanced products and increase public acceptance. Government should increase investment in infrastructure, expand the scale of the industry, reduce the cost of hydrogen production, storage and transportation, and thus reduce the cost of end use. In addition, the construction of refuelling station should be accelerated to prevent infrastructure from becoming a factor hindering industrial development.

2.2. Japan
The R&D of FCVs in Japan began in the 1990s. Japanese automobile companies such as Toyota and Honda have successively carried out R&D of FCVs by virtue of rich technological accumulation and the pursuit of innovation. With the successful launch of the Toyota Mirai in 2014, Japanese government accelerated the promotion of the development of the hydrogen energy industry. In 2014, the Ministry of Economy, Trade and Industry of Japan (METI) released The Strategic Road Map for Hydrogen and Fuel Cells and Basic Hydrogen Strategy, then released Basic Hydrogen Strategy in 2017, announcing that Japan will realize a “Hydrogen Society” in 2050 [9-10]. In 2019, METI revised The Strategic Road Map for Hydrogen and Fuel Cells to match the Basic Hydrogen Strategy and formulated more detailed technical goals.
Table 2. Basic Hydrogen Strategy.

|                | 2017 | 2020 | 2030 | Future                  |
|----------------|------|------|------|-------------------------|
| Hydrogen supply|      |      |      |                         |
| Hydrogen from fossil fuel | 10 $/kg | Below 3 $/kg | Below 2 $/kg |
| FCV            | 2500 | 40,000 | 800000 | Replace conventional gasoline mobility |
| FC bus         | 2    | 100   | 1200  | Introducing large FCVs |
| FC forklift    | 40   | 500   | 10000 | Replace traditional residential energy systems |
| Refuelling station | 100  | 160  | 900   |                         |

Table 3. The Strategic Road Map for Hydrogen and Fuel Cells.

| Target                      | Action plan                                                      |
|-----------------------------|------------------------------------------------------------------|
| Hydrogen supply             | The success of Japan-Australia Brown Coal-to-Hydrogen project.    |
| Fossil fuel +CCS            | Scaling-up and improving efficiency of brown coal gasifier.       |
| Green hydrogen              | Enables highly efficient hydrogen liquefaction.                   |
| Establishment of the technology of hydrogen production from Renewable energy | Low-cost CO₂ capture technologies.                               |
| FCV                         | Expansion of the demonstration in model regions for social deployment utilizing the achievement in the demonstration. |
| Achieving a cost reduction of FCV to the level of HV around 2025 | Development of electrolyser with high efficiency and durability. |
| Reducing cost of main elemental technologies around 2025 | Development of supply chain utilizing local resources. |
| Hydrogen refuelling station (HRS) | Sharing technical information and problems.                           |
| Reduction of cost for construction and operation by 2025 | Reducing the amount of platinum used.                              |
| Setting of cost target for each component | Reducing of amount of carbon fiber in hydrogen storage systems. |
| Expansion of regions where FC buses run | Thoroughly integrate promotion of regulatory reform and technological development. |
| Reducing FC bus’s price by half | Consideration for nation wide networking of HRS.                  |
| Expansion to overseas markets | Extending opening hours.                                           |
| FC bus                      | Increasing of the number of HRS with gasoline station/convenience store |
| Expansion of types other than city buses | Developing technology for enhancing the fuel efficiency and durability of such vehicles. |
| FC forklift                 | Promotion of deployment of HRS for FC buses.                       |

Constrained by energy resources, Japan faces the problem of high hydrogen use cost. Therefore, the main plans of Japan’s hydrogen energy strategy is to obtain cheap hydrogen energy, reduce the cost of hydrogen energy industry, and expand the application of hydrogen energy. In terms of hydrogen energy supply, Japan will establish an overseas supply chain to obtain cheap hydrogen or raw materials for
hydrogen production. At the same time, it will implement a “Power-to-Gas” strategy to develop low-cost electrolytic hydrogen production technology and realize domestic low-cost renewable energy hydrogen production in 2032. In order to reduce hydrogen use cost, Japan will develop low-cost hydrogen energy storage and transportation technology to reduce the transportation cost of imported hydrogen. In terms of hydrogen energy use, FCVs are Japan’s key promotion direction, and fuel cell passenger cars are the mainstay. Therefore, the Japanese government will accelerate the construction of refuelling station, reduce the purchase and use costs of vehicles, and realize the replacement of traditional fuel vehicles by FCVs in 2050 [11-12].

2.3. EU

In 2019, FCH-JU released the Hydrogen Roadmap Europe, proposing that hydrogen energy has huge economic, social and environmental benefits for Europe, and planned the development route of the European hydrogen energy industry in the next 30 years. Based on two scenarios of “ambitious” and “business as usual”, the report shows the development prospect of hydrogen and FCVs in Europe [13].

Mass market acceptability is defined as sales >1% within segment as shown in Figure 2. In ambitious scenario, buses are expected to be the first to gain market acceptability in 2020, while heavy trucks and small cars may take 10 years to develop. In business as usual scenario, taxis, trucks, trams, etc. are expected to be accept by the market in 2030, and passenger cars are difficult to promote in a short period of time. With the promotion of FCVs, the number of refuelling stations will also increase. There are currently 120 refuelling stations in Europe. In ambitious scenario, the number of refuelling stations will reach 3750 by 2030, with a total investment of 8.2 billion euros. This number will reach 33,000 by 2050, with a total investment of 27.5 billion euros.

Table 4. Hydrogen Roadmap Europe.

|                  | 2030   | 2050   |
|------------------|--------|--------|
| **FCV**          |        |        |
| Small car        | 0%     | 14%    |
| Larger car       | 2%     | 28%    |
| Taxis            | 8%     | 57%    |
| Vans/LCVs        | 3%     | 30%    |
| Buses            | 2%     | 25%    |
| Trucks           | <1%    | 21%    |
| **Refuelling station** | 3750  | 33000  |
| **Investment**   | 8.2 billion euro | 27.5 billion euro |

In terms of hydrogen energy supply, steam methane reforming (SMR)+CCS technology and electrolytic water hydrogen production technology will be the main hydrogen production technologies in Europe in the future. SMR+CCS technology can reduce CO₂ emissions by up to 90%. It has the advantages of low cost and large-scale hydrogen production, and is the main hydrogen production method used in the transition from traditional energy to hydrogen energy. Hydrogen production by electrolyzed water has the advantages of pollution-free and distributed development, and it is expected to significantly reduce costs in the long term. It is suitable for small hydrogen supply sites such as refuelling stations, so it also has development potential.
Europe has many powerful automobile companies, and the R&D of FCV started early. The European Commission and the European Industry and Research Organization launched a public-private joint fuel cell and hydrogen energy action plan (FCH JU) in 2008 to support the development and demonstration of hydrogen and fuel cells in Europe. Hydrogen Roadmap Europe pays more attention to the energy transition in Europe and the economic, social and environmental benefits that hydrogen can bring to Europe.

3. FCV Industry situation in China

It is found that the ultimate goal of the hydrogen energy roadmap in developed countries is to promote energy transition, expand the application of hydrogen energy, and finally achieve the leading role of hydrogen energy in the energy structure. Regarding the application of hydrogen energy, FCH JU predicts that in Europe, hydrogen energy consumed in transportation will account for 30% of total hydrogen energy in 2050, and FCHEA estimates that this proportion will reach more than 40% in the US. It can be seen that FCVs will become an important application area for hydrogen energy. Due to the huge differences in natural resources and technologies in different countries, the marketization processes in different countries are also different. This section analyses China’s resource endowment and the status quo of the FCV market, and analyses the prospects for the commercialization of FCVs in China.

3.1. Resource endowment

In China’s energy production structure in 2017, raw coal accounted for 68.6%, crude oil accounted for 7.6%, natural gas accounted for 5.5%, hydropower, nuclear power and wind power accounted for 18.3% [14]. The energy structure of “rich coal, lean oil, and low gas” has resulted in China’s current reliance on coal gasification to produce hydrogen. With the transformation of China’s energy consumption structure, the proportion of coal in the energy consumption structure will continue to decline, and the proportion of clean energy will increase [15].

![Figure 3. Hydrogen costs from hybrid solar PV and onshore wind systems in the long term [16].](image)

According to the report released by the IEA: China’s central and western regions are rich in solar and onshore wind energy resources and have great potential for using renewable energy to produce hydrogen. As the cost of electrolyzed water equipment decreases, the cost of hydrogen from renewable sources in China is expected to fall below 1.6 $/kgH₂, as shown in Figure 3 [16]. Therefore, hydrogen from coal+ CCS technology can guarantee the recently increased demand for hydrogen in China, and the hydrogen production process is relatively environmentally friendly. In the long run, China’s use of renewable energy for electrolytic hydrogen production has more development potential and can accelerate China’s transition to clean energy.

3.2. FCV market situation in China

The development of FCVs started late in China, but as the world’s largest automobile market, China has unique advantages in developing FCVs and has made many breakthroughs in demonstration applications. By the end of 2019, China had sold 2,737 FCVs, increased by 79.2% from a year before. A total of 66 refuelling stations have been built, of which 46 have been put into operation [18].
The commercialization of FCVs in China has been accelerated significantly in recent years, as shown in Figure 4. The important reason is the strong support of the government (Table 5). The 2019 Chinese Government Work Report mentioned promoting the construction of refuelling stations for the first time, and the new energy vehicle development plan (2021-2035) (draft for comment) mentioned promoting the commercial operation of FCVs and accelerating the construction of refuelling stations. At the same time, a number of local governments have also issued FCV development plans and launched FCV demonstration operation projects.

![Figure 4. The sale volume of FCV in China.](image)

Table 5. FCV policies in China.

| Date     | Policy                                                                 | Content                                                                 |
|----------|------------------------------------------------------------------------|------------------------------------------------------------------------|
| 2009.03  | **Auto Industry Adjustment and Revitalization Plan**                   | Support the development of NEV, including FCV.                         |
| 2012.06  | **Energy Saving and New Energy vehicle Industry Development Plan (2012-2020)** | Catch up with advanced technology in hydrogen and FCV industry.         |
| 2016     | **Technology Roadmap for Energy Saving and New Energy Vehicles**       | FCV development goals from 2015-2025.                                  |
| 2017.05  | **Medium- and Long-term Development Plan of Automobile Industry**      | Encourage to intensify R&D of FCV.                                     |
| 2019.03  | **2019 Government Work Report**                                        | promote the construction of refuelling infrastructures.                |
| 2019.12  | **Development Plan of New Energy Vehicle Industry (2021-2035) (draft for comments)** | promote the commercialization of FCV, develop refuelling infrastructures, encourage innovation and technology breakthrough. |

With the strong support of the government, the scale of FCV market in China has increased significantly. By July 2019, 905 FCVs have been put into demonstration operation in Shanghai, and 768 FCVs have been put into demonstration operation in Foshan. Zhangjiakou has taken the opportunity of the Winter Olympic Games to promote FCVs, and 174 FCVs have been put into demonstration operation [19].

3.3. Prospect of FCV in China

The commercialization of FCVs in China is in its infancy. The main driving force for the promotion of FCVs at this stage is government incentives and demonstration operation projects, so commercial vehicles are the mainstay. According to planning goals of Technology Roadmap for Energy Saving and New Energy Vehicles, China will start the promotion from fuel cell commercial vehicles, gradually increase the number of fuel cell passenger vehicles, and accelerate the construction of hydrogen supply systems and refuelling stations.
### Table 6. FCV development goal in China [17].

| Overall target | 2020 | 2025 | 2030 |
|----------------|------|------|------|
| Small-scale demonstration and application of 5,000 public service vehicles in specific areas | A large number of applications accumulated to 50,000 in the field of private vehicles and public service vehicles | A total of 1 million private passenger cars and commercial vehicles have been commercialized on a large scale |
| Renewable energy distributed hydrogen production; co-oven gas and other by-product hydrogen production. | Efficient and low-cost hydrogen separation and purification technology. | Renewable energy distributed hydrogen production |
| Hydrogen supply | Hydrogen transportation | Refueling station |
| High pressure gaseous hydrogen storage and transportation | Cryogenic liquid hydrogen transport | 100 | 350 | 1000 |

At present, the cumulative promotion of FCVs in China has exceeded 5,000, which is currently completed in advance by 2020, but the construction of refuelling stations has not yet reached the target. In addition, China should increase its investment in the hydrogen supply system and continuously improve its industrial base in order to achieve the goals of scale in early 2025 and large-scale promotion in 2030.

### 4. Enlightenment to hydrogen and FCV industry in China

According to the roadmaps of hydrogen energy and FCVs in various countries, the following conclusions can be made:
Table 7. Comparison of roadmaps.

| Country | Characteristic | 2030 target |
|---------|---------------|-------------|
| US      | The technology is advanced but the marketization process is slow, so the roadmap focuses on applications such as FCVs | Hydrogen supply: FCV 5,300,000, FCV forklift 300,000, Refueling station 5,600 | Hydrogen production: hydrogen from NG, nuclear and renewable resources, Transportation: focus on pipeline |
| Japan   | Aiming at a hydrogen society, the emphasis is on FCVs replacing fuel vehicles and FCV exports. Passenger vehicle technology has advantages. | Hydrogen supply: FCV 800,000, FCV forklift 10,000, Refueling station 900 | Hydrogen production: import fossil fuel or hydrogen, hydrogen from renewable resources, Transportation: Low-cost liquid hydrogen transport |
| EU      | Focus on the social, economic, and environmental benefits of hydrogen, and hope to drive European economic growth. Optimistic about the application of hydrogen in long-distance and heavy-duty vehicles | Hydrogen supply: FCV One in 12 are commercial vehicles, one in 22 are passenger vehicles, 45,000 trucks and vans | Hydrogen production: hydrogen from NG, renewable resources |
| China   | There is a certain gap between technology and developed countries, but the development speed is relatively fast. At present, commercial vehicles are mainly used. | Hydrogen supply: FCV Refueling station 3750 | Hydrogen production: hydrogen from coal, renewable resources, Transportation: combination of multiple methods |

In contrast, the US, Japan, and the EU have all established the important position of hydrogen energy in the energy system, and FCVs are an important area for hydrogen energy applications. Although China has determined its support for FCVs, it has not paid enough attention to the hydrogen energy industry, which may easily lead to lack of infrastructure. In addition, China’s planning for the number of hydrogen refuelling stations is obviously too small. In 2030, the planned number is only 100 more than that of Japan, and China’s land area is almost 25 times that of Japan. The number of hydrogen refuelling stations is closely related to the promotion of FCVs. China should increase the number of infrastructure plans and accelerate infrastructure construction. Finally, China’s fuel cell core technology still has a large gap compared with developed countries [20], and should follow the establishment of institutions such as FCH-JU and FCHEA, and set up special hydrogen and fuel cell industry R&D institutions to increase technology investment, break through the bottleneck of industrial development and narrow the gap with developed countries.

5. Conclusion
Based on the above analysis, this paper believes that China’s hydrogen energy and FCV industry has begun to take shape, but it is still not sustainable. The government should clarify the position of hydrogen energy in China’s energy structure and determine the development route and application scope of the hydrogen energy industry. In the future, China should increase investment in technology research and development and infrastructure construction, set up hydrogen and FCV industry R&D institutions to fund the development of advanced technologies, and accelerate the construction of hydrogen energy.
production, storage, transportation, and refuelling infrastructure construction to promote industrial development.

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