Fuel Cell and Hydrogen Technology Development Roadmap: Fuel Cell Roadmap for FCVs/HDVs

New Energy and Industrial Technology Development Organization (NEDO)
Date created: October 2024

1. Background and Scenarios for Widespread Use

1.1 Background on the establishment of the roadmap

Recently, there has been a significant push to implement hydrogen-related measures to achieve global carbon neutrality (CN). Around the world, efforts are underway to develop hydrogen-related technologies and implement them in society, with the EU announcing its hydrogen strategy in July 2020, major European countries such as Germany and France also formulating their own national hydrogen strategies, and the U.S. announcing its hydrogen program plan in November of the same year.

Meanwhile, the use of fuel cell (hereinafter referred to as "FC") systems, which are the most important devices for utilizing hydrogen and can contribute to low carbon emissions while maintaining high energy efficiency, is expected to further expand as a key technology for solving the global warming problem. As such, the "Fuel Cell and Hydrogen Strategy Roadmap (established in June 2014, and revised in March 2016 and March 2019)" established by the Council for a Strategy for Fuel Cell and Hydrogen presents the government's basic policy and policy objectives for expanding the use of FCs, as well as projections for future market expansion. The New Energy and Industrial Technology Development Organization (hereinafter referred to as "NEDO"), whose mission is to solve energy and global environmental problems and strengthen industrial technological capabilities, formulated the "Fuel Cell and Hydrogen Technology Development Roadmap" (hereinafter referred to as the "Roadmap") in 2005, which clarifies the technological issues to be addressed to realize these government goals and organizes them in chronological order. The Roadmap has been revised four times in the past to reflect the latest policy, market and technology trends. The last revision was made in 2017, and since then, the social environment has changed rapidly, including the global spread of the SDGs and CN declarations by major countries. In the Roadmap, the transformation of mobile vehicles plays one of the key roles in reducing CO_2 emissions in the transportation sector, and in addition to the passenger cars (FCVs) indicated in the 2017 Roadmap, the category of mobile vehicles to be transformed is rapidly expanding. In particular, the use of FCs for mobile vehicles is expanding worldwide to include heavy-duty vehicles (HDVs), with applications for trucks being a representative category, as well as trains and ships. The industrial world is also actively moving towards electrification, which is expected to extend beyond conventional forklifts to construction and farm machinery and equipment. As the electrification of these mobile vehicles is being considered, there are many actual cases where it is difficult to provide sufficient energy for normal operation with power from batteries. To compensate for this problem, the adoption of FCs is being considered from the point of view of using hydrogen as a promising candidate for a carbon neutral fuel.

Against this backdrop, we discussed on many occasions with industry, universities, and research institutes about having FCs support a wide range of operating temperatures and durability improvements that are important in the case of FC applications for HDVs, and examined the product targets for each HDV application that will be required when FCs are widely used around 2030, and the common FC stack performance specifications that will meet these product requirements. We then broke these product targets and the common specification goals down to the target materials that make up the stack and the direction of development, and established in March 2022 a new roadmap for fuel cells for HDVs. In addition, we examined the FC target for HDVs around 2040 and the targets for hydrogen storage systems to be achieved around 2030 and 2040, as well as the material development scenarios to achieve the FC target around 2040, formulated production technology targets for FCs based on the premise that full-scale, extensive use of FCVs and HDVs will begin around 2030, organized the ideal form of digital transformation (DX) technology to strengthen hydrogen and FC development capabilities (shorten development time). Then in February 2023 we updated the roadmap for HDV fuel cells.

In fiscal 2023, we established a system for regularly discussing benchmarking strategies and strategies for widespread use with relevant parties, and gathered information on changes in social and industrial trends, future market prospects, and so on. Meanwhile, we were examining the targets for liquid hydrogen storage systems that could not be established by fiscal 2022, and set targets for HDV fuel cells and high-pressure hydrogen storage systems around 2035, which is halfway between 2030 and 2040, as well as production technology targets for FCs.

This guidebook summarizes the following topics: (1) the approach to the product targets in the Roadmap; (2) the targets for FC systems and hydrogen storage systems; (3) the assumptions and calculation results from the simulation models used to examine the targets for FC systems; (4) the target materials and development direction for FCs and the policies on how to evaluate material properties; (5) the FC production technology; (6) the objectives and technical development issues facing hydrogen storage technology systems (high-pressure hydrogen and liquid hydrogen); and (7) the basic technologies related to DX to accelerate and streamline these developments.

In addition, while continuing to work toward the FCV targets around 2035 and 2040, we also plan to consider the need to review the fuel cells and hydrogen storage systems for HDVs in light of the latest trends, and to consider specific approaches to materials development using DX technology.

1.2 Importance of fuel cell vehicles as an industry and scenarios for their widespread use

As mentioned in the previous section, the extensive use of FCVs and large commercial vehicles equipped with FC systems is one of the keys to reducing CO_2 emissions in the transportation sector. The market size in the future around 2050, the year marked for achieving carbon neutrality, is estimated to be about 15 trillion yen for FCVs and about 21 trillion yen for FC trucks worldwide, and fuel cell vehicles could be an important industry for the use of hydrogen, even when compared to the future market size of power generation, green steel, and green chemicals, which are expected to drive high demand for hydrogen.

Table 1.2-1 shows the market size outlook for each hydrogen-using industry (fuel cell vehicles, green steel, green chemicals, and hydrogen power generation) around 2050. The total market size for fuel cell vehicles (FCVs and FC trucks) is estimated at 36 trillion yen (about 5 trillion yen for FCs and hydrogen storage systems). Japan is heavily dependent on imports of fuel and raw materials from overseas, and the automobile industry is also the largest contributor to the country's trade surplus. Consequently, it is important for Japan's green growth strategy to stimulate technological innovation in the field of FC mobile vehicles and ensure international competitiveness, including strengthening the supply chain, to capture the global market.

Table 1.2-1 Market outlook by industry

Industry	Market size	Calculation conditions
Fuel cell vehicles (FC and hydrogen storage system segment)	Approx. 36 trillion yen (approx. 5.0 trillion yen)	3.8 million FCVs (including light commercial vehicles) and approximately 1 million FC trucks per year in 2050*1
Green steel	Approx. 60 trillion yen	Up to 500 million tons per year in 2050*2 (trading unit price: 120,000 yen/ton)
Green chemicals	Approx. 6.6 trillion yen	Up to 57 million tons per year in 2050*2 (ethylene equivalent, trading unit price 140 yen/kg)
Hydrogen power generation	Approx. 97 trillion yen	1,850 GW in 2050*2 (50% operating rate, 12 yen/kWh power generation cost)

*1 Calculated based on the market share (forecast) of FCVs (passenger cars and vans) and FC trucks in 2050 according to reference [1], and data from the International Organization of Motor Vehicle Manufacturers (OICA) on the sales volume of passenger cars, light commercial vehicles, and trucks. (Assumptions: FCVs: 4 million yen per vehicle, FC trucks: 20 million yen per vehicle)

FC system: FCV system cost 4,000 yen/kW (assuming a 100-kW FC stack per vehicle), FC truck 9,000 yen/kW (assuming a 200-kW FC stack per vehicle), creating a market of about 3.4 trillion yen.

Hydrogen storage system: Assuming a system cost of 20,000 yen/kg (for hydrogen storage of 5 kg for FCVs and 60 kg for trucks), a market of about 1.6 trillion yen will be created.

*2 Calculated based on information in the Net Zero Emissions (NZE) scenario in reference [2].

*3 Calculated on the basis of the annual production capacity in the NZE scenario in reference [3].

1.3 Market size and scenario for the widespread use of future onboard FCs

Next, the market size (in terms of capacity) of FCs used in FCVs and FC trucks and the assumed scenario for widespread use are shown in Table 1.3-1. The market size was estimated for FCVs and FC trucks for around 2030, around 2035, and around 2040.

Regarding FCVs, for average annual global production volume for the past three years by passenger car segment, we made the following assumptions in the estimate: (1) that the market potential for FCVs lies in the large-sized, long-distance use segment (E) and above (including SUVs), which require high energy density, and in MPVs and pickup trucks; and (2) that there is potential for a gain in market share for the medium-sized SUV segment (D), which can utilize the potential of FCVs (refueling time, cruising range, etc.), including the space allowance for FC and hydrogen storage systems. The share of each segment in 2030 was assumed to be 1% for sedans in the E segment and above, SUVs in the D segment and above, and MPVs, and 2% for pickup trucks. For the period from 2030 to 2040, we assumed a compound annual growth rate (CAGR) of 20% (since the CAGR for BEVs in the 2020s is assumed to be in the 20% range, we assumed that the competitiveness of BEVs and FCVs will be equal in the 2030s).

For FC trucks, referring to reference [4], we estimated the market size based on the projected sales volume in 2030, 2035, and 2040 in China, the U.S., and Europe, which are considered to be the major markets. Based on the sales volumes of FCVs and FC trucks, the market size for onboard FCs (in terms of FC capacity) was calculated using 100 kW for FC stacks in FCVs and 200 kW for FC trucks.

We expect to see the market for FC vehicles expand slowly until around 2030. From now until then, there will be promotion of technology development and multiple applications of such vehicles secured through using DX to enhance development capabilities plus subsidies and other forms of support. From 2030 the hydrogen supply should start to become sufficient, the full use of DX technology will accelerate and improve the efficiency of materials and production technology development, and the performance of FC and hydrogen storage systems will improve and their costs will decrease. These factors together should bring down the price of hydrogen and take us into a phase of approaching fuel parity, which should in turn accelerate the widespread use of FC vehicles.

In such a future outlook, the key is to promote technology development based on collaboration among industry, academia, and government, assuming that the targets for FC and hydrogen storage systems and FC production technology outlined below will be achieved and that DX technology will be actively applied to achieve these targets.

Table 1.3-1 Size of future markets for onboard FCs and assumed scenarios for their widespread use

		From present	From 2030	From 2035	From 2040
Market size (Year)	In terms of FC capacity	Around 2 GW (FY2022)	Around 60 GW (around FY2030)	Around 150 GW (around FY2030)	Around 300 GW (around FY2040)
	Number of FCVs	Approx. 15,000 vehicles	Approx. 0.3 million vehicles	Approx. 0.7 million vehicles	Approx. 1.8 million vehicles
	Number of FC trucks	Approx. 2,000 vehicles	Approx. 0.15 million vehicles	Approx. 0.4 million vehicles	Approx. 0.6 million vehicles
Possible scenario for widespread use		Gradual market expansion, including government subsidies.	The supply of hydrogen is sufficient and the costs of FC and hydrogen storage systems are falling, leading to an expanding market.	Approaching fuel parity, and the market is expanding further.	Low-cost, clean hydrogen is in circulation and its use in all industries is becoming more widespread.

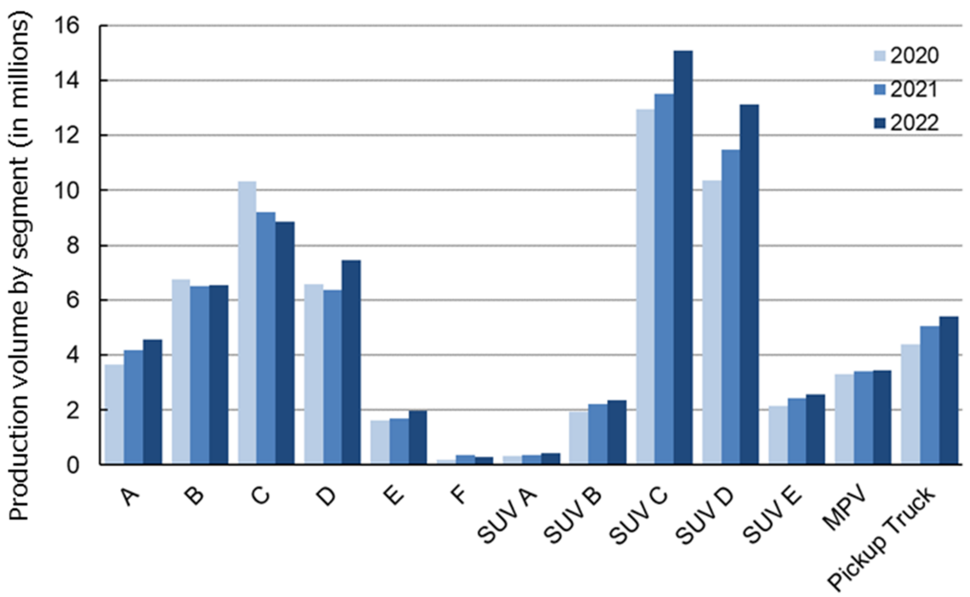


Fig. 1.3-1 Annual production volume by passenger car segment (3-year average for 2020–2022, based on data from Marklines' database)

(References)

[1] IEA, "Net Zero Roadmap—A Global Pathway to Keep the 1.5°C Goal in Reach", https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach

[2] IEA, "Net Zero by 2050", https://www.iea.org/reports/net-zero-by-2050

[3] IEA, "Energy Technology Perspective 2023", https://www.iea.org/reports/energy-technology-perspectives-2023

[4] PwC Strategy&, "The Dawn of Electrified Trucking" (2022/10)

2. Product Targets

This chapter presents targets that encompass requirements based on requirement specifications in each product's general usage environment. However, when looking at the world as a whole, there are cases where the usage environment conditions and the like are unique to the categories of some products, so we will continue to consider requirements for some of them and add them in the future.

In addition to conventional passenger cars, the categories of vehicles that are expected to use FC systems around 2030 and the applications that should be targeted are listed below. In this revision of the guidebook, the following application specifications were assumed so as to target categories of vehicles that include trucks, railroads, industry, industrial machinery, farm machinery, and ships.

- Trucks: 25 tons or less (expected to be the segment that consumes the most hydrogen based on market size and operating area)
- Ships: Coastal cargo ships, coastal passenger ships (requiring long operating hours)
- Railroads: Replacement of existing diesel trains (e.g. on lines where electrification is difficult). Some trains are being considered for replacement in the future.
- Construction machinery: Medium to large units that currently have diesel engines and carry a lot of fuel on board
- Industry: Forklifts (vehicles requiring long operating times)
- Farm machinery: Vehicles requiring continuous, long operating hours over relatively large agricultural areas

(*) Ocean-going ships and aircraft were excluded from the ship's category, taking into account their suitability for hydrogen-based fuels (such as synthetic fuels) and biofuels.

If the requirements for 25-ton class heavy-duty trucks could be met in terms of output and durability by around 2030, those for the applications listed above could also be met; however, this is unlikely for 44-ton class trucks. Therefore, the target values for the specifications required from around 2035 onwards have been extended to include heavy trucks in the 44-ton class, which would then cover most of the heavy-duty truck market.

Table 2-1 sets out definitions of the requirement specifications, and Table 2-2 shows the key requirement specifications for each application around 2030. In Table 2-2, the requirement specifications for heavy-duty trucks in the 44-ton class in 2035 and 2040 have also been added.

Table 2-1 Definition of requirements specification

Requirements specification item	Definition
Maximum system output [kW]	The maximum output of FCs and rechargeable batteries combined.
FC system rated power output [kW]	The rated power output of the FC system (net output).
Outside air temperature [°C]	The outside air temperature when using the product.
Durability [10,000 hrs]	The durability required for the product.
Cooling capacity [kW/°C]	Cooling capacity = Radiator cooling capacity/(Coolant temperature − outside air temperature) Here, the coolant temperature is 105°C and the outside air temperature is 45°C.
Altitude [1,000 m]	The maximum altitude at which the product can be used.
Allowable FC system installation space [L]	The allowable space for the FC system that can be installed in a product.
Allowable FC system weight on board [kg]	The maximum allowable weight for the FC system that can be installed in a product.
Allowable hydrogen storage installation space [L]	The maximum allowable space for the hydrogen storage that can be installed in a product.
Allowable hydrogen storage weight on board [kg]	The maximum allowable weight for the hydrogen storage that can be installed in a product.

Table 2-2 List of key requirement specifications for each application around 2030
(also shows the requirement specifications for around 2035 and 2040, only for 44-ton class heavy-duty trucks)

Application	Max. system output [kW]	FC system rated power output [kW]	Outside air temperature [°C]	Durability [10,000 hrs]	Cooling capacity [kW/°C]	Max. operating altitude [1,000 m]	Max. allowable FC system installation space [L]	Max. allowable FC system weight on board [kg]	Max. allowable hydrogen storage installation space [L]	Max. allowable hydrogen storage weight on board [kg]
25-ton class heavy-duty truck	300	200	−30 to 50	5	3.5	3 5 (when performance degradation is allowed)	502	230	2,500*1	400
44-ton class heavy-duty truck (2035)	425	325	−30 to 50	5	4.7	3 5 (when performance degradation is allowed)	502	460	2,500*1	400
44-ton class heavy-duty truck (2040)	450	350	−30 to 50	5	3.5	3 5 (when performance degradation is allowed)	502	460	2,500*1	400
Coastal cargo ship	600	600	−25 to 50	6	100	0.02	18,000	11,000	72,000	*2
Coastal passenger ship	480	480	−25 to 50	3	100	0.02	7,000	4,000	24,000	3,000
Two-car train formation	800	400	−30 to 45	5	6	1.3	1,300	1,000	5,086	2,000
20-ton class hydraulic shovel	120	120	−30 to 50	1	1.27	5 (when output is limited)	1,300	1,000	1,463	400
13-ton class hydraulic shovel	70	70	−30 to 50	1	1.0	5 (when output is limited)	400	500	1,280	400
1-2-ton class forklift	30	8	−20 to 40	2	1.0	0.5	339	500	84	80
Farm tractor	50 kW or more	50 kW or more	−30 to 45	1	1.14	2	125	250	500	120
				Assuming a 50-kW class						

*1 When the installation space is secured on the premise of extending the wheelbase due to the relaxation of the overall length regulations.

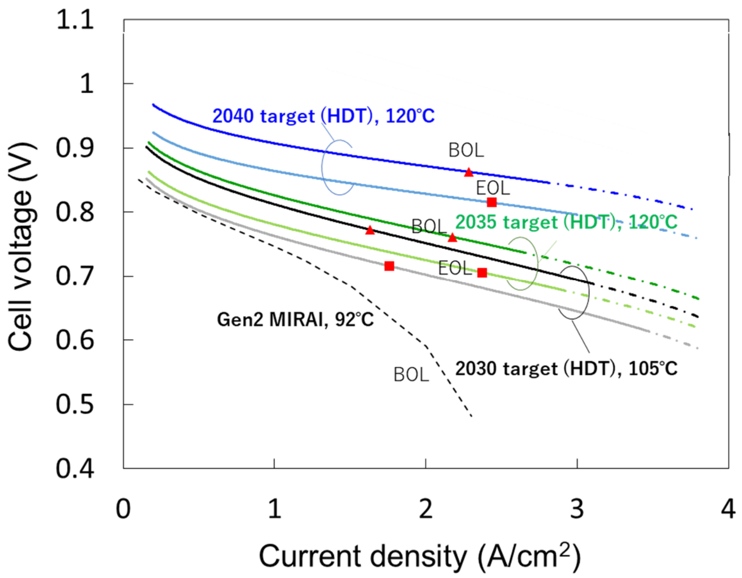
*2 Because there is a mass tolerance for coastal cargo ships.

3. FC System Targets

This chapter covers the performance targets (I-V characteristics, endurance time, cost, Pt usage, volumetric power density) for around 2030, 2035, and 2040, based on the requirement specifications derived from the general usage of each application shown in Chapter 2 and assuming general operating patterns for each application. These targets include the target performance for each application.

3.1 Required I-V characteristics (BOL/EOL)

Figure 3.1-1 shows the I-V characteristics derived from the product requirements, including durability requirements, assuming the FC system specifications for each application.



Note 1: BOL (Beginning of Life: initial performance), EOL (End of Life: durability after performance), durability pattern: WHVC + start/stop (1 time/cycle).

Note 2: Target I-V characteristics around 2030 (assumed amount of Pt: 0.19 g/kW): ▲: Current density: 1.63 A/cm^2, voltage: 0.77 V, ■: Current density: 1.76A/cm^2, voltage: 0.72 V.

Note 3: Target I-V characteristics around 2035 (assumed amount of Pt: 0.13 g/kW): ▲: Current density: 2.18A/cm^2, voltage: 0.76V, ■: Current density: 2.37 A/cm^2, voltage: 0.71 V.

Note 4: Target I-V characteristics around 2040 (assumed amount of Pt: 0.07 g/kW): ▲: Current density: 2.29 A/cm^2, voltage: 0.86 V, ■: Current density: 2.44 A/cm^2, voltage: 0.81 V.

Note 5: The temperature is the temperature at the outlet of the coolant for the stack.

Fig. 3.1-1 Target I-V characteristics curves around 2030, 2035, and 2040 derived from heavy-duty truck product requirements

In this revision, in addition to the target values for I-V characteristics around 2030 and 2040, a new target value for around 2035 has been added. The target value for around 2030 was derived from the product requirements for the 25-ton class heavy-duty truck, which is assumed to be the most stringent of all applications in this assumed age group. The target values for 2035 and 2040 were derived from a requirement that the existing engines for all classes up to the 44-ton class can be replaced with FC systems, including the installation conditions (diesel parity). In addition, the target value for around 2035 was derived as an intermediate one between the years around 2030 and 2040. Note that in the figure, a ■ on the I-V characteristics curve indicates the rated thermal operating point from which the characteristics curve was derived, and a ▲ indicates the operating point for the equivalent rated thermal power at BOL. Also note that the dotted part of each line represents the area that was not used in the simulation for each of the applications, but this will vary depending on the application, including passenger cars and control design. The method for deriving the I-V characteristics is described in Section 3.2.

3.2 Examination of required I-V characteristics

The required I-V characteristics presented must be common specifications that meet the product requirements for any envisioned future applications. To derive common target I-V characteristics, we calculated target values for heavy-duty trucks, which are considered to encompass the way FC stacks are used in each application, and confirmed that the target values could meet the product requirements of other applications (system feasibility verification), and then determined common target I-V characteristics.

Table 3.2-1 shows the product requirements and system configuration for heavy-duty trucks around 2030, 2035, and 2040.

Table 3.2-1 Product requirements (calculation assumptions) for heavy-duty trucks around 2030, 2035, and 2040

Item		Target values for around 2030		Target values for around 2035	Target values for around 2040
Vehicle		25-ton truck	44-ton truck	44-ton truck	44-ton truck
Product targets	Durability	50,000 hours	←	←	←
	Cruising range	1,000 km or more	←	←	←
Output	FC steady output [kW] * When the current running resistance value is used	200	300	325	350
	Max. system output [kW] * When the current running resistance value is used	300	400	425	450
Vehicle/ System	Running resistance (air resistance Cd)	Current value (not disclosed)		←	Current value reduced by 10%
	Number of FC stacks [units]	2	4	2	2
	Number of cells [cells]	330		330, 396	330
	Cell area [cm^2]	273		273, 283	293
	Rechargeable battery capacity [kWh]	90		←	←
	Radiator heat dissipation [kW]	210	336	282–420	263
	Max. water temperature for FCs [°C]	105		105, 110, 120	120
	Power consumption of FC BoP components *Ratio when Gen2 is 100%	100% each		ACP: 96.5%, WP: 95%, HP: 50%, FDC: 90%, RadFan: 90%	ACP: 93%, WP: 90%, HP: 0% FDC: 80%, RadFan: 80%

These are the preconditions for calculating the I-V characteristic targets. As the table indicates, heavy-duty trucks have a long service life of 50,000 hours, and after the durability run, they must be able to run under high-load running conditions on a high-speed slope. In addition, the installation requirements for the system are stringent, and the product requirements must be met with the FC stack, rechargeable battery, and cooling system installed in a limited space. This is a more demanding requirement than for other applications.

The required I-V characteristics are calculated by estimating the performance degradation for each I-V characteristic through durability-run simulations, assuming multiple candidates for the BOL I-V characteristics and extracting the one that meets the performance requirements with the EOL I-V characteristics once performance has deteriorated. In the durability-run simulation, the I-V characteristic degradation due to catalyst deterioration is predicted when the durability-run pattern is repeated for the required durability period. Whether the power performance requirements are met is determined by whether the vehicle can continuously run under high-speed uphill running conditions (90 km/h on average expressway hills) with the EOL I-V characteristics and the specified cooling capacity.

For the I-V characteristics, using Eq. (1), the changes in activation, gas diffusion resistance, and ohmic resistance are given to the existing base I-V characteristics, and several candidate (sample) I-V characteristics are set. The EOL I-V characteristics are calculated for each sample to determine whether the performance requirements are met. From the set of candidates for I-V performance that meet the requirements, samples with the lowest activity, samples with the highest gas diffusion resistance, and others are presented and selected according to the objectives.

$$V = V_{OCV} - R_{\Omega} I - \frac{RT_{cl}^{out}}{\alpha F} \log\left(\frac{I}{i_0}\right) - \frac{RT_{cl}^{out}}{\alpha F} \log\left(\frac{C_{ref}}{C_{O2} - R_{gas}\frac{I}{4F}}\right) \qquad (1)$$

Here, I is the current density and V is the cell voltage. The exchange current density, which is an indicator of activity, is represented by i_0, gas diffusion resistance by R_{gas} and ohmic resistance by R_{Ω}.

The I-V characteristics that meet the required durability values were found using the calculation procedure shown below:

1) Set the vehicle requirements (specifications, durability, durability-run pattern, power performance requirements).
2) Generate the I-V characteristics based on Eq. (1) by extracting the values from the upper and lower limits of each parameter, namely the exchange current density (i_0) (an activity indicator), the ohmic resistance (R_{Ω}) (including resistance components such as proton resistance), and the gas diffusion resistance (R_{gas}).
3) Calculate the degradation of the I-V characteristics from the initial I-V characteristics due to FC degradation when the vehicle is repeatedly driven for the durability period in a simulated durability-run pattern.
4) Determine whether the power performance requirements are met with the I-V characteristics after the durability period.

3.3 Other technology targets for FC systems/stacks

Table 3.3-1 shows a list of targets other than I-V characteristics that are important for FC systems and stacks. We will continue to examine and fill in the blank sections in the future.

Table 3.3-1 FC system/stack target values for around 2030, 2035, and 2040

Item	Target values for around 2030	Target values for around 2035	Target values for around 2040	Remarks
Durability [h]	50,000	50,000	50,000	*Refer to Section 2.2.2
FC system cost [10,000 yen/kW]	0.9			*Refer to Section 2.3.1
FC stack cost [10,000 yen/kW]	0.45			*Refer to Section 2.3.1
Pt loading [mg/cm^2] of which: Pt loading of the cathode catalyst layer [mg/cm^2] and Pt loading of anode catalyst layer [mg/cm^2] Pt usage [g/kW]	0.24 0.20 0.04 0.19	0.22 0.18 0.04 0.13	0.14 0.12 0.02 0.07	*Refer to Sections 2.3.3 and 2.5.1 For the Pt usage, refer to the description on the thermal rating for heavy-duty trucks
Volumetric power density of FC systems [kW/L] *Max. output basis	0.6	0.75	0.8	*Refer to "heavy-duty truck" in section 2.3.2
Volumetric power density of FC stacks [kW/L] *Rated power output basis	6.76	8.42	10.38	*Refer to Section 2.3.2

4. Target FC Materials

4.1 Target FC materials

Based on the physical property parameters required in order to meet the target BOL I-V characteristics for around 2030, 2035, and 2040 shown in Figure 3.1-1, the target physical property items and values for the main materials for around 2030, 2035, and 2040 were determined as shown in Table 4.1-1. The maximum temperature of the electrolyte membrane surface is +5 to 10°C compared to the coolant outlet temperature, but under most driving conditions in normal driving, the temperature is around 70°C, and the materials are designed to be able to withstand a wide range of operating conditions. For reference, the measured values of the physical properties and characteristic values of the membrane electrode assembly (MEA) made of the current materials are also shown for each item.

Table 4.1-1 Physical property targets for main materials around 2030, 2035, and 2040

(The ★ symbol indicates that measurements will be taken in the future.)

Element	Physical properties	Target values for around 2040	Target values for around 2035	Target values for around 2030	Gen2-MIRAI[*4]	General material	
Air electrode catalyst layer	Pt loading ($mg\ cm^{-2}$)	0.12	0.178	0.20	0.17	0.20	TKK, Pt/C TEC10V30E[*4]
	ECSA ($m^2\ g^{-1}$)	200	60	60	48	61	
	Mass activity @120°C, 100% RH, O_2 partial pressure 100 kPa_{abs}, 0.9 V ($A\ g^{-1}$)	42,500	4990	—	—	—	
	Mass activity @80°C, 100% RH, O_2 partial pressure 100 kPa_{abs}, 0.9 V ($A\ g^{-1}$)	39,000	4630	1740	500	95	
	Catalyst layer gas diffusion resistance ($s\ m^{-1}$)	8	10@80°C, 80% RH	10@80°C, 80% RH	9.1@80°C, 80% RH	18.1@80°C, 80% RH	
	Catalyst layer thickness (μm)	3.6	6.0	6.0	9.1	7.4	
	Ionomer H^+ conductivity @120°C ($S\ cm^{-1}$)[*1]	0.15@12% RH	0.05@30% RH	—	—	★	Chemours Nafion™ D2020 Catalyst layer resistance[*5]
Electrolyte membrane	Film thickness (μm)	1	5.0	8.0	8.5	25	Chemours Nafion™ NR211[*5]
	H^+ conductivity @120°C ($S\ cm^{-1}$)[*1]	0.15 @12% RH	0.05 @30% RH	0.032 @30% RH	0.018 @30% RH	0.016 @30% RH	
GDL/flow channel/ separator	GDL area resistance (Ωcm^2)	0.0010	0.0010	0.0010	★	<0.01	SGL Carbon SIGRACET® 22BB[*6] Molecular diffusion resistance[*5]
	Flow channel/GDL (Molecular diffusion resistance) (s/m)[*2]	16[*3]	16@80°C, 80% RH	18@80°C, 80% RH	58.3@80°C, 80% RH (Parallel flow channel)	60.8@80°C, 80% RH (Parallel flow channel)	
	GDL/separator, separator/separator, etc.: Total contact resistance (Ωcm^2)	0.0004	0.0065 (After EOL)	0.0065	★	—	

*1: The H^+ conductivity of the electrolyte membrane is the conductivity including the reinforcing material. Conductivity under conditions that ensure durability, such as the addition of quencher. The table shows the conductivity at 120°C compared to the 2030 target, but this target must be met in the range of 55 to 125°C (humidity of 12% RH or more). For the upper temperature limit, the simulation results shown in Figure 4.2-3, which indicate that the electrolyte temperature rises about 3°C above the coolant outlet temperature of 120°C, were taken into account in the performance requirements, and a margin of 2°C was added to account for simulation error, resulting in a setting of 125°C. The lower limit temperature was set with the aim of ensuring fuel efficiency during normal driving (coolant outlet temperature of around 70°C) as mentioned above, assuming a cathode inlet temperature of 55°C under these conditions. Proton conductivity in even lower temperature regions is considered a topic for future study. As for the humidity, it was set based on the fact that the humidity does not fall below 12% at the cathode inlet, as shown in the humidity distribution in Figure 4.2-3.

*2: A characteristic value determined by the combination of GDL and flow channel structure.

*3: The value has been updated from those in the 2022 edition of the guidebook, taking into account the progress of the current NEDO project and the scope for future improvements.

*4: Actual measurements using the MEA of the second-generation MIRAI and analysis results (measurement by FC-Cubic)

*5: Values measured with MEA composed of the following: catalyst: Tanaka Kikinzoku Kogyo TEC10V30E; cathode catalyst loading: 0.2 mg-Pt/cm^2; anode catalyst loading: 0.1 mg-Pt/cm^2; ionomer: Chemours Nafion™ D2020; I/C: 1.0, electrolyte membrane: Chemours Nafion™ NR211; GDL: SGL Carbon SIGRACET® 22BB. (Measured using FC-Cubic)

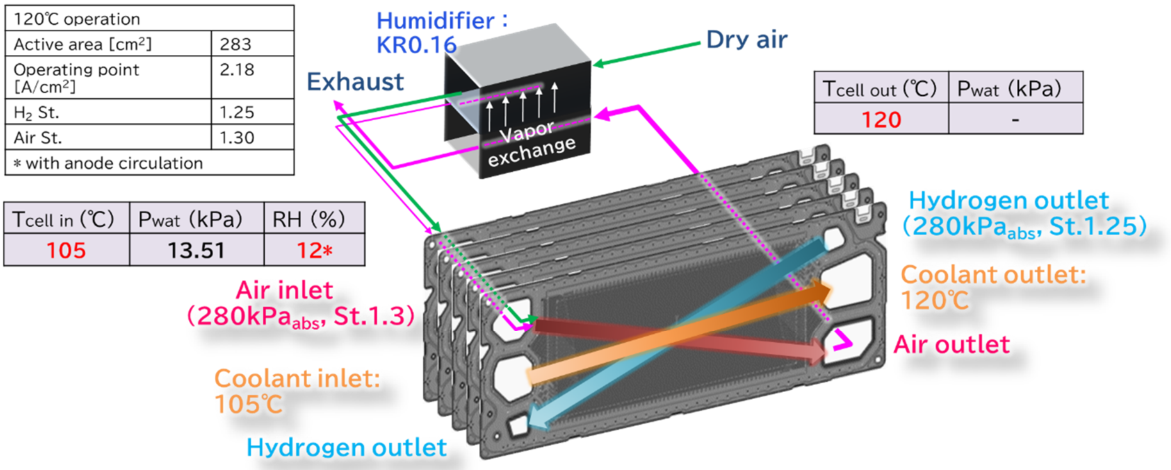
*6: Manufacturer's published values: https://www.sglcarbon.com/en/markets-solutions/material/sigracet-fuel-cell-components/

4.2 Examination of target materials

Whereas Figure 3.1-1 showed the BOL and EOL I-V characteristics required to achieve system performance, this section presents the target physical properties for each element necessary to achieve this target I-V. The target physical properties are presented in two stages. First, a simulator that predicts steady-state I-V based on physical properties is used to calculate the material property values that meet the target BOL I-V. Then, using the results of this trial calculation as a reference, the target physical properties are set, taking into account the actual measurement technology.

The model in reference [1] is used for the simulation. The length of the cell channel is much greater than the thickness of the MEA, and the concentration distribution of the matter in the direction of the channel is negligibly small compared to that perpendicular to the electrolyte membrane. Based on such nature, this model applies the so-called 1+1D model, which treats the transport phenomena of heat and matter in the flow direction and perpendicular direction separately. In this approximation, the gas composition, flow rate, and temperature change in the flow direction are calculated by taking into account the conservation of energy and matter between the flow channel and the MEA at each location. Vertical heat and mass transport can be obtained by solving the governing equations for heat and mass transport or reactions in the vertical direction at each location.

Figure 4.2-1 shows the cell configuration and operating conditions corresponding to the power performance requirements based on product and system examination around 2035. The coolant outlet temperature has been raised to 120°C. The aim is to cool the heat generated by the cells using a limited-area radiator in accordance with the power performance requirement. With the increase in operating temperature, the humidity at the cathode inlet is assumed to be 12% RH.



Continuous rating point (120°C operating condition)/with hydrogen circulation			
Active area	283 cm^2	Air inlet pressure/outlet pressure	280/250 kPa_{abs}
Operating point current	2.18 A cm^{-2}	Humidification module outlet pressure	240 kPa_{abs}
H_2 stoichiometric ratio	1.25	Amount of water vapor exchange	16%
Air stoichiometric ratio	1.30	Cell inlet coolant temperature	105°C

Fig. 4.2-1 System configuration and operating conditions assumed for around 2035

The initial I-V characteristics obtained by simulation are shown in Figure 4.2-2 along with the I-V characteristics presented by MBD and other I-V characteristics. For reference, the I-V characteristics after degradation are also shown in the same figure. The initial overpotential obtained from this simulation are also shown. The distribution of current density, relative humidity, oxygen partial pressure, and temperature inside the cell obtained through simulation are shown in Figure 4.2-3.

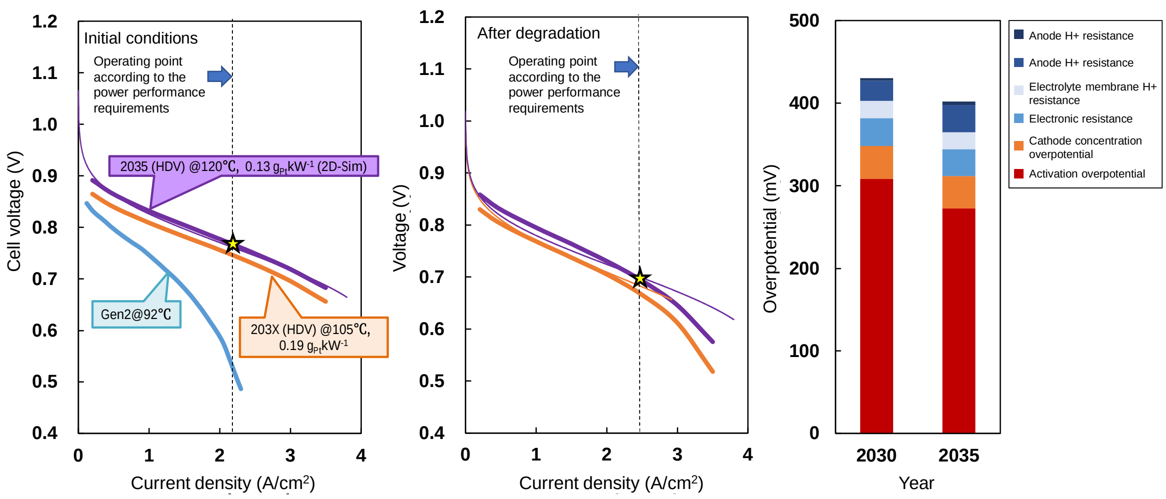


Fig. 4.2-2 Two-dimensional simulation results for the required initial and post-degradation I-V characteristics and overpotential breakdown

The figure on the left shows the initial I-V characteristics of Gen2 MIRAI (blue), the initial I-V characteristics required around 2030 (orange), and the initial I-V characteristics required around 2035 (purple; the thick line is 2D simulation, the thin line is MBD). The middle figure shows the I-V characteristics after degradation that would be required around 2030 and 2035. The diagram on the right shows the simulation results for the breakdown of the overpotential in the I-V characteristics around 2030 and 2035. Overpotential isolation was evaluated under operating conditions with power requirements of around 2030 and 2035, respectively, but at a current density of 2.5 A cm^{-2}.

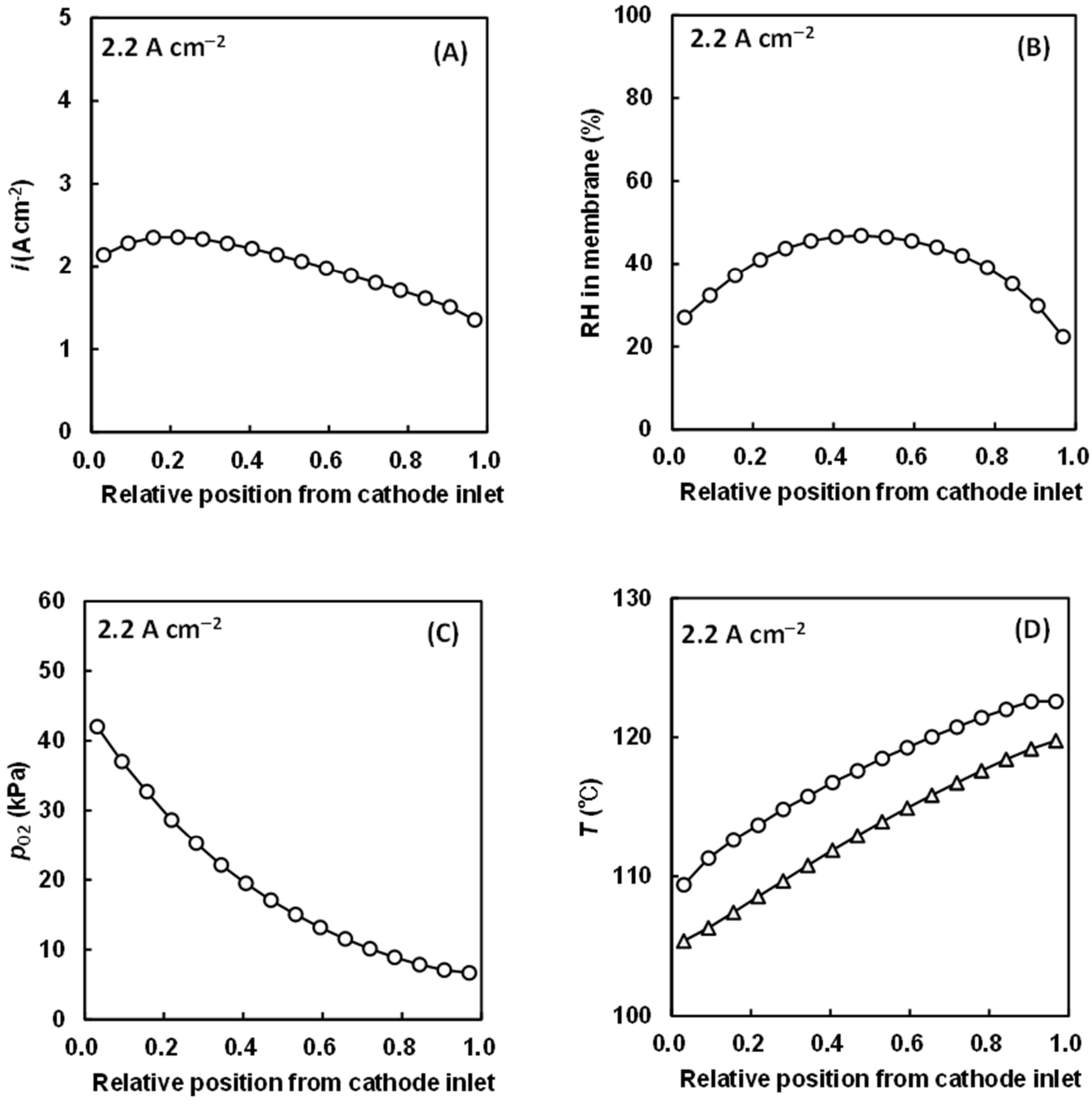


Fig. 4.2-3 (A) Current density distribution, (B) relative humidity distribution, (C) oxygen partial pressure distribution, (D) temperature distribution in the FC cell plane during continuous rated point operation (2D simulation I-V curve in Fig. 2.5.3-5) under the performance requirements for around 2035, where △ (triangle) indicates the cooling water temperature and O (circle) indicates the electrolyte membrane surface temperature

4.3 Direction of FC material development

Table 4.1-1 shows the target FC materials for around 2030, 2035, and 2040. It is impossible to achieve these goals for FC materials at the current speed of research and development, in addition to the traditional trial-and-error approach of experimentation in FC material research and development. Therefore, promoting the use of advanced analysis technologies such as various quantum beams, various simulation and trans-scale simulation technologies, high-speed search technologies such as material informatics (MI), measurement informatics (MEI) and process informatics (PI), and automated and autonomous experiments, etc., and link them organically to accelerate research and development is crucial. In light of this, advanced analysis technology is discussed in Section 4.6, and other DX technologies are covered in Chapter 7.

4.4 PFAS regulations

In January 2023, five European countries (Denmark, Germany, the Netherlands, Norway, and Sweden) submitted draft regulations to the European Chemical Agency (ECHA) on the manufacture, marketing, and use of more than 10,000 types of organic fluorine compounds (per- and polyfluoroalkyl substances, or PFAS). However, there have been cases in the past where the ECHA has received comments through open consultations as part of its deliberation process and then withdrawn or modified the proposed regulations (e.g. bisphenol A, PFHxA). It is considered that there is a possibility that the regulations for fuel cell materials may also be modified or withdrawn, or that the grace period may be modified, depending on future deliberations [2]. However, since deliberations take time, it is expected that those on regulations for fuel cell materials will continue during the review period of the "NEDO Roadmap for Fuel Cell and Hydrogen Technology Development: Roadmap for Fuel Cells for FCVs/HDVs" and the regulations will not be finalized. For this reason, there is a need to develop technologies that can be used both when the proposed PFAS regulations are enforced and when they are withdrawn.

4.5 Issues regarding the development of FC materials

Issues regarding the development of FC materials for around 2030, 2035, and 2040 are shown in Table 4.5-1.

Table 4.5-1 Issues regarding the development of FC materials for around 2030, 2035, and 2040

Material system	Target	Development phase *	Technical issues
Catalyst	Around 2030	Phase 3	Low-temperature operation, improvement of durability, impurity tolerance
		Phase 4	Development of high durability technology, establishment of technology for recycling precious metals from waste products, mass production of new high-temperature catalysts
	Around 2035	Phase 3	Extreme catalyst based on the current principle (high activity, Pt elution suppression), high-performance anode (radical suppression, impurity tolerance), ultra-durable, high-performance support (operates over a wide range of temperatures and humidity)

		Phase 4	Mass production of extreme catalyst based on the current principle, mass production of high-performance anodes, mass production of ultra-durable, high-performance support
	Around 2040	Phase 1	Non-platinum (acid nitride, etc., novel surface sites that replace precious metals)
		Phase 2	Novel precious-metal active sites, ultra-low platinum (alkaline atmosphere, (monoatomic/few atomic catalyst active sites))
		Phase 3	Catalyst that defies scaling rules, ultra-durable, non-Pt elution, non-platinum model catalyst
Electrolyte membrane material	Around 2030	Phase 3	Low-temperature operation, improvement of durability (radical quencher)
		Phase 4	Development of high-durability technology
	Around 2035	Phase 3	Achievement of both thin-film and durability (radical quencher and reinforcing layer compatible with new materials, film-forming properties)
		Phase 4	Large-area thin films, roll-to-roll
	Around 2040	Phase 1	Investigation of membrane formation technology for materials without accompanying water Turning membrane technology into a platform, ultra-thin film, web handling in MEA manufacturing technology
		Phase 2	Development of new materials, clarification of the correlation between F-series and HC-series polymer structure and performance, membrane enhancement with accompanying water
MEA/catalyst layer	Around 2030	Phase 3	Low-temperature operation, improvement of durability, ionomer coating form control, optimization of catalyst layer structure
		Phase 4	Increasing the output and durability of FC stacks
	Around 2035	Phase 3	Ideal catalyst layer structure, reduction of catalyst layer gas diffusion resistance, catalyst layer process to bring out performance, ensuring MEA durability
		Phase 4	Establishment of technology to improve MEA performance
	Around 2040	Phase 1	Conceptual study of new catalyst layer and MEA structure
		Phase 2	Investigation of catalyst layers and new MEA manufacturing processes for new materials
		Phase 3	Development of catalyst layers and MEA mass production technology for new materials
GDL/MPL, flow channel etc.	Around 2030	Phase 3	Reduction of gas diffusion resistance, optimization of GDL and MPL functions through combination with other members
		Phase 4	Design for high MEA durability
	Around 2035	Phase 3	Thin GDL, GDL-free, ensuring GDL mechanical properties, improving diffusion under ribs, low-cost porous flow channels, improving GDL electronic and thermal conductivity
		Phase 4	Overall design, including flow channels
	Around 2040	Phase 1	Conceptual study of new GDL/flow channels
		Phase 2	Investigation of GDL/flow channels for new catalyst layer
		Phase 3	New GDL/flow channel optimization design
Separator, seal, etc.	Around 2030	Phase 3	Development of separators with high corrosion resistance and low contact resistance, development of gaskets and adhesives that can be used in a wide range of operating conditions
		Phase 4	Development of high durability technology, development of materials that can be produced at high speed and low cost, accelerated evaluation, life prediction analysis technology
	Around 2035	Phase 3	Technology that can operate at high temperatures
		Phase 4	Application of materials that can operate at high temperatures, surface treatment, balancing low cost and performance, low-cost flow channel molding technology

* Phase 1: Discovery of new seeds and scientific principles, Phase 2: Establishment of concept and technology seeds based on new scientific principles, Phase 3: Elemental technology development, Phase 4: Technologies for practical application.

4.6 Advanced analysis technology

Within a fuel cell there is a hierarchical structure of reactions with different spatial and temporal distributions. These include charge transfer at the catalyst interface, reaction distribution in the micrometer-scale catalyst layer, and reaction and water distribution in the cell and stack on spatial scales of tens of micrometers or more as a result of the reaction. Therefore, it is necessary to combine various analysis methods. In addition, the search for and development of the materials envisioned by the 2040 target will require the application of advanced analysis that uses the elucidation of advanced phenomenological approaches and mechanisms to determine the fundamentals of functional expression and to visualize complex structures and processes. Table 4.6-1 lists quantum beam facilities in Japan and their features.

Table 4.6-1 Quantum beam facilities in Japan and their features

	SPring-8	NanoTerasu	J-PARC
Radiation source	Synchrotron radiation X-rays High-energy region (hard X-rays)	Low-energy region (soft X-rays)	Neutron beam
Target	Structures Cell imaging Process technology	Chemical bonds High temporal and spatial resolution Development of new materials based on new principles	Structures and molecular motion Wide-field imaging Material and component development
Technology (example needs)	High-energy X-ray diffraction and total scattering Medium- to long-term structure of catalysts and catalyst supports under controlled atmosphere	Soft X-ray XAFS Electronic structure and local structure of oxygen species on the catalyst during the fuel cell reaction process	Neutron imaging Water/ice distribution in a full-size cell when the fuel cell is operating
	Small-angle X-ray scattering (SAXS) Analysis of the regular structure of electrolytes on a macroscale under controlled atmospheres	High-resolution soft X-ray RIXS Electronic and local structures of oxygen species on catalysts and catalyst supports under controlled atmospheres	Small-angle neutron scattering (SANS)/Neutron reflectivity (NR) Ionomer/electrolyte membranes, nanoscale structures of bonded interfaces
	GI-WAXS, GI-SAXS Structure and orientation of ionomers under controlled atmospheres	High-resolution soft X-ray ptychography Three-dimensional structure of carbon supports and ionomers in the catalyst layer	Quasielastic neutron scattering (QENS) Molecular motion (diffusion, vibration, rotation) of water and protons in the catalyst layer/electrolyte membrane
Organization and human resources	Linked to industry, dynamic system management, budget		

In Japan, synchrotron radiation and neutron experimental facilities such as the world-class large-scale advanced synchrotron radiation facility SPring-8 and the high-intensity proton accelerator facility J-PARC are in operation, and the 3-GeV advanced synchrotron radiation facility (NanoTerasu), which mainly handles high-intensity soft X-ray radiation, will be commissioned in 2024. Large-scale upgrades are planned for each of the large experimental facilities over the next few years, and it is hoped that the beam intensity will lead to a significant strengthening of Japan's international competitiveness in analysis by world-leading experimental facilities. Thanks to significant increases in beam intensity and the introduction of new high-performance detectors and new measurement techniques, dramatic improvements in measurement and analysis methods are expected, including operando (under actual operation, or in the case of fuel cells, under power generation) measurement and DX. The hard X-rays available at SPring-8, the soft X-rays available at NanoTerasu, and the neutrons used at J-PARC have different properties, and their complementary use is expected to cover advanced multi-scale phenomenon analysis. The data obtained at the three facilities will be linked using DX technology and used in an integrated manner, which will be a strength of Japan.

(References)

[1] N. Nonoyama and Y. Ikogi, *ECS Trans.* **16** 13-21 (2008).

[2] Mizuho Research & Technologies, Ltd., "Proposed regulation of the eternal chemical substance 'PFAS' in Europe," February 2023

5. FC Production Technology Targets

5.1 FC production technology targets

In this edition of the guidebook, the targets for FC production technology are summarized in Table 5.1-1. Based on the assumption that the target of 800,000 FCVs by 2030 will be achieved, a scenario was created in which the scale of domestic production is increased from the current tens of thousands per year to 200,000 per year by 2030. The target tact time (TT) is set at 0.5 seconds per cell for the sheet process and 15 meters per minute for the continuous process. This is close to the calculated value based on a two-shift system at a manufacturing plant with an annual production capacity of 70,000 vehicles. Looking at the trends in FC development in Germany, France, South Korea and the U.S., many countries are planning to produce 200,000 vehicles per year with a tact time of 0.5 seconds.

The target values for FC system cost and FC stack cost have been set as shown in the table below based on the targets in the Ministry of Economy, Trade and Industry's (METI) "The Strategic Road Map for Hydrogen and Fuel Cells" and the DOE's estimates. The cost of both materials and processing needs to fall by about 70% from the current level. From the perspective of CN, we also set a goal of turning FC production plants into green factories.

Table 5.1-1 List of FC production technology targets

	Present	Around 2025		Around 2030	Around 2035	Around 2040
Scenario for widespread use (HDVs)	Hundreds of vehicles in Japan			100,000 vehicles in Europe, tens of thousands in Japan		15 million vehicles globally[*2]
HDV cost target			FC system FC stack	9,000 yen/kW[*1] 4,500 yen/kW	Further cost reduction	Equivalent to conventional vehicles (Numerical value being considered)
Scenario for widespread use (FCV)	7,500 vehicles in Japan			Equivalent to 800,000 vehicles in Japan[*3]	Equivalent to 2 million vehicles in Japan (estimate)[*8]	3–6 million vehicles in Japan[*4]
FCV cost target			FC system FC stack	4,000 yen/kW)[*1] 2,000 yen/kW	Further cost reduction	Equivalent to conventional vehicles (Numerical value being considered)
Manufacturing capacity target HDV+FCV*	30,000 vehicles/year (published figure)	→ 70,000 vehicles/year → 210,000 vehicles/year		210,000 vehicles/year	320,000 vehicles/year	→0.5 to 1.2 million vehicles/year
Line basic unit (estimated scale)	2,500 vehicles/month	6,000 vehicles/month × 1 location → × 3 locations or so		6,000 vehicles/month × 3 locations or so	7,000 vehicles/month × 4 locations or so	→ 10,000 vehicles/month × multiple locations
Production speed (Tact time)	Sheet process: 1 sec/cell[*6] Continuous process: 6 m/min[*7]			0.5 sec/cell[*6] 15 m/min[*7]	0.4 sec/cell[*6] 19 m/min[*7]	→ 0.33 sec/cell[*6] → 25 m/min[*7]
Target for reducing processing costs Target for reducing material costs	100% 100%			−70%[*5] −70%	−72%[*5] −72%	−74%[*5] −74%
Greening the energy consumption of factories	About 50%			80%		→100% achieved

[*1] According to the NEDO Roadmap for Fuel Cell and Hydrogen Technology Development: Roadmap for Fuel Cells for FCVs/HDVs (The values are set using the DOE 2030 target values as a reference)
[*2] Estimates based on the Hydrogen Council's "Hydrogen Scaling up" and other sources
[*3] METI's The Strategic Road Map for Hydrogen and Fuel Cells
[*4] The target number of vehicles was set by the Fuel Cell Commercialization Conference (FCCJ) with reference to the IEA's "Technology Roadmap Hydrogen and Fuel Cells," published in 2015 (the number was set to contribute to the 2050 target of an 80% reduction in greenhouse gas emissions, and 6 million vehicles in the high-level scenario, which assumes significant technological progress)
[*5] DOE Mass-Production Cost Estimation of Direct H_2 PEM Fuel Cell Systems for Transportation Applications: 2018 Update; ratio of current cost to 2030 cost projection; assumption that both material and processing costs are reduced by 70%; reduction rate to meet DOE Ultimate Target by 2050 set to the value after 2035.
[*6] Assumptions for the trial calculation: The tact time was calculated based on the stack specifications: 125 kW, 300 cells, and active area 250 cm^2, 20 days' operation, 2-shift production, and the production quantity (vehicles/month).
[*7] Assumptions for the trial calculation: The coating speed was estimated based on the production quantity (vehicles/month) and the shorter side length of the area when manufactured for an active area of 250 cm^2, width of 320 × 130, and under the operating condition according to [*3].
[*8] The value is an estimate based on the rate of growth of hydrogen consumption in the transportation sector according to the IEA's "Net Zero by 2050."

5.2 Production technology issues

Figure 5.2-1 shows the general FC manufacturing line process. At present, there is a significant loss of expensive materials, and the electrode coating process, the cell formation process, the separator process, the surface treatment process, and the aging process all take a long time. Even if production continues to increase, a huge amount of capital investment and factory space will be needed.

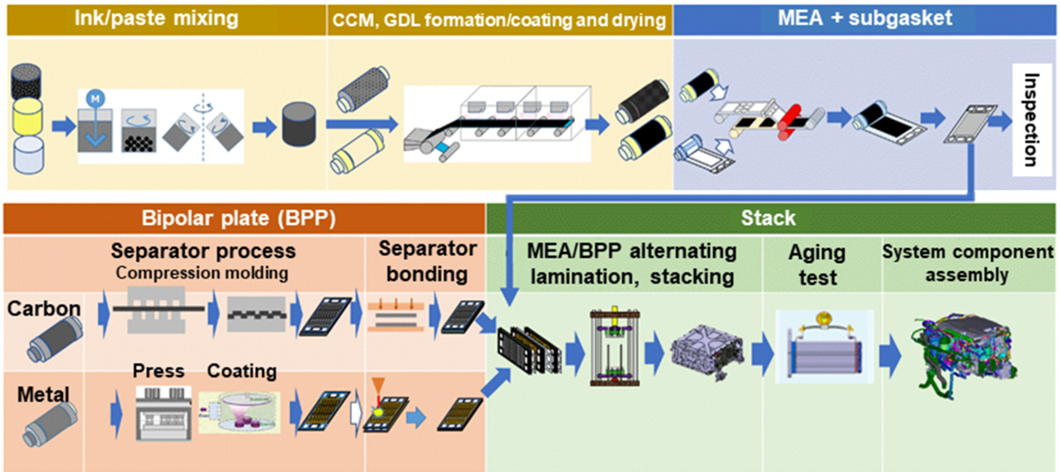


Fig. 5.2-1 Fuel cell stack production process

The direction of development for each of the main processes is shown in (1) to (6).

(1) Catalyst blending, coating, and drying process / MPL blending, coating, and drying process

These processes are important in determining the performance of the cell stack. In the past, however, optimizing the various manufacturing conditions to produce good catalysts involved trial and error, relying on intuition and experience, or experimenting by trying all possible combinations of the vast number of process parameters. All of these were very costly and time consuming. In addition, the catalyst metals and electrolyte materials used in these processes are expensive, but at present it cannot be said that the ideal microstructure has been achieved, with the minimum amount of material required in the optimum location. To reduce costs, it is necessary to pursue a microstructure closer to the ideal and to work on improving the yield of expensive materials. In addition, in trying to speed up this process, the drying process for the catalyst ink and GDL + MPL paste has become a bottleneck. Since the drying process requires a large amount of capital investment and energy, developing a method that can shorten the drying time has become a major issue.

(2) MEA and cell formation process

This process is important to ensure the reliability and durability of the seals in the cell stack. The adhesive used for the seal must have high durability and sufficient adhesion, and the adhesive must not contain volatile or eluting components that could poison the catalyst. In addition, many of the processes involved, such as applying and curing adhesives, are time-consuming and a barrier to improving productivity. Furthermore, since all the parts handled in this process are thin and soft, the difficulty of gripping, transporting, positioning, etc. is also a factor that takes time to solve.

(3) Bipolar flow channel formation process

The shape and pattern of the flow channel has a significant impact on fuel and oxidant supply, power generation distribution, and drainage. To further improve performance in the future, the flow channel is expected to become finer. Carefully selecting the appropriate processing technology, surface treatment technology, hydrophilization technology, etc. for the substrate to be applied should make it possible to ensure the separator functionality and stack durability.

(4) Surface treatment

HDVs will be need have a service life of 50,000 hours in the future, so further improvements in corrosion resistance and maintenance of low-contact resistance performance are required for the metal separator substrate and conductive surface treatment. Currently, the application of thin carbon-film coating (PVD, CVD, etc.) on SUS or titanium substrates is being considered, but the high vacuum process is a factor that increases cost. As such, adopting low-vacuum CVD and other methods is crucial, and there is a need to search for surface treatment technologies that do not use expensive vacuum equipment.

(5) Aging

Aging is a process in which a power-generation testing device is used to generate power after the stack has been assembled, simultaneously performing two tasks: (1) wetting the electrolyte in the cell to reduce the proton resistance, and (2) cleaning and removing contaminants that have adhered to the catalyst surface. There are many components in the FC manufacturing process that poison the catalyst, and the effects of each need to be understood. Measures must be taken to avoid or eliminate the use of components that strongly affect catalytic activity. Such components include adhesive-derived components, resin sheets, dirt on metal substrates, and other detritus derived from manufacturing machinery. Poisoning can also be accelerated by heating the workpiece. Consequently, the selection of materials and processing conditions must be considered in advance.

(6) Quality inspection

The current fuel cell production process includes inspection, leakage inspection (cells, stacks, pre-shipping), stack power generation inspection various inspection processes, including metal foreign object inspection in MEAs, short-circuit, and visual inspection, and the inspection cost accounts for 30% to 50% of the processing cost. In order to increase productivity, the acceleration, simplification, and elimination of inspection processes will be promoted in the future. The need also exists to promote greater efficiency in the current quality inspection for the sheet process by reducing intermittent operations and making it a continuous process.

6. Hydrogen Storage System Targets

6.1 Hydrogen storage system targets

Table 6.1-1 shows the hydrogen storage targets sorted by storage method.

Table 6.1-1 Hydrogen storage system targets

Storage method	Target type	Around 2030	Around 2035	Around 2040	Around 2050
High-pressure hydrogen storage High storage efficiency specification *1	Mass storage density [wt%]	10	—	15	—
	Volumetric storage density [g-H_2/L]	28*2	—	29*2, 3, 4	—
	Cost [10,000 yen/kg-H_2]	4	—	2	—
High-pressure hydrogen storage Low-cost specification *1	Mass storage density [wt%]	—	4*7	4*7	—
	Volumetric storage density [g-H_2/L]	—	28	29	—
	Cost [10,000 yen/kg-H_2]	—	2	(1)	—
Liquid hydrogen storage *1	Mass storage density [wt%]	—	20–30*5	30–40*5	—
	Volumetric storage density [g-H_2/L]	—	35	40	—
Hydrogen storage material *1	Mass storage density [wt%]	—	—	8 or more*2, 6	8 or more*2, 6
	Volumetric storage density [g-H_2/L]	—	—	70 or more*2, 6	70 or more*2, 6

Mass storage density = hydrogen mass loaded (kg) / storage container mass (kg) × 100

Volumetric storage density = amount of hydrogen loaded (g) / storage container volume (L)

*1 The target for the hydrogen storage system does not include BoP components.

*2 Hydrogen storage density for a container should be targeted at an $L/D \approx 5$.

*3 Ultra-high-strength FRP fibers, inspection technology using IoT and DX technology, and deregulation of safety factors for storage containers, etc., should be pursued in combination.

*4 For industrial applications other than HDVs and FCVs, the premise is to address the issue of developing a means to deliver hydrogen to the operation site.

*5 The target mass density for liquid hydrogen storage is determined for each application and specification.

*6 A storage pressure of 1 MPa or less is targeted.

*7 The target will be reviewed in fiscal 2024 in light of technological advances in Type 3 tanks.

The above targets are sufficiently competitive and challenging even when compared with overseas targets.

6.2 Hydrogen storage density required for each application

Figure 6.2-1 shows the mass and volumetric storage densities required for each application, calculated based on the required hydrogen volume calculated from the fuel efficiency of each FC application. The 2040 target for high-pressure hydrogen in Table 6.1-1 sets out the storage densities required for a wide range of applications. Although the 2040 target for liquid hydrogen covers applications where there is a particularly high need for weight reduction, we believe there is a potential need to improve volumetric storage density. For applications that require a large amount of hydrogen to be stored in a limited volume with few weight restrictions, there are high hopes for the development of breakthrough technologies that increase the density of hydrogen storage materials.

We will continue to examine the consistency of such applications in more detail.

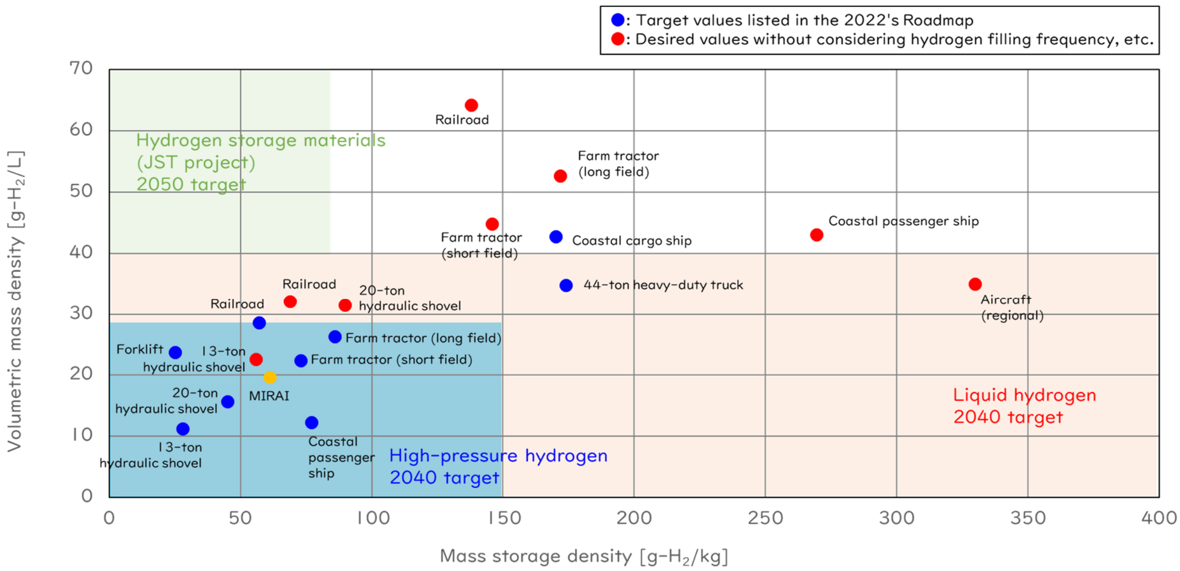


Fig. 6.2-1 Depiction of storage density for various applications

6.3 Concept of target values for high-pressure hydrogen storage systems

To reduce the cost of carbon fiber reinforced plastic (CFRP) high-pressure tanks, efforts are underway to reduce the price of the materials themselves, such as carbon fiber and epoxy resin, which are the constituent materials, as well as the amounts of these materials used. Conventionally constructed CFRP high-pressure tanks are manufactured using the filament winding (FW) method and consist of continuous carbon fibers. Because of this, the fibers are not necessarily placed in the most mechanically optimal way across the tank, and there are areas where there is some leeway in strength. Studies are being conducted to reduce the amount of constituent materials used by optimizing conventional structures and adopting innovative structures to achieve the best possible placement of carbon fiber, which will help to reduce costs and mass storage density. Figure 6.3-1 shows scenarios for 2040 and estimated values for lowering the amount of carbon fiber itself as well as the amount of other constituent materials used.

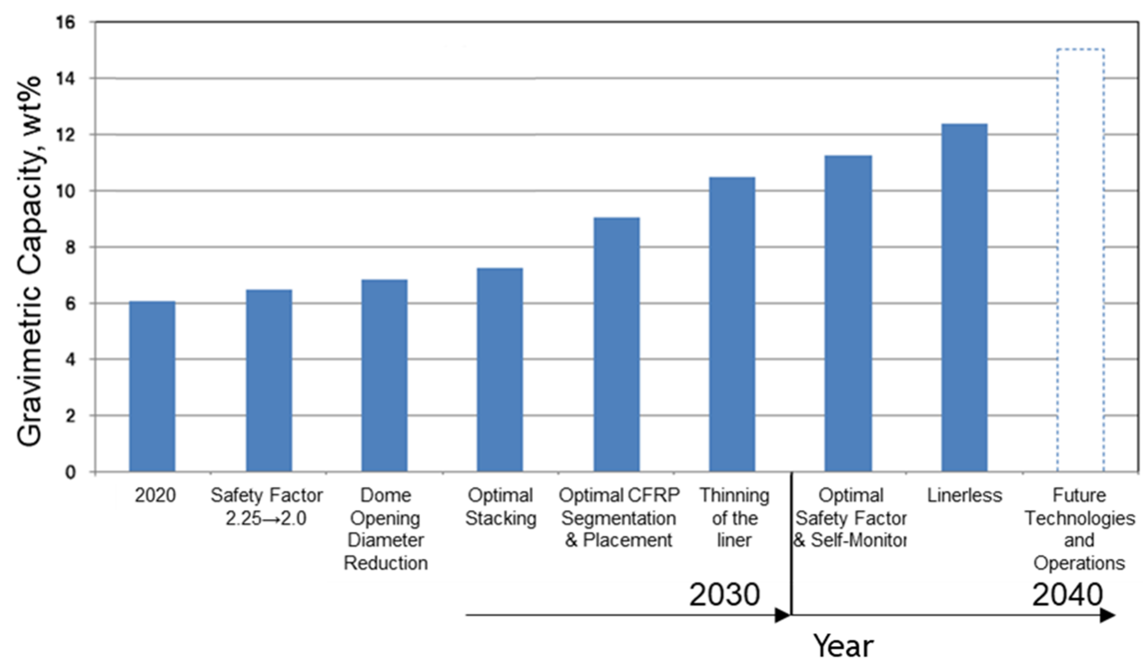


Fig. 6.3-1 Relationship between scenarios for reducing materials used and mass storage density (trial calculation)

The volume of the CFRP tank is downsized because the carbon fiber is reduced by the mass reduction measures shown in Figure 6.3-1. Figure 6.3-2 shows the estimated potential cut in volumetric storage density.

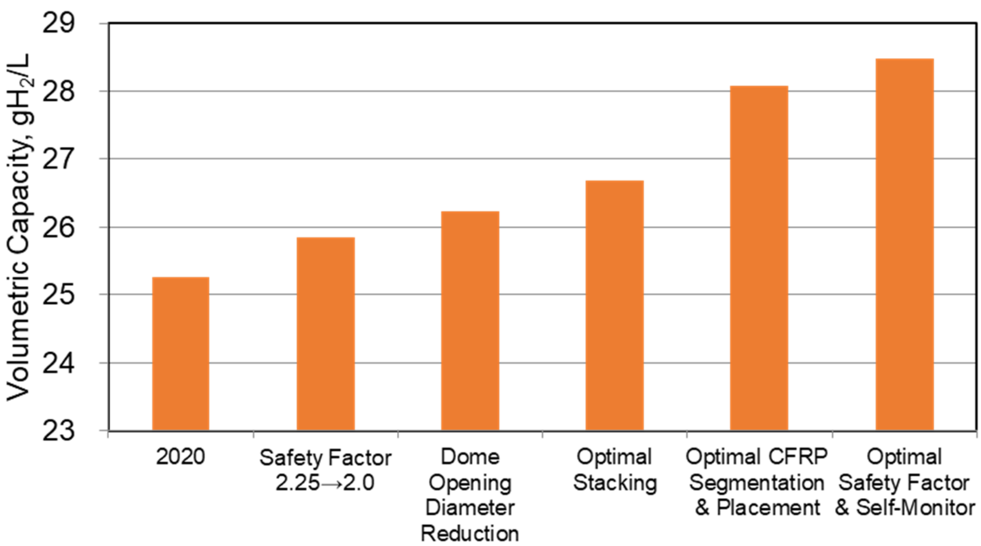


Fig. 6.3-2 Relationship between volumetric mass density and scenario for reducing materials used (trial calculation)

Based on these considerations, we have set the high-pressure hydrogen storage targets for around 2030 and around 2040 as shown in Table 6.1-1. The target for around 2040 is a level that also aims to relax regulations such as the safety factor for storage containers, etc., using inspection technology that utilizes ultra-high strength FRP fibers, IoT, and DX technology.

6.4 Concept of target values for liquid hydrogen storage systems

Liquid hydrogen storage is expected to be a potential solution for applications that require continuous long-distance or long-term operation, for amounts of hydrogen that cannot be stored using high-pressure hydrogen storage. To set the technology target for liquid hydrogen storage, we created a hypothetical tank model and conducted a parameter study.

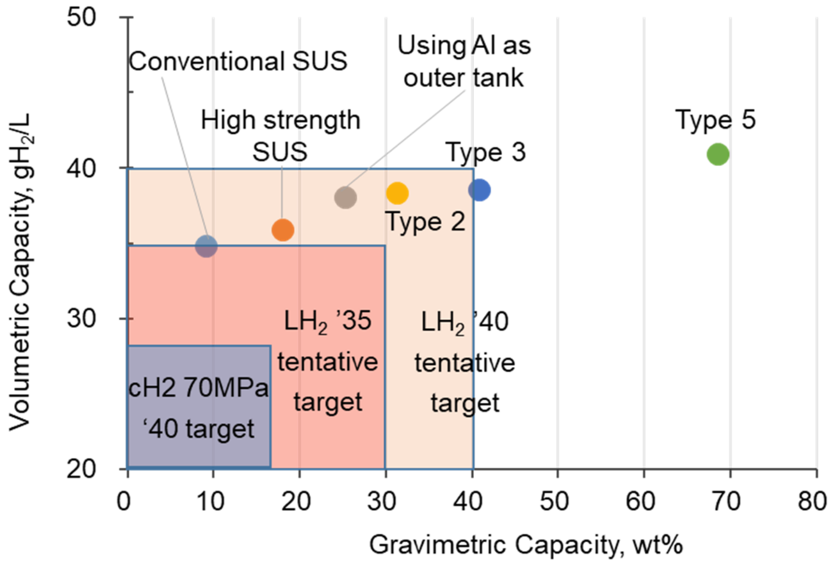


Fig. 6.4-2 Storage density calculation results

Figure 6.4-2 shows the results of the parameter study. With current liquid hydrogen storage tank technology, the mass storage density is around 9wt% using type 1 tanks made of SUS316L material, but by strengthening the inner tank and using aluminum material (A6061-T6, etc.) for the outer tank to reduce the weight of the whole tank, the mass storage density is expected to reach 18 to 25wt%. In addition, the results indicated that the mass storage density could reach 30 to 40wt% by using type 2, type 3, and type 5 (linerless) tanks made of CFRP (tensile strength ≥ 3,000 MPa). Regarding the volumetric storage density, in order to achieve 45 g-H_2/L, it is necessary to reduce the volume of the heat-insulating section required to maintain the vacuum, but the target values above were set without considering this due to the lack of data.

Based on the results of the aforementioned parameter study, the liquid hydrogen storage targets for around 2030 and around 2040 were set as shown in Table 6.1-1. In addition, since we were able to roughly quantify the relationships between pressure, volume, material strength, etc., it is possible to reconsider the target according to the specification if the needs are different for each application.

6.5 Concept of target values for hydrogen storage material systems

We will seek to reduce the size of storage containers by increasing the volumetric storage density, which is difficult to achieve with high-pressure or liquid hydrogen storage (Figure 6.5-1). The provisional storage density target for 2050 is "(on a container basis) 80 g-H_2/kg or more and 70 g-H_2/L or more," which is equivalent to the storage density of liquefied ammonia, a carbon-free fuel that does not emit CO_2. In addition, by targeting a storage pressure of "1 MPa or less" as an ultimate goal, we will help reduce container costs, improve flexibility of container shapes, and further reduce hydrogen supply costs. As an interim milestone, we have set the "60% achievement rate of the 2050 interim target" as the provisional target for 2040. In addition to storage density, other requirements in the implementation stage include "(tentative) the ability to quickly absorb and release hydrogen within the upper and lower temperature limits of the tank interior (−40°C to 85°C)" and "(tentative) a loss of storage capacity of up to 10% after 11,000 cycles." The validity of the above provisional targets will be reviewed on an ongoing basis.

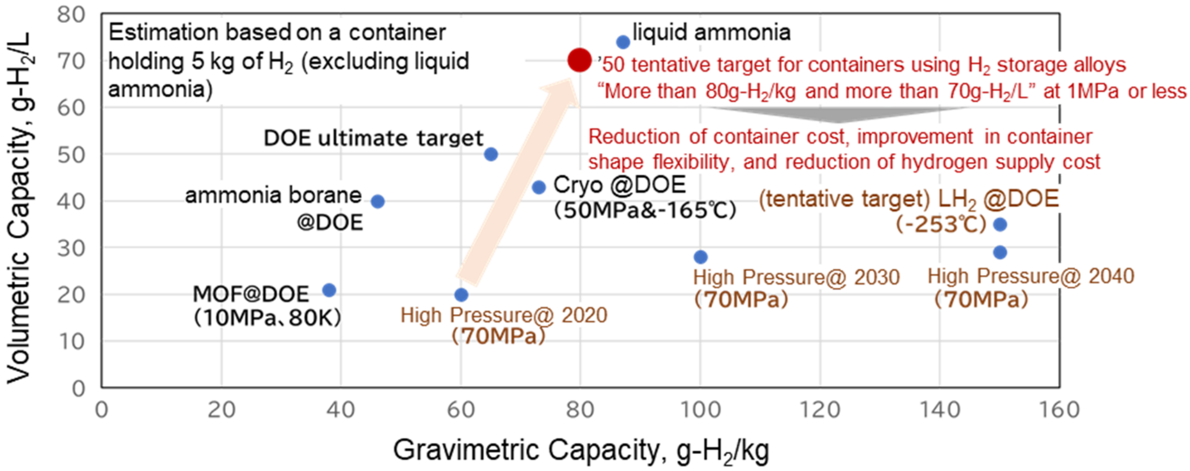


Fig. 6.5-1 Hydrogen storage density of each technology

7. DX Technology Targets

7.1 DX technology targets

In order for Japan to lead the world in the field of hydrogen and fuel cell technology development, which is advancing every day through the SDGs and CN, and to contribute to the global spread of this technology and its own industry, setting appropriate targets for market and technological evolution and improving development capabilities to achieve these targets are paramount.

To accelerate the latest technological developments, we need to promote early adoption of DX and combine it with the strengthening of development capabilities (shortening of development time). While well aligned with national initiatives for DX in other technology areas, the roadmap for the DX technologies used individually in the development of hydrogen and fuel cell technologies covers challenges in technology development, including the development of infrastructure such as databases and data platforms, informatics (MI, PI, MEI), automated and autonomous experiments, computational and modeling technologies, and natural language processing.

The goals for DX technology must be high enough to achieve the targets for each part of the FC stack, production technology, and hydrogen storage system, but they must also be realistic and achievable. Based on the index information for the required levels for each part as well as for the current level of technology, we have set the following targets for DX technology as a whole.

- Bring fuel cell and hydrogen industry materials technology development to more than 20 times the current R&D capabilities
- To achieve product and system targets in 2035, achieve DX technology by 2030

Figure 7.1-1 displays the processes that can be accelerated and made more efficient with DX technology during the research and development process. The aim is to improve research and development capabilities by speeding up and streamlining tasks in material and process searches, elucidating phenomena and mechanisms, and focusing the resources of researchers and developers on creative activities. The search for these materials and processes and the elucidation of the phenomena and mechanisms involve a cycle of repeated trial and error, and the manual process in this cycle is particularly rate-limiting. The key is how to make these processes faster and more efficient.

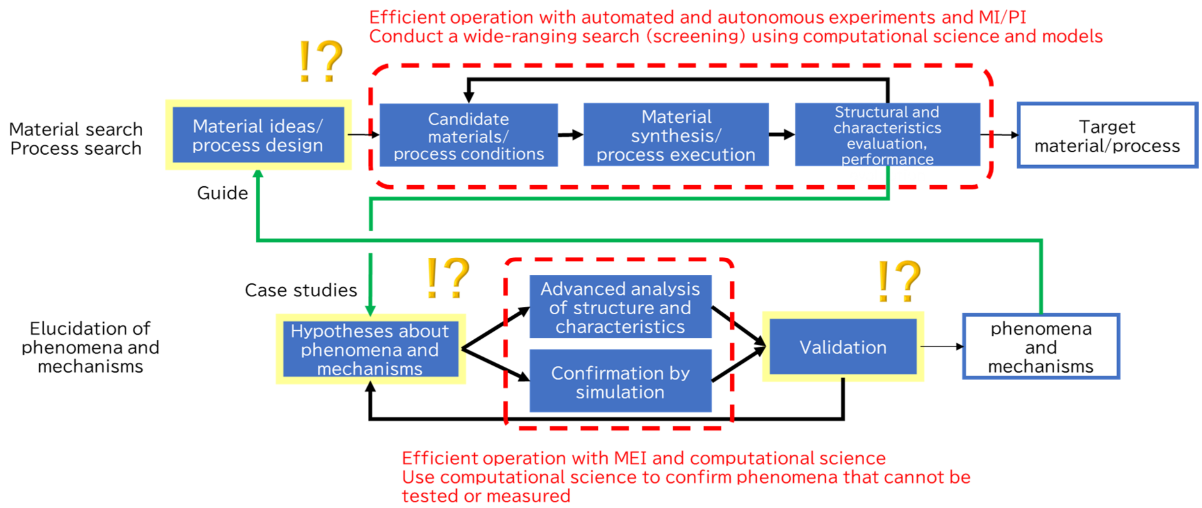


Fig. 7.1-1 Acceleration and increased efficiency through applying DX technology to research and development

Examples of the speed and efficiency gains for each DX technology include: 20 to 100 times faster material search speeds through MI and automated and autonomous experiments (see Figure 7.1-2 for reference); 20 to 100 times faster PI process condition optimization speeds; 10 to 30 times faster MEI advanced analysis speeds; and 1/100 to 1/250 reduction in the cost of data extraction through natural language processing, as reference values from index information, etc. These figures fluctuate depending on the target, purpose, and scope to be considered for DX, so it is appropriate to recognize them as a rough guide.

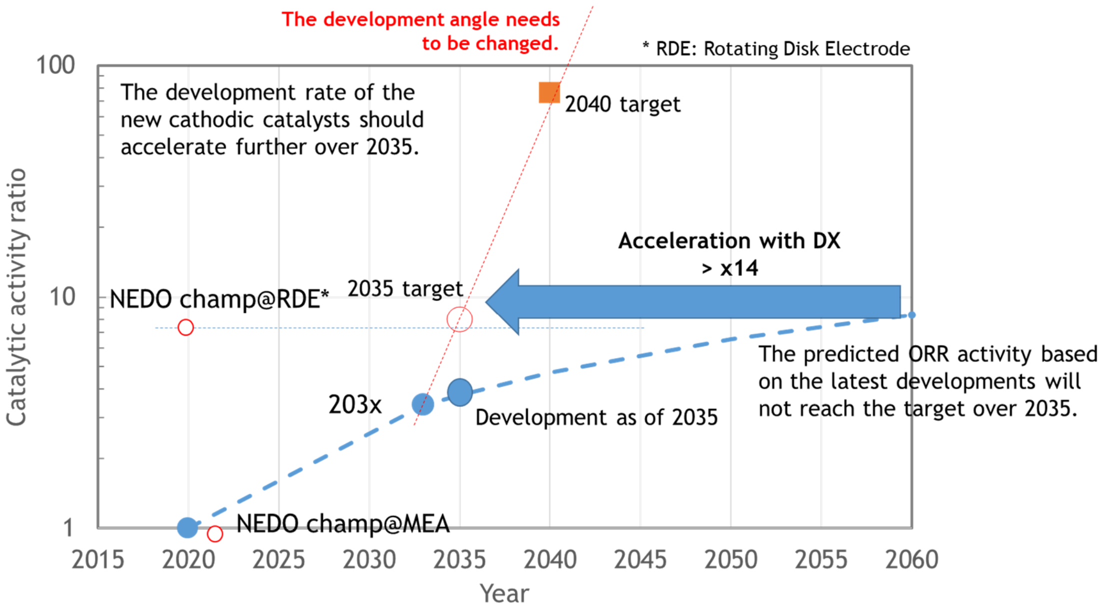


Fig. 7.1-2 Acceleration factor required to improve catalytic activity

As shown in the fuel cell performance targets in Table 4.1-1 and the hydrogen storage targets in Table 6.1-1, basic research (the creation of new scientific principles and innovative concepts) is important to overcome the limitations of current technology. If we provide guidelines for material and process design based on the elucidation of phenomena and mechanisms using advanced analytical and computational science and technology, and if these analytical and computational data are accumulated and DX technology is utilized, the conventional trial-and-error development method can be overcome and scientific and efficient search of materials and processes can proceed.

7.2 Basic technology for promoting DX

Databases and data platforms are important basic technologies for advancing DX. They are used to analyze the various data generated in research and development and to speed up and improve the efficiency of the trial-and-error cycle. In particular, analysis and measurement data for groups of materials such as catalysts and electrolytes developed through NEDO projects are registered in the "NEDO PEFC Database," and we expect to see the volume of data expand as the synthesis and evaluation of materials progresses. From the perspective of strengthening industry-academia collaboration, it is important to categorize data hierarchically and strategically extract and apply data that should be shared among companies and between companies and universities/research institutions. The goal of building the data platform is to collect all data related to fuel cell and hydrogen technology development and to fully demonstrate the power of data in technology development.

7.3 Informatics

(1) Materials Informatics (MI)

To improve the performance and durability of fuel cell systems, there is a need to develop materials that constitute the cell stacks and hydrogen tanks. In particular, it is important to improve the material properties of electrocatalysts, electrolytes, hydrogen storage materials, etc., and in the global development race, the key is how quickly and efficiently promising materials can be searched for and developed. For this reason, we hope that the application of a technology called Materials Informatics (MI) to fuel cell and hydrogen materials development will dramatically accelerate materials research and development.

MI is a method that uses statistical and informatics techniques, such as machine learning, based on a large amount of data obtained from actual measurements or theoretical calculations, to predict material performance and search for materials with desired performance. Because it is a methodology based on large amounts of data, material development using MI is also called data-driven material development. In terms of the benefits of applying MI to materials development, for example, if a highly accurate predictive model can be created, it will be possible to quickly and rationally select useful candidates from the vast number of materials that can have a wide range of compositions and shapes. In addition, it can greatly streamline the process of actually synthesizing and evaluating materials, leading to accelerated development.

(2) Process Informatics (PI)

Process Informatics (PI) is a technology that uses a data-driven approach to optimize process conditions in the material manufacturing process to improve fuel cell performance and durability. There are many process parameters in the fuel cell manufacturing process, and it is very important to optimize them. In the past, process conditions were determined by trial and error or extensive experimentation, but PI, can efficiently optimize these process conditions.

The use of PI begins with collecting process data, and it is important to optimize the process with as little data as possible. The period from the present to about 2030 is defined as that for creating a track record of PI use, and the time from about 2030 to the late 2030s is defined as the era for expanding the application process, and the research tasks to be addressed in each period will be organized during those times. During the period of creating a track record of PI use, it is necessary to collect data on processes such as the ink mixing process and the coating and drying process, and to work on upgrading PI analysis technology and developing elemental technology. The use process expansion period will require horizontally deploying PI to all processes of the fuel cell system, including hydrogen tanks, because it will be to develop technologies for high-speed data collection and organization, as well as for automated and autonomous experiments, and for efficient analysis of large amounts of data.

(3) Measurement Informatics (MEI)

Measurement Informatics (MEI) is a technology that uses measurement data collected during the research and development process to predict the properties and performance of materials. MEI is expected to accelerate the development process by using machine learning and statistical methods based on measurement data to predict the properties and performance of materials. This technology should help to streamline the trial-and-error cycle in material development, and contribute to improving research and development capabilities.

7.4 Automated and autonomous experiments

Conducting automated and autonomous experiments is a technique introduced to speed up and improve the efficiency of the trial-and-error cycle in the research and development process. This technique accelerates tasks such as material and process searches and the elucidation of phenomena and mechanisms, enabling researchers and developers to focus their resources on creative activities. We expect to see the speed of material search through automated and autonomous experiments increase by 20 to 100 times, which will improve research and development capabilities.

7.5 Computational and modeling technologies

Computational technology and modeling technology are essential for advancing DX. Computational science-based simulation, computer science methods such as machine learning and AI, and quantum computing technology are emphasized as DX technologies for accelerating the development of fuel cell and hydrogen-related technologies. Simulation is a powerful tool for modeling objects based on physical and chemical laws, understanding phenomena, and analyzing factors such as the physical properties of materials and molecules, chemical reactions, and the mechanical properties of structures. Using informatics methods such as machine learning and AI, it is possible to construct models that express the characteristics and features of an object based on data, and it is also possible to perform modeling and simulation for complex phenomena and unexplained phenomena that are difficult to express using physical and chemical laws. Quantum computing is a technology that applies the principles of quantum mechanics to perform calculations, and it is expected that calculations using quantum bits, which cannot be expressed by ordinary computers, will enable high-precision and high-speed evaluations.

7.6 Natural language processing (NLP)

As we move toward decarbonization, there is a growing interest in fuel cells and hydrogen around the world, and their status is in the news every day. A huge number of papers and patents are published every year, and the number is only increasing. This information is written in text created by humans, but it is impossible for a human to read the vast amount of text and understand the big picture, so natural language processing (NLP) technology is required. The purpose of NLP is to sort and organize important information from a vast amount of data and support the formulation of policies on development strategy. Technical literature requires technology to accurately extract and organize information such as material names, physical properties, performance indicators, and process information. We expect to see the organized and systematized information used as base information for MI and other purposes, as well as for presenting hypotheses on understanding various phenomena.

7.7 Human resource development

There is concern about a lack of human resources who can apply DX technology to research and development. Japan in particular suffers from a lack of knowledge and literacy in digital technology, so METI is promoting the development of digital human resources. The types of people needed for DX include business architects, designers, data scientists, software engineers, and security, and they need to be developed without delay.

In terms of research and development of fuel cell and hydrogen technology, there is strong demand for people adept at DX, especially people with skills equivalent to those of business architects and designers are particularly important. There is also a need for many human resources with skills equivalent to those of data scientists and software engineers. Furthermore, the field will need robotics experts to handle technologies such as automated and autonomous experiments, PIs, and MEIs, and engineers who can handle not only software but also hardware.