ENGLISH VERSION

Hydrogen Fuel Cell Vehicle Technology Roadmap

Developed by the

Strategy Advisory Committee of the Technology Roadmap for Energy Saving and New Energy Vehicles

SAE CHINA 中国汽车工程学会 Society of Automotive Engineers of China

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Preface

On May 8, 2015, the Chinese Government published《中国制造 2025》- “Made in China 2025,” a 10-year plan by the Chinese Central Government to comprehensively upgrade China’s manufacturing industry. The Plan highlights 10 priority sectors, including New-Energy Vehicles and Equipment.

Based on the above New-Energy Vehicles and Equipment Plan outlined in “Made in China 2025”, in October 2016 the Strategy Advisory Committee of the Technology Roadmap for Energy Saving and New Energy Vehicles and the Society of Automotive Engineers of China (SAE-China) jointly published the *Energy Saving and New Energy Vehicle Technology Roadmap*, the Chapter 4 of which is the Hydrogen Fuel Cell Vehicle (FCV) Technology Roadmap.

This booklet is the English version of the above FCV Technology Roadmap, which is for reference only and the original Chinese version shall prevail.

CONTENTS

ACRONYMS

BEV	Battery Electric Vehicle
EV	Electric Vehicle
FC	Fuel Cell
FCV	Fuel Cell Vehicle
FCEV	Fuel Cell Electric Vehicle
HRS	Hydrogen Refueling Station
ICE	Internal Combustion Engine
LOHC	Liquid Organic Hydrogen Carrier
MEA	Membrane Electrode Assembly
NEV	New Energy Vehicle
PEM (FC)	Proton Exchange Membrane (Fuel Cell)
PHEV	Plug-in hybrid electric vehicle
RD&D	Research, Development and Demonstration
T&D	Transportation & Distribution
UPS	Uninterruptible Power Supply

1 INTRODUCTION

1.1 STRATEGIC SIGNIFICANCE OF THE DEVELOPMENT OF HYDROGEN FUEL CELL VEHICLES IN CHINA

Hydrogen, used to power fuel cell vehicles (FCVs), can be produced from multiple fossil sources (such as coal, petroleum, natural gas, etc.) as well as non-fossil and renewable sources (such as solar, wind, hydro power, etc.).

Hydrogen as an energy carrier can be stored in large quantities, distributed through pipelines and tank trucks, and permits relatively quick refueling. These characteristics enable hydrogen to be complementary with electricity for future energy framework that is zero-emission and uses multiple sources of energy. Together, hydrogen and electricity will provide the necessary energy for transportation, domestic and industrial applications.

Hydrogen fuel cells are energy conversion devices that generate electricity through an electrochemical reaction between hydrogen and oxygen from air. The process doesn’t involve high-temperature combustion, and the only discharge is pollution-free water. As long as hydrogen is supplied, fuel cells will provide continuous electrical energy.

The development of FCVs will have significant importance to China’s future energy security and provide low-carbon emission transportation. In addition, it will enhance China’s technical innovation, global competitiveness, and sustainable development of auto industry.

1.2 THE STUDY SCOPE AND GOALS OF CHINA’S FCV TECHNOLOGY ROADMAP

Based on China’s Key Fields Technology Roadmap of *Made in China 2025*, the Hydrogen Fuel Cell Vehicle Technology Roadmap describes FCVs’ development history, current status, and outlook. The Roadmap discusses China’s overall objectives and strategies, along with corresponding technical innovation requirements and priority action plans for its FCV development. The Roadmap provides a reference guide at this strategic time for China to accelerate its auto industry’s transition and development, a key pillar in China developing an advanced economy in manufacturing.

The FCVs discussed in this Chapter have the characteristics below, and don’t include those vehicles powered by fossil fuels or generating hydrogen on the vehicle from fossil fuels.

- Hydrogen stored on the vehicle as the primary energy source;
- Electricity generated from hydrogen chemical energy by proton exchange membrane fuel cells (PEMFC);
- Electric motor-driven vehicles; and
- Used for transportation.

The Technology Roadmap in this Chapter covers four areas:

- Fuel cell stacks, including key materials and components;
- Fuel cell system, including fuel cell engines for commercial vehicles and passenger cars;
- Fuel cell vehicles, including commercial vehicles and passenger cars; and
- Hydrogen technology, including hydrogen infrastructure and on-board storage system.

2 HYDROGEN FUEL CELL VEHICLES - CURRENT & FUTURE TECHNOLOGY DEVELOPMENT

2.1 CURRENT STATUS OF FCV TECHNOLOGY DEVELOPMENT

2.1.1 FCV Development Review

Hydrogen fuel cell vehicles (FCV) generally experience four phases of development:
- Before 2000: FCV concept design, demonstration and testing of the basic principles, and validation;
- 2000-2010: extensive FCV R&D as well as technology validation and demonstration;
- 2010-2015: early commercial niche-market deployment; and
- After 2015: early commercialization with passenger FCVs' first selling to private users in selected areas.

Before 2000, FCVs were first introduced to the global market as concept vehicles. Representative models included the Daimler-Chrysler *NECAR* 1/2/3 - a series of three FCV concept models (1994-1997), the Toyota *FCHV* 1/2/3 hybrid FCV concept models (1997 -2001), the Honda *FCX* V1/2/3/4 FCV concept models (1999-2001), and the GM *HydroGEN* 1/2/3 FCV concept models (2001-2004).

After 2000, passenger FCVs were introduced to the market by leasing for drivers to gain customer experience. These vehicles, in the order of market release time, included the Honda *FCX* FCV (2002-2007 in California & Japan), Ford *Focus*' FCV version (2003-2006 in California, Florida & Canada), Nissan *X-Trail*'s FCV version (2003-2013 in California & Japan), Mercedes-Benz *F-Cell* (2005-2007 released globally), and GM Chevrolet *Equinox* FCV (2007-2009 in California & New York metropolitan area).

During the same period of passenger FCV leasing, dozens of hydrogen fuel cell (FC) buses around the world conducted commercial demonstration, including:
- The EU HyfleetCUTE project (2003-2010), which included 33 Mercedes-Benz *Citaro* FC Buses - in nine EU cities, Beijing (China), and Perth (Australia);
- Bus commercial demonstration globally in multiple cities (2003-present);
- The Japan JHFC project (2002-2010); and
- The U.S. FC bus demonstration project (2006-present).

During 2010-2015, FCV technology successfully expanded its commercial applications in niche fields. From 2010, hydrogen fuel cell systems were deployed increasingly in materials handling and logistics by the U.S. retail and food wholesale companies such as Wal-Mart, Coca-Cola and Sysco Corporation. As of 2015, there were more than 8,000 hydrogen fuel cell forklifts operated by 34 enterprises. Due to its cost-effectiveness, those FC forklifts purchased without government incentive outnumbered 10 times those with government subsidiary, which provided positive technology and commercial guidance for market-tested commercialization.

From 2015, fuel cell passenger cars entered into early commercialization, marked by its debut of sales to private users in selected areas. For example, Toyota introduced the passenger FCV *Mirai* in Japan, the U.S. and Europe in 2015; and Honda launched passenger FCV *Clarity* to the Japanese market in 2016.

2.1.2 Current Status of Hydrogen Fuel Cell Vehicles

Current FCV development shows major international automakers generally have completed FCV functional and performance development with overall FCV performances equivalent to traditional vehicles. Major technical issues identified during the demonstration stage have been resolved. Future Research and Development will focus on fuel cell power density and lifespan, cold start performance, fuel cell system cost reduction, hydrogen infrastructure scale up, and fuel cell application expansion and commercialization.

1. FCV overall performance meets basic commercial demonstration requirements.

   FCVs' reliability, economy and convenience have already met commercial deployment requirements. Demonstration in multiple cities in North America shows hydrogen fuel cell buses' overall performance, power-train, and fuel cell system reliabilities have already met commercial criteria. For example, Mean Distance between Failures (MDBF) of hydrogen fuel cell systems have exceeded 50,000 km. Demonstration and tracking data from fuel cell forklifts and logistics vehicles indicates fuel cell system durability has exceeded 10,000 hours.

   The performance of fuel cell passenger cars has approached customer acceptance criteria. For example, Toyota *Mirai* FCV can finish hydrogen refuelling in about three minutes for 650 km driving. In 2015, the hydrogen fuel cell engine was listed for the first time by Wards Auto as the world's best engines for mass-production vehicles.

2. Fuel cell stack technology now meets the basic vehicle requirements.

   Fuel cell power density has already met vehicle power requirements after continuous improvement. For example, the power system of Honda 2015 *FCX Clarity*, compared with its 2005 model, has demonstrated significant improvements.

3. Hydrogen infrastructure construction in parallel with FCV development, and ahead of commercial requirements.

   A number of countries have developed hydrogen infrastructure plans to meet FCV deployment requirement, including
   - Japan will increase hydrogen refueling stations along Nagoya-Tokyo-Osaka-Fukuoka from existing 100 to 1,000 stations by 2025, as well as complete nation-wide hydrogen refueling infrastructure by 2030;
   - Korea had 13 completed hydrogen refueling stations in 2015, and is expected to have total 168 hydrogen stations by 2020;
   - USA will complete at least 84 hydrogen refueling stations by 2017.

2.1.3 FCV Development Trend and Outlook

Major international automakers will continue R&D investment in next generation fuel cell technology to further reduce FCV production costs and improve vehicle reliability and durability. Meanwhile, FCV development has shown the following trends in the horizon.

1. Fuel cell modularization and serialization.
   Fuel cells stacks are being modularized to improve reliability and durability and reduce costs. The combination of single fuel cell module - each with defined power range - will enable the stacks to meet power grade requirements for various vehicle applications.

2. Electrification of hydrogen fuel cell electric vehicle (FCEV) power system.
   In contrast to the original power architecture of only using the fuel cell stack to power the vehicle, today hydrogen fuel cell vehicles have adopted a hybrid power-train system (i.e., hydrogen fuel cell and battery) for fuel cell durability and vehicle cost reduction. This hybrid design initiated by Chinese researchers has been adopted widely.

3. On-board hydrogen storage as energy carrier from multiple sources.
   After years of development, onboard hydrogen production by fossil fuel reforming has not proven to be commercially viable. On-board hydrogen

storage, mainly in high pressure 70MPa (approx. 10,000 PSI), has been adopted widely. Hydrogen is produced from a diverse range of sources that are available locally.

4. FCV industry alliance and collaboration
   Traditional automakers in most cases developed hydrogen fuel cell technology by themselves. However, this type of in-house development has rapidly evolved into a new win-win business model, with deep technology integration and extensive collaboration between fuel cell developers and automakers.

2.2 CURRENT STATUS OF FCV DEVELOPMENT IN CHINA

Supported by the key projects of the following three sequential national “Five-Year” Plans, China has made significant progress in FCV research development, through close collaboration between academia, research and industry.

- 10th Five-Year: “Electric vehicle” science and technology special project;
- 11th Five-Year: “Energy-saving and new-energy vehicle” key project;
- 12th Five-Year: “Electric vehicles critical technology & system integration” key project

2.2.1 Hydrogen Fuel Cell Vehicles

Based on power-system technology platforms of fuel cell passenger cars and buses, China has developed five FC passenger car models and three FC bus models. With manufacturing capability of power system platform (100-units scale) and FCV production, Chinese automakers have entered the global market, and participated in the following international events.

- 2008 Summer Olympics (Beijing)
- World Expo 2010 (Shanghai)
- Hydrogen fuel cell bus commercial demonstration project - supported jointly by the Global Environment Facility (GEF) and the United Nations Development Programme (UNDP)
- 2010 Summer Youth Olympics (Singapore)
- Demonstration project in California

Technical specifications of above fuel cell passenger cars include maximum speed 150 km/hr, 0-100 km/hr acceleration in 14 seconds, and vehicle range 300 km. The power system platform has been deployed on SAIC *Shanghai*, VW *Passat*, FAW *Besturn*, Changan *Z-SHINE*, Chery *EASTAR*, and other FCVs, which participated in the following demonstration projects.

- 2008 Summer Olympics (Beijing)
- 2009 demonstration project in California
- 2010 World Expo (Shanghai)
- 2010 Asian Games (Guangzhou)

For fuel cell buses, Chinese self-developed fuel cell power system platform has been used on Foton Motor, Suzhou King Long, and Shanghai Volvo. These FC buses have participated in the demonstration during 2008 Beijing Olympics, 2010 Shanghai World Expo, and Singapore 2010 Youth Olympics, as well as completed one-year transit service in Beijing. The results have verified FC bus' power performance, fuel economy (hydrogen 8.5 kg/100km) and reliability.

In 2008 three fuel cell buses successfully completed demonstration projects for the Beijing Olympics as well as one-year public transit services in Beijing (as shown in Figure 2-1), reaching cumulative distance over 60,000 km. The demo fleet of these three fuel cell buses, along with other Chinese fuel cell buses, has highlighted "High-Tech Olympics and Green Olympics," contributing significantly to China's energy efficient and new energy vehicle development.

Figure 2-1: Hydrogen fuel cell buses demonstrated during 2008 Beijing Olympics and public transit services in Beijing

For fuel cell passenger cars, in 2008 a demonstration fleet of 20 FC cars successfully completed 66-day public transit services for the Olympics, despite of unfavorable hot and rainy weather conditions and frequent start-stop urban traffic. In 2009, 16 VW *Passat* FC cars, after their 2008 Olympics demonstration, went to Sacramento in California to participate in an international demonstration operating for six months.

Figure 2-2 on the next page shows a FC bus and a FC passenger car at New Energy Vehicle demonstration during 2010 World Expo in Shanghai. A fuel cell passenger car fleet, including SAIC's *Shanghai*, VW *Passat*, FAW *Pentium*, Changan *Z-Shine* and Chery *Eastar*, participated in China's largest fuel cell demonstration. Through international competitive bidding, Shanghai Automotive Industry (Group) Corporation was selected to provide six fuel cell hybrid buses for Shanghai City.

These hydrogen fuel cell buses carried total 1.83 million passengers with cumulative distance 910,000 km. Hydrogen consumption is 0.912 kg/100km (excluding electricity charge) for passenger cars, 1.375 kg/km for sightseeing cars, and 9.8 kg/km for buses.

During 2010 Youth Olympics in Singapore, Chinese self-developed hydrogen fuel cell city buses successfully completed the opening ceremony and field operation, and served as the official new energy demonstration vehicles for the Youth Olympics - marking China's first fuel cell bus export.

Figure 2-2 Hydrogen fuel cell bus and passenger car during Shanghai World Expo (2010)

2.2.2 FCV Power Systems

Chinese automakers have succeeded in FCV power system integration, control and integration, and established a complete R&D system that encompasses key components and parts for fuel cell system, battery system, DC/DC converter, drive motor, and hydrogen storage and supply. China has realized power system integration with overall technology close to international leading level.

Led mainly by the following R&D teams at Tongji and Tsinghua Universities, the development of fuel cell power system platforms for passenger cars and buses in China has made significant progress.

- FC cars - A team at the Clean Energy Automotive Engineering Center at Tongji University developing hydrogen fuel cell passenger car power systems
- FC buses - A team at the State Key Laboratory of Automotive Safety and Energy at Tsinghua University developing hydrogen fuel cell bus power systems

The power system architecture for fuel cell passenger cars adopts hybrid (fuel cell and power battery) system plan, with integrated power train system platform and capacity of thousand units. For fuel cell buses, the hybrid (fuel cell and battery) power system platform has resolved bottleneck problems such as regenerative braking, integrated electrical and thermal management of power battery system, and dual fuel cell stacks' independent running. In addition, China have developed "collision-hydrogen-electric" multi-coupling safety system and completed the world's first "hydrogen-electric" vehicle crash test for buses.

2.2.3 Fuel Cell Stacks

Chinese companies have developed key fuel cell technologies in materials, components and stacks, and established a complete fuel cell technology platform using Chinese developed intellectual property. Domestic fuel cell stacks have realized power density 2.0kW/L, cold start at -20°C, and on-road lifespan over 3,000 hours for passenger cars.

Chinese main research institutions and universities engaged in auto fuel cell technology development include Dalian Institute of Chemical Physics (DICP), Wuhan University of Technology, Tsinghua University, Shanghai Jiaotong University, Tongji University, and Central South University. Supported by its National Science and Technology Development Plans, China has made significant progresses in fuel cell key materials, components and stacks. Judging from academic publications, Chinese research in fuel cell key indicators such as catalysts, carbon paper, membrane electrode assembly (MEA) and bipolar plate are close to international level.

Major Chinese companies engaged in fuel cell technology development include Sunrise Power Co., Ltd., Shanghai Shen-Li High Tech Co., Ltd., and Wuhan WUT New Energy Co., Ltd. Key technical indicators of their products in proton exchange membrane, catalyst, carbon paper, membrane electrode assembly, and bipolar plate are close to international level.

However Chinese FCV industry hasn’t adequately utilized these domestic fuel cell products and technology, and there is no sufficient finished products in batch production. As a result, China mainly imports key fuel cell materials and components and lacks an entire fuel cell supply chain. With limited investment and few domestic companies manufacturing fuel cell stacks, China has fallen behind the international level in stack technology development and manufacturing capability.

2.2.4 Hydrogen Infrastructure

Chinese companies have developed 35MPa hydrogen refueling station (HRS) design and construction capabilities, both for mobile and stationary stations. China has made significant progress in key refueling equipment manufacturing, and development of HRS codes and standards. So far China has three HRS in operations, located in Beijing, Shanghai and Zhengzhou, with 35MPa delivery pressure. The Beijing station has three types of hydrogen supply (i.e., external hydrogen supply, on-site natural gas reforming, and electrolysis); the Shanghai one only has external hydrogen supply by local industrial by-product gas.

Hydrogen generation in China is mainly from coke-oven and industrial by-product gases, and renewable resources such as wind, solar and hydroelectric.

2.3 KEY TECHNOLOGY AND BOTTLENECK FOR FCV INDUSTRIALIZATION

2.3.1 Key technology analysis for FCV industrialization

FCV commercialization requires power system performance, durability and costs to be comparable to traditional internal combustion engine vehicles, and competitive with battery powered electric vehicles.

1. Power density (or power-to-weight ratio), an important fuel cell power output indicator, has the most important impact on FCV miniaturization, weight and cost reduction. Published data from various resources show current fuel cell stack's power density has reached or even surpassed commercial requirements. However for the following two reasons major automakers remain their focus on power density further improvement.
   - Higher power density reduces fuel cell stack dimension, and provides more freedom for fuel cell power system to maintain its optimal operating conditions;
   - Higher power density reduces required fuel cell materials per unit power, and reduces cost.

   Better fuel cell stack power density can be attained by enhancing rated working current and thinning metal bipolar plate, especially through synchronized structure optimization of membrane electrode assembly (MEA) and bipolar plate flow field to effectively reduce fuel cell mass transfer polarization - which enables the output power of the same-size fuel cell stack to increase substantially due to rated working current improvement.

   In addition, technology development in sheet metal stamping and surface modification has made it possible for a metal bipolar plate to be used in fuel cell stacks, with the same power output to significantly reduce weight and volume and therefore improve power density.

2. Lifespan (durability) is an essential indicator of fuel cell power system performance, and 10% performance degradation after 5,000 working hours (passenger vehicles at average speed 40 km/hr, equivalent to 200,000 kilometers) is an acceptable criterion. Current research shows the durability of key fuel cell materials and components, such as membrane electrode assembly (MEA), bipolar plate, and sealing materials, are some key factors on stack lifespan.

Most research attention has focused on MEA because of the following two technical challenges:

- Higher electrical output requires thinner proton exchange membranes, which increase membrane's mechanical and chemical degradation;
- Cost reduction requires membrane electrode assembly loading with less precious metal catalysts, composites or even non-precious metal catalysts, resulting in insufficient or uneven electrode reactions, or catalytic layer structure instability.

Research attention has also given to metal bipolar plates for higher stack power density. Plate surface modification for corrosion resistance and durability improvement will make plates no longer the bottleneck of stack lifespan.

3. System structure optimization and water management are effective in fuel cell stack durability improvement. A typical case is the United Technologies Corporation's (UTC) large-bus demonstration in U.S., which, as of June 2015, has surpassed 19,000 hours on road operating without any parts replacement.

   In addition, complexities of driving conditions, including temperature variations from -30°C to 40°C, diverse traffic conditions and various air pollutants, also have significant impact on stack lifespan. Therefore, to establish a better understanding of co-relation between stack lifespan and its structures and systems under various environments will enable stack design optimization, and ensure the stack operating under optimal conditions and lifespan improvement.

4. Cost is the primary indicator of fuel cell system development. The U.S. Department of Energy (in its 2015 Fuel Cell System Cost Report) estimates the average cost for vehicle's 80kW fuel cell system is US$ 53/kW (based on 500,000 units per year), among which stack accounts for US$ 26/kW. Cost sensitivity analysis shows key cost factors include membrane electrode assembly's power density, precious platinum usage, and membrane cost. Main cost reduction approaches include:
   a) Stack power density improvement through research on stack mass transfer mechanisms, model optimization of stack water management, and stack key materials design and development;
   b) Development of less expensive metal materials and simplifying surface modification coatings for bipolar plate cost reduction, a key factor contributing to stack total cost; and
   c) In current fuel cell system cost structure, key components of auxiliary system account for US$27/kW. Air compressors, hydrogen recirculation systems, and humidifiers are also key cost factors. Therefore it's necessary to develop self-humidifying technology and simplify system design, with no or less humidifiers for hydrogen recirculation systems.

2.3.2 China’s Major Limitations in FCV Development

China’s main FCV development limitations include fuel cell durability, critical materials, key components, and hydrogen supply.

1. Fuel cell durability
   Fuel cell system lifespan, for example for fuel cell passenger cars, must reach 3,000-5,000 hours to meet commercial requirement. The lifetime of most Chinese fuel cell products is in 3,000 operating-hours level, while latest global technology has surpassed 5,000 hours.

2. Key materials and components
   Chinese companies are relatively weak in critical materials and components such as fuel cell electro-catalysts, proton exchange membranes and carbon paper, which are still in laboratory or prototype stages. Besides, there is no Chinese supplier in air compressors, hydrogen recirculation pumps and other key components, which has slowed down China’s vehicle fuel cell stack development.

3. Hydrogen storage
   Hydrogen tanks used in China are metal-liner and full carbon-fiber wrapping (type III) with hydrogen storage density (i.e. kg H_2/kg system) of 3.9% under operating pressure 35MPa (approx. 5,000 PSI). With pressure increasing to 70MPa (approx. 10,000 PSI), hydrogen storage density can enhance to 5.0%. For 70MPa type III tank, China has R&D results yet no finished products.

   Comparing with type III, polymer-liner and full carbon-fiber wrapping tank (type IV) can further improve hydrogen storage density up to 5.5%. So far no Chinese company possesses this manufacturing technology. In addition, organic liquid hydrogen storage is another R&D direction worthy of attention. China has some basic research in this area, yet lacks product demonstration and validation.

3 VISION & GOAL OF HYDROGEN FUEL CELL VEHICLE DEVELOPMENT

3.1 CHINA’S VISION OF FCV DEVELOPMENT

The vision of hydrogen fuel cell vehicles (FCV) development worldwide is to promote national or regional energy security, reduce carbon emissions, and mitigate climate change. In China, FCV development will also help the country resolve its environmental pollution issues due to urban vehicle traffic, and increase its auto industry’s global competitiveness.

China’s target for FCV development is to deploy one million FCVs by 2030, and zero emission by 2050 through joint development of FCVs and electric vehicles.

The strategy is to develop low-carbon energies and high-efficient power system electrification through FCV collaborative development with pure electric vehicles. The goal is to realize energy security through vehicles powered by multiple energy sources, with zero emissions to improve local urban air quality and reduce global climate change through a low-carbon energy system.

3.2 FCV DEVELOPMENT GOAL

In according with China's Technology and Industrial Development Strategy, Table 3-1 shows Chinese development goal for hydrogen refuelling stations (HRS) and fuel cell vehicles (FCV).

Year	HRS	FCV
2020	Over 100 stations	5,000 FCVs in demonstration, among which 60% are FC commercial vehicles and 40% are FC passenger cars
2025	Over 300 stations	50,000 FCVs in service, among which 10,000 units are FC commercial vehicles, and 40,000 units are FC passenger cars
2030	Over 1,000 stations, and 50+% hydrogen production from renewable resources	Over one million FCVs in service

Table 3-1 China's development goal for hydrogen fuel cell vehicles

I. By 2020 China will demonstrate 5,000 FCVs. Technology development includes:
   - High efficient hydrogen production, purification, storage, transportation and distribution, and hydrogen refueling stations;
   - Low cost and long lifespan electro-catalyst, polymer electrolyte membrane (PEM), low-platinum porous electrodes, membrane electrode assembly, non-precious metal catalysts, novel materials for bipolar plates, uniformity of fuel cell stacks, and system integration; and
   - Breakthrough in FCV key materials and components and system integration.

II. By 2025 China will realize FCVs deployment with 10,000 units of commercial vehicles and 40,000 units of passenger cars.
   - FCV small-scale applications with focus on urban passenger cars and public service vehicles;
   - Optimization of fuel cell system structure; and
   - Accelerating commercialization of FCV key components and cost reduction of fuel cell systems.

III. By 2030 China will complete FCV large-scale deployment of one million units, and over 50% hydrogen production from clean energies.
   - Integrated hydrogen production, storage, delivery and large scale applications;
   - Hydrogen on-site production at hydrogen refueling stations, and its standardization and commercialization; and
   - Establishing entire fuel cell manufacturing and supply chain encompassing FCV materials, components and systems.

4 HYDROGEN FUEL CELL VEHICLE TECHNOLOGY ROADMAP

4.1 FCV OVERALL TECHNOLOGY ROADMAP

China's overall development pathway of hydrogen fuel cell vehicle (FCV) is through three "Five-Year Plans" in technology R&D, demo and evaluation, and expanding fuel cell industrial applications, to achieve the following objectives as listed in Figure 4-1 on the next page.

- Capable of the design and system integration of fuel cell buses and passenger cars;
- Establishment of an entire FCV technology and industry chain, including fuel cell stacks and key materials, fuel cell system and core components, FCVs and critical parts, and hydrogen supply infrastructure; and
- Realization of overall development of future clean, low carbon, high-efficient FCV R&D and application system.

2020 Targets

- Vehicle: characterized by hybrid fuel cell electric vehicles (FCEVs) with low fuel cell power and high capacity battery power;
- Cost: FCV manufacturing costs similar to all-electric vehicles;
- Demo scale: FCVs reach 5,000 units for public services in selected areas; and
- H_2 supply: hydrogen production by adequately utilizing industrial by-product gas, and uneven loads of intermittent renewable energies such as abandoned wind, solar and hydro powers.

2025 Targets

- Vehicle: characterized by FCEVs with high fuel cell power and medium capacity battery power;
- Cost: FCV manufacturing costs similar to hybrid vehicles;
- Demo scale: FCVs reach 50,000 units in expanding areas; and
- H_2 supply: hydrogen production mainly from renewable resources.

2030 Targets

- Vehicle: characterized by 100% hydrogen powered, and all five key performance indicators (i.e. auto power, economic, durability, environmental adaptability, and costs) meet commercial requirements;
- Demo scale: FCVs reach one million units, and scale up commercialization of private passenger cars and large commercial vehicles;
- H_2 supply: increasing hydrogen production from decentralized renewable resources.

Table 4-1: Development objectives of hydrogen fuel cell vehicles in China

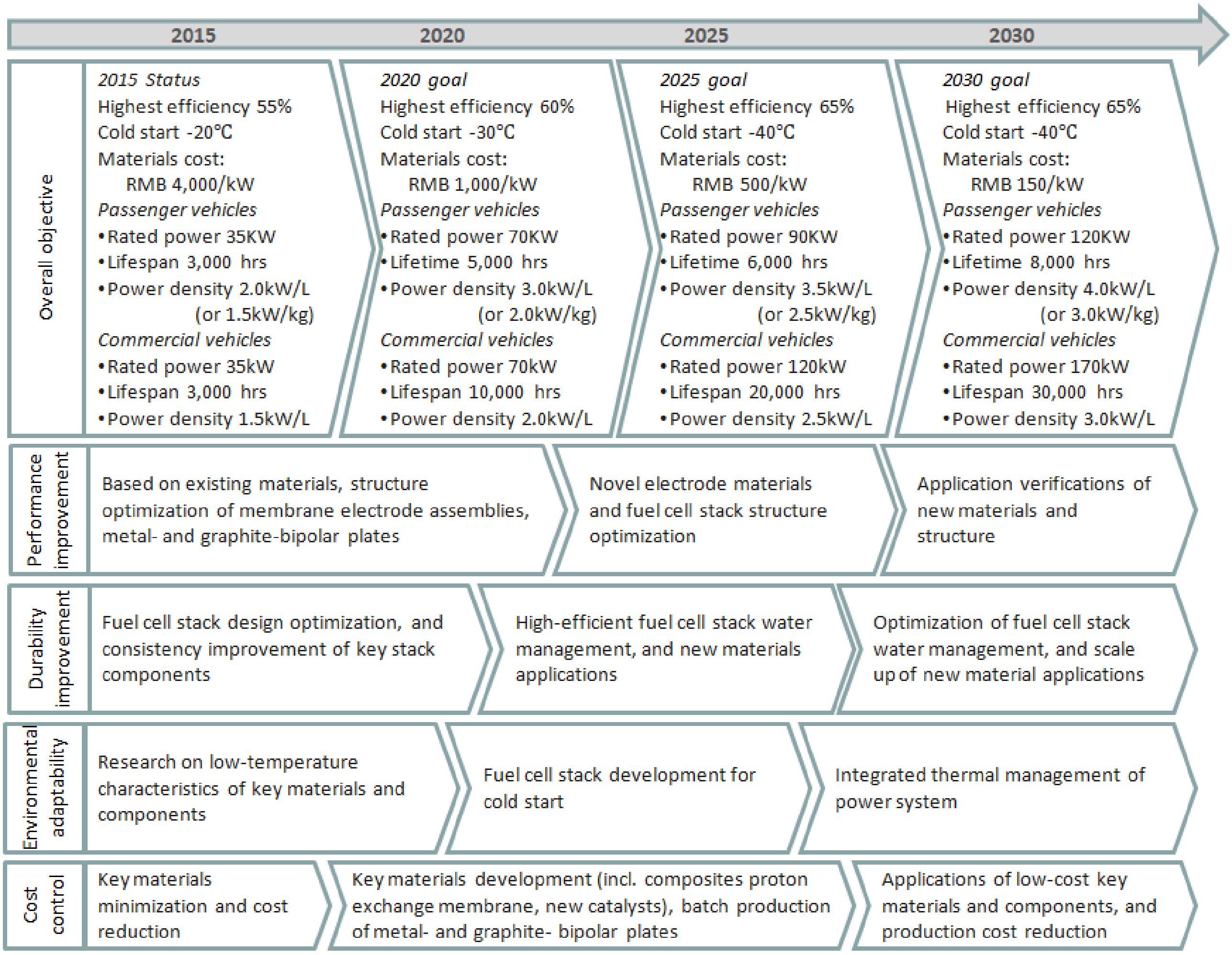
		2020	2025	2030
Overall objective		Small scale public sector demonstration in selected areas (5,000 FCVs)	Large scale deployment of FC passenger cars and service vehicles in urban areas (50,000 FCVs)	Large scale commercial deployment of passenger cars and commercial vehicles (one million FCVs)
		Fuel cell system production capacity > 1,000 units per enterprise	Fuel cell system production capacity > 10,000 units per enterprise	Fuel cell system production capacity > 100,000 units per enterprise
Hydrogen Fuel Cell Vehicles *	Functional Requirements	Cold start -30°C, power system structure optimization, FCV cost close to all-electric vehicles	Cold start -40°C, small volume production, FCV cost similar to hybrid vehicles	FCV overall performance comparable with traditional ICE vehicles - achieving competitive advantage
	Commercial vehicle	Cost ≤ RMB 1.5 million	Cost ≤ RMB 1.0 million	Cost ≤ RMB 600,000
	Passenger car	Max speed ≥ 160km/h Lifespan 200,000 km Cost ≤ RMB 300,000	Max speed ≥ 170km/h Lifespan 250,000 km Cost ≤ RMB 200,000	Max speed ≥ 180km/h Lifespan 300,000 km Cost ≤ RMB 180,000
Key common technologies	Fuel cell stacks	Cold start < -30°C Power density 2.0kW/kg Lifespan 5,000 hrs	Cold start < -40°C Power density 2.5kW/kg Lifespan> 6,000 hrs	Lifespan > 8,000 hrs
	Critical materials	High performance membrane materials, Low platinum catalysts, metal bipolar plates	Membrane reliability improvement, catalysts and bipolar plates	Low cost membrane electrode assemblies and bipolar plates
	Control tech	Fuel cell system control optimization	Fuel cell control reliability improvement	Fuel cell cost reduction and control integration
	Hydrogen storage	Key component development of Hydrogen supply system	Key component reliability improvement of hydrogen supply system	Key component cost reduction of hydrogen supply system
		High pressure hydrogen storage and safety	Hydrogen storage reliability	Cost reduction of hydrogen storage
Critical components		Key system components (incl. high speed oil-free air compressors, hydrogen recirculation system, and 70MPa hydrogen cylinders) to meet vehicle specifications; system cost below RMB200/kW		
H2 infrastructure	H2 supply	Decentralized hydrogen production from renewable sources; industrial by-products such as coke-oven gas		Decentralized H2 production from renewable sources
	H2 delivery	High pressure hydrogen storage and delivery	Cryogenic liquid hydrogen delivery	High density organic liquid hydrogen storage and delivery at normal pressure
	HRS	100 stations	350 stations	1,000 stations

* Note: In this Chapter, unless otherwise specified, all studies use 12-meter city bus for commercial vehicles, and class B car for passenger vehicles

4.2 FUEL CELL STACK TECHNOLOGY ROADMAP

China’s vehicle fuel cell stack technology roadmap has three developmental milestones projected to be accomplished by 2020, 2025, and 2030, respectively. Following the plan of product development, manufacturing validation and scale applications, the objective is for fuel cell stack’s three key indicators (i.e., performance, durability and cost) to meet commercial requirements, and volume manufacturing capability of stacks and critical materials. Figure 4-1 shows the Roadmap’s targets as below.

- Product consistency improvement for membrane electrode assembly, bipolar plates, and other critical materials and components;
- Fuel cell stack power density and overall performance improvement;
- Auxiliary system and control strategy optimization to improve system reliability and durability;
- Manufacturing capability improvement through R&D on fuel cell stack engineering, production equipment update, and manufacturing lines to gradually meet production in volume and cost target.



	2015	2020	2025	2030
Overall objective	*2015 Status* Highest efficiency 55% Cold start -20°C Materials cost: RMB 4,000/kW *Passenger vehicles* • Rated power 35KW • Lifespan 3,000 hrs • Power density 2.0kW/L (or 1.5kW/kg) *Commercial vehicles* • Rated power 35kW • Lifespan 3,000 hrs • Power density 1.5kW/L	*2020 goal* Highest efficiency 60% Cold start -30°C Materials cost: RMB 1,000/kW *Passenger vehicles* • Rated power 70KW • Lifetime 5,000 hrs • Power density 3.0kW/L (or 2.0kW/kg) *Commercial vehicles* • Rated power 70kW • Lifespan 10,000 hrs • Power density 2.0kW/L	*2025 goal* Highest efficiency 65% Cold start -40°C Materials cost: RMB 500/kW *Passenger vehicles* • Rated power 90KW • Lifetime 6,000 hrs • Power density 3.5kW/L (or 2.5kW/kg) *Commercial vehicles* • Rated power 120kW • Lifespan 20,000 hrs • Power density 2.5kW/L	*2030 goal* Highest efficiency 65% Cold start -40°C Materials cost: RMB 150/kW *Passenger vehicles* • Rated power 120KW • Lifetime 8,000 hrs • Power density 4.0kW/L (or 3.0kW/kg) *Commercial vehicles* • Rated power 170kW • Lifespan 30,000 hrs • Power density 3.0kW/L

Performance improvement	Based on existing materials, structure optimization of membrane electrode assemblies, metal- and graphite-bipolar plates	Novel electrode materials and fuel cell stack structure optimization	Application verifications of new materials and structure
Durability improvement	Fuel cell stack design optimization, and consistency improvement of key stack components	High-efficient fuel cell stack water management, and new materials applications	Optimization of fuel cell stack water management, and scale up of new material applications
Environmental adaptability	Research on low-temperature characteristics of key materials and components	Fuel cell stack development for cold start	Integrated thermal management of power system
Cost control	Key materials minimization and cost reduction	Key materials development (incl. composites proton exchange membrane, new catalysts), batch production of metal- and graphite- bipolar plates	Applications of low-cost key materials and components, and production cost reduction

Figure 4-1: Technology roadmap of vehicle hydrogen fuel cell stacks

Fuel cell stack lifespan is projected to meet commercial requirements in 2020. During this stage, the lifespan of passenger vehicle stacks will reach 5,000 hours through electrode structure optimization and development of integrated and reliable stack solutions. In addition, stack costs will reduce steadily through minimization of key materials usage and enhancement of current density.

Fuel cell stack cost is projected to meet basic commercial requirements in 2025. During this stage, stack cost will reduce to RMB 500/kW through key materials and components development as well as high-volume manufacturing. To further improve stack lifespan, water management optimization and durable key materials and components will be developed and verified.

Fuel cell stack overall performance is projected to meet commercial requirements in 2030, which include:

- Lifespan: comprehensive usage of new materials and components to improve stack durability;
- Cost: mass production of stacks and key materials to significantly reduce production costs; and
- Manufacturing capability: vehicle stack mass production to meet FCV development requirement.

Research & Development on key stack components will be conducted, which, as shown in Table 4-2 on the next page, includes stable proton exchange membranes, gas diffusion layers, carbon paper and durable and highly-active catalysts, bipolar plates, and high performance membrane electrode assembly with increasing volume production during 2025-2030.

Table 4-2: Development objectives of fuel cell stacks and key components in China

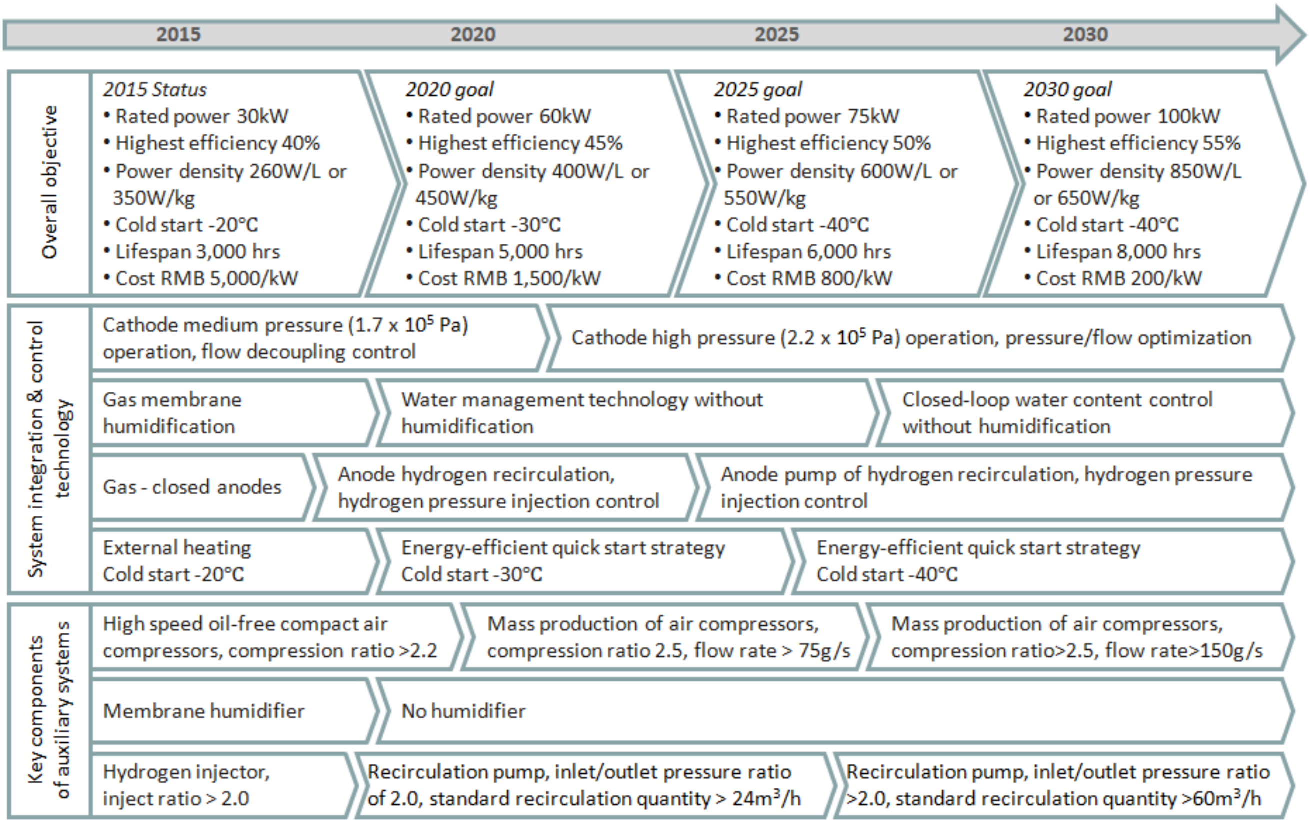
	Parameters		Unit	2015	2020	2025	2030
Membrane electrode assembly	Electrode power density		W/cm^2	0.7	1.0	1.2	1.5
	Pt consumption		g/kW	0.4	0.3	0.2	0.125
	Mass-specific activity (Pt, 0.9V)		mA/mg	≥ 300	≥ 440	≥ 480	≥ 570
	Electrochemical surface area (Pt)		m^2/g	≥ 65	≥ 65	≥ 80	≥ 80
Catalyst	Activity degradation rate of cyclic voltammogram (0.6-1.0V, Vs. RHE, 50mV/s)		-	20 (3,000 times)	≤ 40 (3,000 times)	≤ 40 (3,000 times)	≤ 40 (3,000 times)
	Activity degradation rate of potentiostatic operation at 1.2V		-	20 (100h)	≤ 40 (400h)	≤ 40 (400h)	≤ 40 (400h)
Proton exchange membrane	Proton conductivity		S/cm	0.05	0.08	0.1	0.1
	Mechanical strength		MPa	35	40	45	50
	Hydrogen permeation current		mA/cm^2	2.5	2.0	1.5	1.5
	Mechanical stability (20,000 dry-wet cycles, hydrogen permeation current)		mA/cm^2	>10	< 10	< 10	< 10
	Chemical stability (1,000 hrs open circuit, H_2 permeation current)		mA/cm^2	>10	< 10	< 10	< 10
Carbon paper	Electrical resistivity		mΩ*cm	80 (vertical) /6.0 (parallel)	60 (vertical) /4.0 (parallel)	50 (vertical) /3.0 (parallel)	50 (vertical) /3.0 (parallel)
	Gas permeability		$ml*mm/cm^2*h*mmH_2O$	1,500	2,000	2,500	3,000
	Tensile strength		N/cm	≥ 30	≥ 50	≥ 60	≥ 60
	Corrosion resistance (24 hr, 80°C, 1.4V, 0.5mol/L H_2SO_4 + 5 x 10^{-6}HF)	Electrical resistivity increment	mΩ*cm	≤ 1.50	≤ 1.00	≤ 0.80	≤ 0.50
		Wetting angle increment	°	≤ 50	≤ 30	≤ 20	≤ 15
Bipolar plate	Metallic plate	Thickness	mm	1.5	1.2	1.0	1.0
		Corrosion current	uA/cm^2	5.0	1.0	< 1.0	< 1.0
	Graphite plate	Thickness	mm	2.0	1.6	1.5	< 1.5
		Corrosion resistance	uΩ*cm	16	15	< 15	< 15
		Mechanical strength	MPa	50	60	65	> 65
		Porosity	%	≤ 0.12	≤ 0.10	≤ 0.10	≤ 0.10

4.3 FUEL CELL SYSTEM (ENGINE) TECHNOLOGY ROADMAP

4.3.1 Passenger car fuel cell system technology roadmap

China's passenger car fuel cell system (engine) development, as shown in Figure 4-2, has three developmental milestones projected to be accomplished by 2020, 2025, and 2030, respectively. The plan will roll out fuel cell engine applications in plug-in hybrid to leverage the market and realize commercialization.

Continuous improvement will focus on rated power and power density enhancement as well as other system functions, following the path "plug-in hybrid - electric hybrid – pure fuel cell vehicle" to develop and mass-produce passenger car fuel cell engines. Through simultaneous R&D and industrial commercialization, the goal is for all five key indicators (i.e. specific power, efficiency, environmental adaptability, durability and costs) to meet commercial requirements, as well as develop volume manufacturing capability of fuel cell engines and auxiliary systems to meet FCV development requirements.



Overall objective

2015 Status
- Rated power 30kW
- Highest efficiency 40%
- Power density 260W/L or 350W/kg
- Cold start -20°C
- Lifespan 3,000 hrs
- Cost RMB 5,000/kW

2020 goal
- Rated power 60kW
- Highest efficiency 45%
- Power density 400W/L or 450W/kg
- Cold start -30°C
- Lifespan 5,000 hrs
- Cost RMB 1,500/kW

2025 goal
- Rated power 75kW
- Highest efficiency 50%
- Power density 600W/L or 550W/kg
- Cold start -40°C
- Lifespan 6,000 hrs
- Cost RMB 800/kW

2030 goal
- Rated power 100kW
- Highest efficiency 55%
- Power density 850W/L or 650W/kg
- Cold start -40°C
- Lifespan 8,000 hrs
- Cost RMB 200/kW

System integration & control technology

Cathode medium pressure (1.7 x 10^5 Pa) operation, flow decoupling control

Cathode high pressure (2.2 x 10^5 Pa) operation, pressure/flow optimization

Gas membrane humidification

Water management technology without humidification

Closed-loop water content control without humidification

Gas - closed anodes

Anode hydrogen recirculation, hydrogen pressure injection control

Anode pump of hydrogen recirculation, hydrogen pressure injection control

External heating Cold start -20°C

Energy-efficient quick start strategy Cold start -30°C

Energy-efficient quick start strategy Cold start -40°C

Key components of auxiliary systems

High speed oil-free compact air compressors, compression ratio >2.2

Mass production of air compressors, compression ratio 2.5, flow rate > 75g/s

Mass production of air compressors, compression ratio>2.5, flow rate>150g/s

Membrane humidifier

No humidifier

Hydrogen injector, inject ratio > 2.0

Recirculation pump, inlet/outlet pressure ratio of 2.0, standard recirculation quantity > 24m^3/h

Recirculation pump, inlet/outlet pressure ratio >2.0, standard recirculation quantity >60m^3/h

Figure 4-2: Passenger car fuel cell system technology roadmap

By 2020, the first commercial applications of fuel cell systems will be in the form of fuel cell-battery hybrids. During this stage, technical specifications will meet the following criteria.

- Fuel cell system rated power: no less than 60kW;
- Power density: 400W/L or 450W/kg;
- Cold start: -30°C to be suitable for winter in most areas in China;
- System lifespan: 5,000 hrs (in the condition of power battery as main power source); and
- System cost: below RMB 1,500/kW (10,000 units).

Key technologies for system control will include:

(1) Medium cathode pressure (0.17MPa) as main system operating pressure, and pressure/flow decoupling control;
(2) Water management system transition from gas-gas humidification to no external humidification;
(3) Cold start -30°C.

Key technologies for critical materials and components in fuel cell stack auxiliary systems will include:

(1) Compact high-speed oil-free air compressor: compression ratio up to 2.2 and flow rate no less than 70g/s;
(2) Hydrogen recirculation pump: inlet/outlet pressure ratio 2.0, standard recirculation quantity > 24m^3/h, and realization of self-humidification of anode circulation.

2025 will be a transition point of further performance improvements for passenger vehicle fuel cell systems. During this phase, the improvement of power density, system efficiency and environmental adaptability will enhance fuel cell system overall performance, including cold start -40°C (for all winter conditions in China), lifetime 6,000h (with low-capacity battery power as buffer during peak power requirement), and system cost around RMB800 /kW. Rated power will increase to ~75kW, maximum efficiency to 50%, and power density to 600W/L or 550W/ kg, enabling fuel cell system to be used as main power source for vehicles.

Key technologies for system control will include:

(1) High cathode pressure (0.22MPa) operation to enhance power density;
(2) Overall performance improvement of fuel cell stack;
(3) Further improvement of anode hydrogen recirculation system with enhanced water management without external humidifier; and
(4) Hydrogen recirculation through recirculation pump.

Technologies for auxiliary system key components will include high-volume production of air compressors with compression ratio up to 2.5 and flow rate no less than 75g/s, as well as research on high-flow recirculation pump.

2030 will be the year for the fuel cell systems of high-power passenger cars to reach industrialization. Key parameters will include:

- Commercial availability of high power (100kW) fuel cell system, engine power comparable with regular gasoline engine;
- System efficiency 55%;
- Power density up to 850W /L (or 650W/kg);
- Cold start temperature further down to -40°C;
- System lifespan 8,000 hours with hydrogen as main energy source; and
- System cost around RMB 200/kW.

Key technologies for system control will include closed-loop water management without external humidification, cathode pressure control/flow optimization under high-pressure operating conditions, and hydrogen recirculation pump with hydrogen pressure injection control.

For auxiliary system components, it will realize high-volume production both for small air compressors (with compression ratio > 2.5 and flow rate > 150g/s), and recirculation pumps (with input/output pressure ratio >2.0 and recirculation volume above >60 m^3/h under standard operating conditions).

4.3.2 Commercial vehicle fuel cell system technology roadmap

China’s technology roadmap of fuel cell system (engine) development of commercial vehicle (12-meter bus used as typical vehicle for studies), as shown in Figure 4-3 on the next page, has three developmental milestones projected to be accomplished by 2020, 2025, and 2030, respectively.

It will start market entry by introducing low-power fuel cell system to begin volume production of commercial vehicle fuel cell system and its small-scale vehicle deployment. It will follow the development path of the passenger vehicle system by transiting from a hybrid combination of low-power fuel cell and high-capacity battery to high-power fuel cell and low-capacity battery. To achieve this, it will gradually enhance commercial vehicle fuel cell system power, optimize system functions and architecture, and improve system performance - with the objective for rated power, efficiency, environmental adaptability, durability, and costs to meet commercial requirements. To meet commercial vehicle development requirements, it will also develop high-volume manufacturing capability of commercial vehicle fuel cell systems, especially for its auxiliary system.

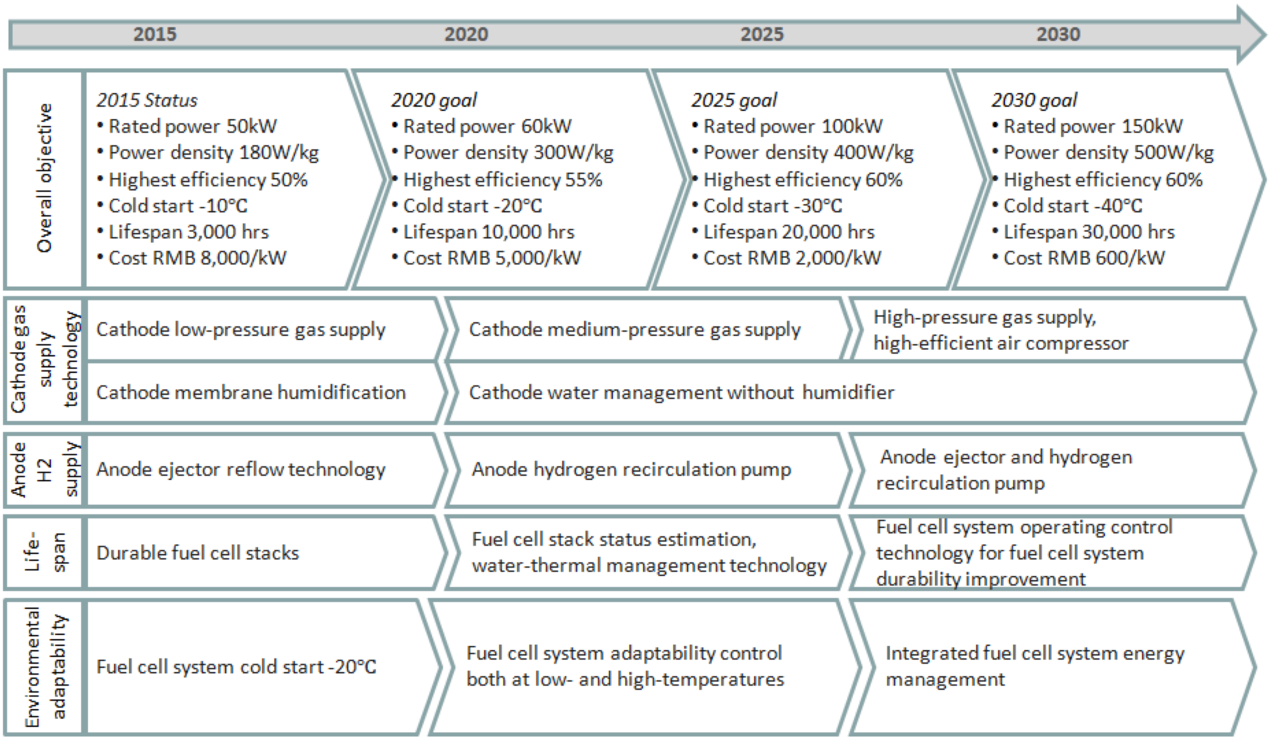


Figure 4-3 Commercial vehicle fuel cell system technology roadmap

In 2020, fuel cell systems will meet whole vehicle's average power requirements and start commercial vehicle deployment. During this stage, fuel cell system rated power will reach 60kW and will use power batteries to meet commercial vehicle's power requirements. Technical specifications will include:

- Fuel cell system power density up to 300W/kg;
- Cold start -20°C for winter in most parts of China;
- Lifespan 10,000 hours with power batteries used to meet the vehicle power requirements; and
- System cost RMB 5,000/kW.

Meanwhile, fuel cell system's working pressure will transit from low to medium, system lifespan will improve through system control optimization, and the system will be self-humidifying through intake air circulation.

2025 will be the year for fuel cell system to reach large scale applications in commercial vehicles, through continuous fuel cell system performance improvement, cost reduction, and reliability enhancement. During this stage, the fuel cell system will gradually improve its performance, through enhancing system's rated power, power density, system efficiency, and environmental adaptability:

- Fuel cell system rated power up to 100kW;
- Fuel cell system maximum efficiency up to 60%;

- Fuel cell system power density 400W/ kg;
- Cold start -30°C for almost all winter conditions in China;
- Lifespan above 20,000 hours; and
- System costs below RMB 2,000/kW.

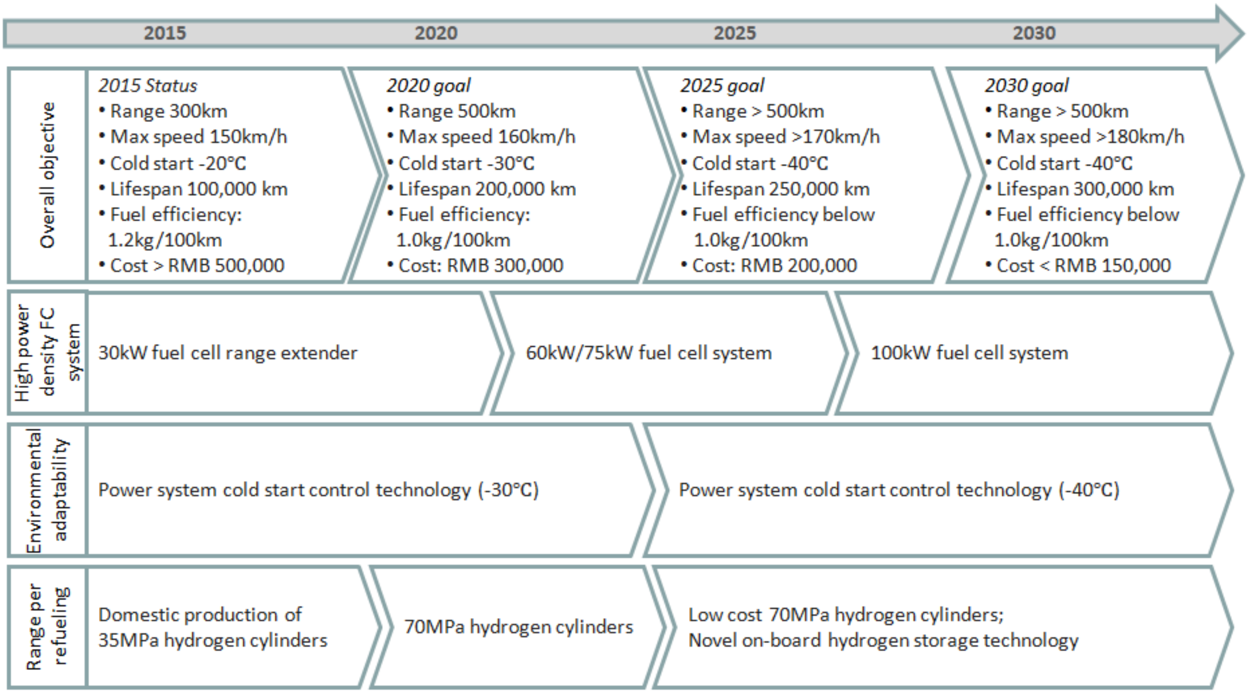
2030 will be the year for fuel cell system to meet commercial requirements. During this stage, the fuel cell system will fulfill commercial requirements, through further improvement of its rated power, power density, system efficiency and environmental adaptability:

- Fuel cell system rated power up to 150kW;
- Fuel cell system maximum efficiency up to 60%;
- Fuel cell system power density 500W / kg;
- Cold start -40°C for all winter conditions in China;
- Lifespan over 30,000 hours; and
- System costs below RMB 600/kW.

4.4 HYDROGEN FUEL CELL VEHICLE TECHNOLOGY ROADMAP

4.4.1 Hydrogen fuel cell passenger car technology roadmap

China's technology roadmap of hydrogen fuel cell passenger car (B-segment passenger car used for studies as a typical vehicle), as shown in Figure 4-4, has three developmental milestones projected to be accomplished by 2020, 2025, and 2030, respectively.



	2015	2020	2025	2030
Overall objective	*2015 Status* • Range 300km • Max speed 150km/h • Cold start -20°C • Lifespan 100,000 km • Fuel efficiency: 1.2kg/100km • Cost > RMB 500,000	*2020 goal* • Range 500km • Max speed 160km/h • Cold start -30°C • Lifespan 200,000 km • Fuel efficiency: 1.0kg/100km • Cost: RMB 300,000	*2025 goal* • Range > 500km • Max speed >170km/h • Cold start -40°C • Lifespan 250,000 km • Fuel efficiency below 1.0kg/100km • Cost: RMB 200,000	*2030 goal* • Range > 500km • Max speed >180km/h • Cold start -40°C • Lifespan 300,000 km • Fuel efficiency below 1.0kg/100km • Cost < RMB 150,000
High power density FC system	30kW fuel cell range extender	60kW/75kW fuel cell system	100kW fuel cell system	
Environmental adaptability	Power system cold start control technology (-30°C)		Power system cold start control technology (-40°C)	
Range per refueling	Domestic production of 35MPa hydrogen cylinders	70MPa hydrogen cylinders	Low cost 70MPa hydrogen cylinders; Novel on-board hydrogen storage technology	

Figure 4-4 Hydrogen fuel cell passenger car technology roadmap

Fuel cell passenger cars will begin their commercial rollout through fuel cell and power battery of combined electric-electric driven technology for its market entry, and gradually transit to complete hydrogen fuel cell powered vehicles. It will continuously improve passenger car fuel cell system performance for its five key parameters (i.e. vehicle power, efficiency, durability, environmental adaptability, and costs) to meet commercial requirements.

2020 will be the year for hydrogen fuel cell passenger cars to start its commercialization. During this stage, vehicle highest speed will reach 160km/h, and cold start -30^{o}C. For onboard hydrogen tanks, 70MPa hydrogen cylinders will be produced domestically at low cost, and driving range will be comparable to current ICE vehicles. Vehicle lifespan will close to 200,000 km, and cost will be below RMB 300,000. The initial applications will be in hydrogen fuel cell passenger cars, light-duty cars, and light-duty trucks.

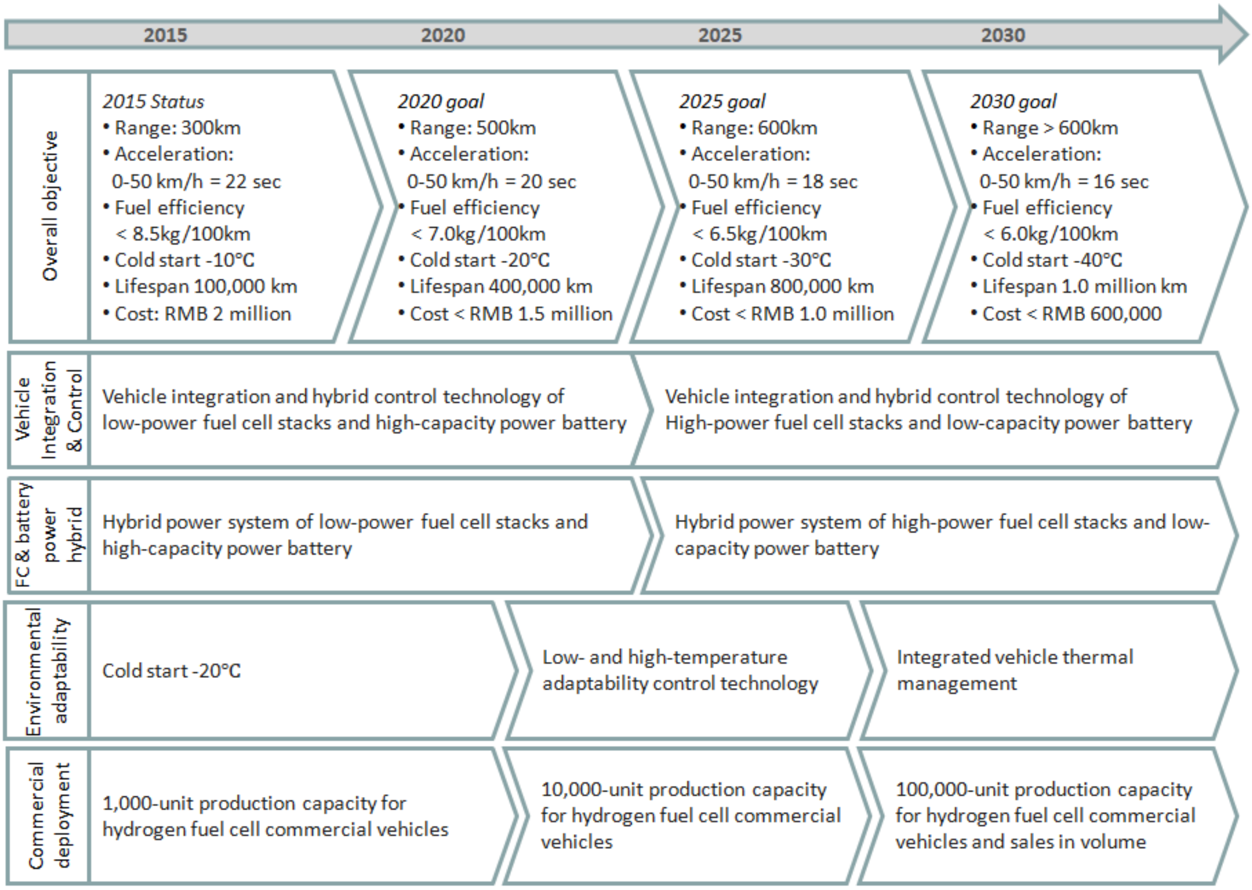
2025 will be the transition point for continuous performance improvement of passenger vehicle fuel cell systems. During this stage, vehicle power, efficiency, durability, environmental adaptability, and costs will improve gradually, through enhancing fuel cell engine’s rated power, optimizing power system energy management strategy, and gradually improving fuel cell system overall performance. Vehicle top speed of more than 170 km/hr will be equivalent to ICE vehicles. Environmental adaptability will continuously improve, with vehicle lifespan up to 250,000 km, and cost will be below RMB 200,000.

2030 will be the year for passenger vehicles fully powered by hydrogen fuel cells to realize their commercialization. During this stage, the vehicle power will be solely supplied by hydrogen fuel cells, through the application of high power (100kW) fuel cell systems. The vehicle will exceed 500km range and reach 300,000 km lifespan to fully meet commercial requirements. Meanwhile, the costs will further reduce to RBM 150,000 to enable large scale application.

4.4.2 Hydrogen fuel cell commercial vehicle technology roadmap

China’s technology roadmap of hydrogen fuel cell commercial vehicles (12-meter bus used for studies as a typical vehicle), as shown in Figure 4-5, has three developmental milestones projected to be accomplished by 2020, 2025, and 2030, respectively.

Fuel cell commercial vehicles will begin their commercial rollout through a power system combination of low-power fuel cell and high-capacity power battery for its market entry. It will follow the path of gradually increasing fuel cell system power and reducing battery capacity, optimization of the hybrid system control technology to enhance vehicle performance, enabling its five key parameters (i.e. vehicle power, efficiency, durability, environmental adaptability, and costs) to meet commercial requirements. To meet fuel cell commercial vehicle deployment requirements, it will develop high-volume manufacturing capabilities of fuel cell power systems as main power source.


2015 2020 2025 2030

Overall objective

2015 Status
- Range: 300km
- Acceleration: 0-50 km/h = 22 sec
- Fuel efficiency < 8.5kg/100km
- Cold start -10°C
- Lifespan 100,000 km
- Cost: RMB 2 million

2020 goal
- Range: 500km
- Acceleration: 0-50 km/h = 20 sec
- Fuel efficiency < 7.0kg/100km
- Cold start -20°C
- Lifespan 400,000 km
- Cost < RMB 1.5 million

2025 goal
- Range: 600km
- Acceleration: 0-50 km/h = 18 sec
- Fuel efficiency < 6.5kg/100km
- Cold start -30°C
- Lifespan 800,000 km
- Cost < RMB 1.0 million

2030 goal
- Range > 600km
- Acceleration: 0-50 km/h = 16 sec
- Fuel efficiency < 6.0kg/100km
- Cold start -40°C
- Lifespan 1.0 million km
- Cost < RMB 600,000

Vehicle Integration & Control

Vehicle integration and hybrid control technology of low-power fuel cell stacks and high-capacity power battery

Vehicle integration and hybrid control technology of High-power fuel cell stacks and low-capacity power battery

FC & battery power hybrid

Hybrid power system of low-power fuel cell stacks and high-capacity power battery

Hybrid power system of high-power fuel cell stacks and low-capacity power battery

Environmental adaptability

Cold start -20°C

Low- and high-temperature adaptability control technology

Integrated vehicle thermal management

Commercial deployment

1,000-unit production capacity for hydrogen fuel cell commercial vehicles

10,000-unit production capacity for hydrogen fuel cell commercial vehicles

100,000-unit production capacity for hydrogen fuel cell commercial vehicles and sales in volume

Figure 4-5 Hydrogen fuel cell commercial vehicle technology roadmap

2020 will be the year for hydrogen fuel cell commercial vehicle's scalable deployment and high-volume production, with vehicle durability 400,000 km, range 500km, and whole vehicle cost under RMB 1.5 million. Fuel cell commercial vehicles will expand their deployment through fuel cell and battery hybrid FCEV, with fuel cell of 60kW rated power as main power source supplemented with power battery. It will realize cold start -20°C, and hydrogen consumption below 7.0kg/100km under China's typical urban driving traffic conditions.

2025 will be the year of large scale deployment of hydrogen fuel cell commercial vehicles, with continuous improvement of its system performance and vehicle cost reduction. During this stage, through enhancing fuel cell engine's rated power, optimizing energy management strategy, vehicle power performance, efficiency, durability, environmental adaptability, and costs will reduce gradually, and vehicle lifespan will be comparable to traditional ICE vehicles. It will realize hydrogen consumption below 6.5kg/100km under China's typical urban driving traffic conditions, 600km range, cold start -30°C, vehicle lifespan up to 800,000 km, and whole vehicle cost under RMB 1.0 million.

2030 will be the year for hydrogen fuel cell commercial vehicles to meet commercial requirements. During this stage, by deploying high rated-power (150kW) fuel cell stacks, power system reliability will further improve and surpass traditional ICE vehicles. Vehicle overall performance will improve and cost will come down through mass production of fuel cell commercial vehicles. It will realize hydrogen consumption below 6.0kg/100km under China's typical urban driving traffic conditions, 600km range, cold start -40°C, vehicle lifespan up to one million kilometers, and whole vehicle cost under RMB 600,000.

4.5 HYDROGEN TECHNOLOGY ROADMAP

4.5.1 Onboard hydrogen storage technology roadmap

China's onboard hydrogen storage technology roadmap, as shown in Figure 4-6 on the next page, has three developmental milestones projected to be accomplished by 2020, 2025, and 2030, respectively. The main pathway for the accomplishment of these objectives is high pressure tank storage at ambient temperature, while still encouraging the development of innovative storage technologies. To support FCV industrialization, the immediate plan is the deployment of 35MPa compressed hydrogen storage, and the long-term solution and plan is the development of 70MPa hydrogen storage. During its industrialization, R&D regarding on-board hydrogen storage will be conducted to gradually meet commercial requirements such as hydrogen storage weight ratio, volume density, and system cost. Meanwhile, high-volume manufacturing capacity for compressed hydrogen cylinders and critical valve components will be developed.

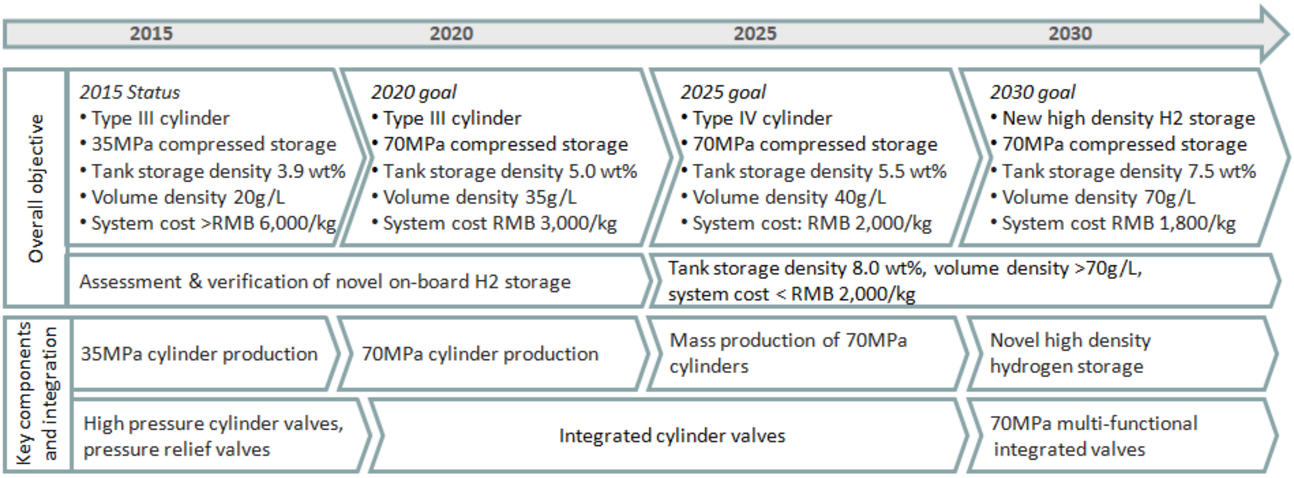


Figure 4-6 Onboard hydrogen storage technology roadmap

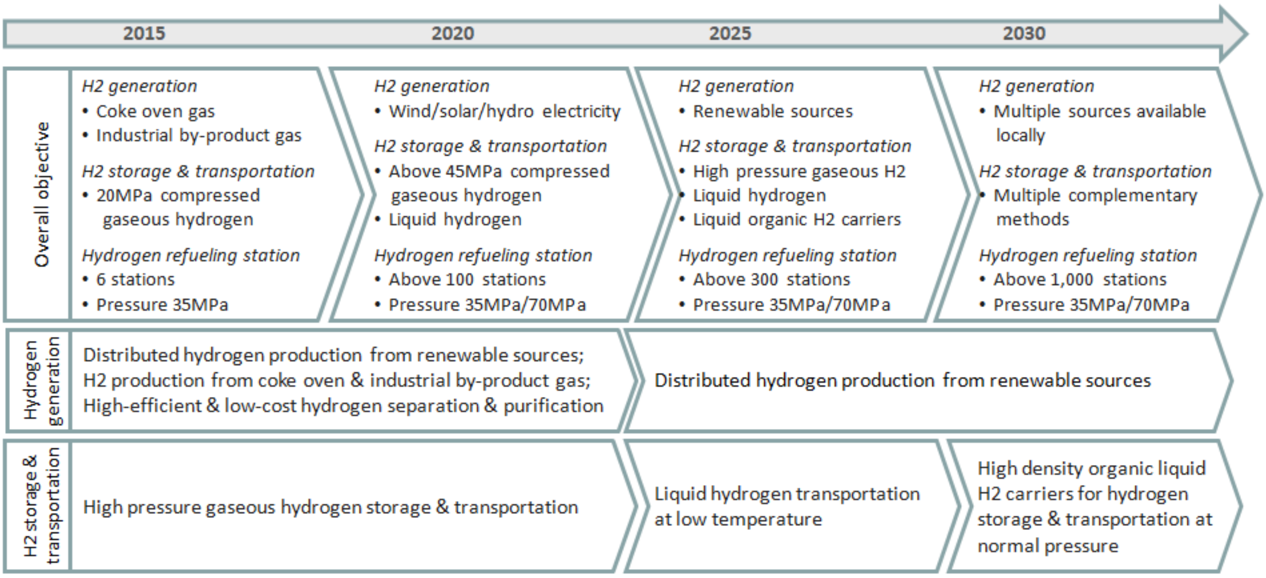
In 2020, onboard hydrogen storage will meet commercial requirements at a basic level. During this stage, single onboard hydrogen cylinders will have a storage capacity of at least 5.6 kg, a storage pressure of 70MPa (to meet international standards), a hydrogen storage weight ratio 5.0%, volume density 35g/L, and a system cost below RMB 3,000/kg. With these developments, the goal of low-cost manufacturing of 70MPa hydrogen cylinders, and domestic production of key materials and parts, such as carbon fibers and pressure reducing valves, will be realized.

The fuel cell systems (engines) of high-power passenger vehicles will fully meet commercial requirements in 2025. During this stage, the storage capacity of single onboard hydrogen cylinders will reach at least 6.0kg, including 70MPa storage pressure, a hydrogen storage weight ratio of 5.5%, a volume density of 40g/L, and a system cost below RMB 2,000/kg. With these developments, the goals of high-volume manufacturing of 70MPa hydrogen cylinders, and that of integrated valve development will be realized.

High-power fuel cell passenger vehicles will meet commercial requirements in 2030. During this stage, hydrogen storage density will further improve, including a hydrogen storage weight ratio of 7.5%, volume density of 70g/L, and system costs under RMB 1,800/kg. These further developments will bring about a realization of the goals of mass production of 70MPa hydrogen cylinders, development of integrated multi-functional valves, and the breakthrough of novel hydrogen storage.

4.5.2 Hydrogen infrastructure technology roadmap

As shown in Figure 4-7, China's hydrogen infrastructure technology roadmap, based on China's current hydrogen production and requirements as well as global technology development trend, has three developmental milestones projected to be accomplished by 2020, 2025, and 2030, respectively. Following the technical progress of R&D, assessment and verification, and then production, the objective is to meet FCV development requirements for four key indicators - hydrogen production costs, energy consumption, production capacity, and hydrogen purification.



	2015	2020	2025	2030
Overall objective	*H2 generation* • Coke oven gas • Industrial by-product gas *H2 storage & transportation* • 20MPa compressed gaseous hydrogen *Hydrogen refueling station* • 6 stations • Pressure 35MPa	*H2 generation* • Wind/solar/hydro electricity *H2 storage & transportation* • Above 45MPa compressed gaseous hydrogen • Liquid hydrogen *Hydrogen refueling station* • Above 100 stations • Pressure 35MPa/70MPa	*H2 generation* • Renewable sources *H2 storage & transportation* • High pressure gaseous H2 • Liquid hydrogen • Liquid organic H2 carriers *Hydrogen refueling station* • Above 300 stations • Pressure 35MPa/70MPa	*H2 generation* • Multiple sources available locally *H2 storage & transportation* • Multiple complementary methods *Hydrogen refueling station* • Above 1,000 stations • Pressure 35MPa/70MPa
Hydrogen generation	Distributed hydrogen production from renewable sources; H2 production from coke oven & industrial by-product gas; High-efficient & low-cost hydrogen separation & purification		Distributed hydrogen production from renewable sources	
H2 storage & transportation	High pressure gaseous hydrogen storage & transportation		Liquid hydrogen transportation at low temperature	High density organic liquid H2 carriers for hydrogen storage & transportation at normal pressure

Figure 4-7 Hydrogen infrastructure technology roadmap

Distributed hydrogen production will meet commercial requirements in 2020. During this stage, China will establish distributed hydrogen production system with onsite hydrogen production at hydrogen refueling stations, characterized by low energy consumption and economically viable water electrolysis. Overall hydrogen production efficiency will improve, through electrode structure optimization, alkaline electrolysis development, and alkaline electrolyte recovery. After 2020 China will further develop low-cost and high-efficient water electrolysis technology, mainly through solid polymers and solid oxide electrolyzers, to enhance distributed hydrogen production capacity to meet increasing FCV market requirements.

For large-scale central hydrogen production, China will develop high value-added hydrogen production technology based on its existing industrial structure, including high-efficient, low-cost hydrogen purification of coke oven and industrial by-product gases. It will develop reforming technology to convert rich hydrocarbon in coke oven gases and industrial by-products into hydrogen, which will connect separated coke oven plants as hydrogen sources into a hydrogen supply network.

From 2015 to 2020, compressed gaseous hydrogen will be stored and transported at 20MPa. Liquid hydrogen, after critical equipment breakthrough and government regulatory approvals, is expected to be deployed in 2020. It is estimated that organic liquid hydrogen storage will improve its reliability and technology, and realize commercialization before 2025. The commercialization of both technologies will closely depend on centralized hydrogen mass-production, driven by large-scale hydrogen demand.

The development of hydrogen refueling station (HRS) in China will match, and lead the progress of FCV commercialization. Before 2020, China will mainly develop 35MPa HRS to meet hydrogen demand from public service and commercial fuel cell vehicles. Fuel cell passenger cars will be introduced into the market in 2020, after which demand for 70MPa HRS will increase significantly. Meanwhile, with the growth number of HRS, the combination with gasoline refueling stations and electric charging stations will be the main form of energy refueling stations.

5 TECHNOLOGY INNOVATION REQUIREMENTS

According to China's hydrogen fuel cell vehicle (FCV) development roadmap and goals, innovative development and technology breakthrough are required in fuel cell stacks and key components, fuel cell systems (engines), power systems as well as whole vehicle integration and hydrogen applications. The goal is to realize the plans outlined in *Made in China 2025*, which require three-level endeavors to develop the entire FCV industry chain.

- Fundamental studies: research capability development in fuel cell key materials, and fuel cell process mechanisms;
- Applied technologies: fuel cell stack performance improvement, critical auxiliary technologies, high power density, durable fuel cell systems (engines), power system and whole vehicle integration of fuel cell passenger cars and commercial vehicles;
- Demonstration: nationwide FCV demonstrations and global collaborations.

5.1 FUNDAMENTAL RESEARCH OUTLOOK

(1) Critical fuel cell materials
  - Low- or non-platinum catalysts and catalytic mechanism;
  - Highly-dispersed nanopowder slurry;
  - Solid electrolytes of high chemical and mechanical stability, and proton conduction mechanism;
  - High-performance and low-cost gas diffusion layers and mass transfer mechanism;
  - Conductive layer modification for low-cost and corrosion-resistant metal bipolar plates;
  - Multi-dimensional precision molding of thin sheet metals without residual stress;
  - Fuel cell stack sealing materials as well as sealing mechanism and structural reliability;
  - Key topics on vehicle metal-air fuel cell systems and fuel regeneration; and
  - Liquid hydrogen storage.

(2) Fuel cell process mechanisms
  - Single fuel cell engineering, structure, and comprehensive fluid flow simulation;
  - Key components' stress-relaxation as well as its prediction and effects on fuel cell stack performance and lifespan;
  - Mass transfer factors analysis, computer simulation, and optimization;
  - Analysis and optimization of fuel cell current distribution and heat distribution;

- Fuel cell characteristics at ultra-low temperature and cold start solutions;
- Mechanism and solutions of air impurities (pollutants) on fuel cell performance;
- Fuel cell stack "gas-liquid-electricity-thermal" multi-coupling characteristics as well as its monitoring and problem diagnosis;
- Multi-physical fields coupling analysis and modeling of fuel cell system, and its durability mechanism;
- Compressor stability under various operating conditions, and integrated utilization of system energy; and
- Fuel cell hybrid power system and multi-coupling modeling, system configuration and control optimization.

5.2 APPLIED TECHNOLOGIES

(1) Fuel cell stack components' performance improvement
  - Manufacturing processes (including stamping, sealing, welding, and coating) as well as testing and assessment of metal bipolar plates of high power density;
  - Key manufacturing technology for high-performance and low-cost membrane electrode assembly;
  - Key manufacturing technology for diffusion layer (carbon paper, carbon cloth), composite films, and low platinum catalysts for fuel cell stacks of high power density;
  - Flow field and flow distribution optimization of single full-scale fuel cell;
  - Uniformity of fuel cell structure, assembly, and stacks;
  - Fuel cell stacks without external humidification;
  - Degradation mechanism of fuel cell stacks, and their durability improvement.

(2) Air compressors, hydrogen recirculation pumps, and key auxiliary system components.
  - Fuel cells of high power density require compact, low-power and high-speed air compressors. Current research will focus on high-speed turbine air compressors using oil-free and high-precision bearing parts (such as air-floating bearing, magnetic bearing, and ceramic bearing) as transmission parts. The challenges will be in the design, processing and fabrication of bearings, impellers/blades and control devices.
  - Hydrogen recirculation pump is critical to enhance hydrogen utilization and anode water management, and its high efficiency will significantly improve fuel cell system performance and economy.

(3) High power density fuel cell systems (engines)

- Key technologies of high power density and low cost fuel cell stacks;
- Modular design, integration, and system control of high power density and low cost fuel cell engines; and
- Testing and assessment of fuel cell engines and key components.

(4) Durable fuel cell systems (engines)

- Modular structure integration and overall configuration of fuel cell engines, and development of full-scale single fuel cell and stacks;
- Fuel cell auxiliary systems (including air, hydrogen, and thermal management systems), and fuel cell engine control system;
- Fuel cell engine system integration and key process technology; and
- Key components of fuel cell engines, and integrated unit testing and evaluation.

(5) Fuel cell power systems of passenger cars and vehicle integration technology

A. Fuel cell system platform for passenger cars

- Platform for fuel cell hybrid system, and key component design, calculation, emulation, and simulation;
- Software design and standardization for fuel cell system control;
- Fuel cell power system integration and matching; and
- Power system optimization in economy, durability, safety, reliability, and environmental adaptability.

B. Integration technology of fuel cell passenger cars

- Component matching, vehicle integration and control technology;
- Energy management strategy;
- Process and procedure development for key components and whole vehicles;
- Economy, durability, and reliability improvement of passenger cars, and vehicle cost reduction.

C. General technical standards for fuel cell passenger cars: key components, power system, and whole vehicle testing and assessment.

(6) Fuel cell power systems for commercial vehicles, and vehicle integration

A. Vehicle durability, reliability, and efficiency optimization at three hierarchical levels - fuel cells, power systems, and vehicle integration - to meet various commercial vehicle requirements.

B. Correlation investigation between fuel cell system working environment, operating conditions, and durability under vehicle operating conditions; optimization of fuel cell operating conditions to improve stack durability, and ensure the reliability and durability of fuel cell system, power system, and other components.

C. Power system control optimization and energy management for fuel cell hybrid commercial vehicles, with power system control to optimize fuel cell operating conditions and realize simultaneous improvement of motor, battery, and fuel cell reliability and durability.

D. Selected vehicles, equipped with cutting-edge fuel cell components or system through international bidding procurement, will be tested and compared with domestic fuel cell vehicles during demonstration operation to gain knowledge for improvement.

E. Vehicle design optimization and integration, including fuel cell commercial vehicle energy efficiency, cost control, vehicle integrated “gas - electricity - structure” coupling security, quick hydrogen refueling, and demon operation monitoring.

F. Durable fuel cell power system and whole vehicle technology, characterized by low cost meeting commercial requirement, and low-temperature adaptability operating normally at -30°C.

G. Engineering improvement of fuel cell power systems and vehicle integration, including:
  - Intelligent control, reliability, safety, and durability of fuel cell systems and whole vehicles;
  - Developing a series of sophisticated fuel cell bus power systems and whole vehicles, based on current mature technologies; and
  - Manufacturing process improvement and volume production capability development, with focus on key fuel cell component quality and the establishment of quality management system tailored for fuel cell bus power systems.

5.3 DEMONSTRATION AND COMMERCIALIZATION

China will conduct FCV commercial demonstration in multiple cities in order to assess and improve FCV development in all categories. To gain experience and better understanding for FCV large-scale commercialization, operations data from the demonstrations will be collected and analyzed, including:

- Design and development of high pressure (70MPa) hydrogen refueling stations (HRS);
- Solid-state hydrogen storage and high-pressure hydrogen storage;
- Hydrogen transportation at normal temperature and system optimization;
- HRS safety and standard development; and
- Hydrogen FCV demonstration operation.

China will promote hydrogen FCV international collaboration, which will focus on technical indicators and evaluation of key FCV components, and system development of parts testing and assessment for large-scale manufacturing. China will cooperate with international standards and testing organizations for the following development:

- Technical indicators and experimental verification for key FCV components;
- FCV adaptability under controllable and uncontrollable operating conditions, including traffic conditions and driving habits as well as temperature, humidity, and atmospheric pressure; and
- Control strategies for FCV engines and power systems.

5.4 FCV TECHNOLOGY PLATFORM

A. FCV power system platform for testing and evaluation, including:
  - Testing and assessment platform for hydrogen fuel cell system and components, with focus on evaluation and technical indicators of key components, and system development of parts testing and evaluation for large scale manufacturing;
  - Overall evaluation of FCV power performance, economy, durability, reliability, and environmental adaptability as well as related assessment methodology and testing equipment development;
  - Simulation and emulation platform for hydrogen FCV engines and hybrid power systems under road conditions;
  - Codes and standards development for quick assessment of fuel cell stack durability, and hydrogen FCV testing specifications and standards.

B. Hydrogen innovation platform, including:
  - Experiment and development platform for hydrogen production, transportation and refueling infrastructure;
  - Hydrogen refueling station (HRS) key technologies, development plans, demonstration operations, and codes and standards;
  - Hydrogen production from renewable energies, and equipment and infrastructure standards development for distributed hydrogen production;
  - Experiment and development platform for hydrogen onboard storage system; and
  - High-pressure hydrogen storage, and novel hydrogen storage in equipment development, testing and assessment, and codes and standards.