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The Potential of Turquoise Hydrogen

Innovative Technology Series*

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Summary

- Mobilization of all available methodologies will be necessary in order to achieve a carbon neutral society. Hydrogen is expected to be an effective way to decarbonize the demand for fuel for thermal power generation, power sources for mobility, and industrial heat, and is attracting attention worldwide as a key to achieving carbon neutrality. In order for Japan to realize a hydrogen-based society, it will be crucial to stably and inexpensively supply the required amount of low-carbon hydrogen to the regions where there is demand. Hydrogen produced through methane pyrolysis (turquoise hydrogen), which is positioned as an innovative hydrogen production technology in the June 2023 revision of Japan's "Basic Hydrogen Strategy," has the potential to stably and inexpensively supply sufficient hydrogen to meet the needs of final hydrogen end-user locations.

- Methane pyrolysis is a technology to produce hydrogen (H_2) and solid carbon (C) by heating methane (CH_4). The production process differs from blue hydrogen since it does not produce any carbon dioxide (CO_2) from the raw materials, and instead produces solid carbon as a byproduct; this means that unlike blue hydrogen, CCS is not required. Because turquoise hydrogen production can utilize LNG facilities and city gas infrastructure, little infrastructure needs to be developed for its social implementation, and hydrogen supply chains can be established quickly and in stages. Moreover, because CCS is not required, turquoise hydrogen also has a competitive advantage in Japan from the standpoint of production cost.

- Dealing with the solid carbon byproducts created in the process of hydrogen production will be vital in order to implement turquoise hydrogen in society. For example, if 4 million tons of turquoise hydrogen is produced, which is equivalent to 30% of the Japanese government's demand target for 2040, 12 million tons of solid carbon will be produced as a byproduct. Some of the solid carbon may be disposed of, but it is also a valuable raw material and fuel.

- Various efforts are currently being undertaken, primarily in the United States, to utilize solid carbon as a raw material for concrete and car tire manufacturing, and in the future, it is expected to be utilized in advanced applications including as a conducting agent for lithium-ion batteries. To effectively utilize this valuable resource, progress in research, development, and proof-of-concept tests along with the system design necessary to utilize byproduct carbon is desirable. We sincerely hope that the importance of turquoise hydrogen, which is the key to the realization of a hydrogen-based society, will be fully recognized, and that the public and private sectors will actively pursue joint efforts to unlock its potential going forward.

* Series of reports highlighting areas of technology and innovation that can contribute to strengthening the competitiveness of Japanese industry and to solving social issues.

1. Introduction

Hydrogen is key to achieving carbon neutrality. The Japanese government plans to support the building of hydrogen supply chains

Hydrogen is expected to be an effective way to decarbonize the demand for fuel for thermal power generation, power sources for mobility, and industrial heat, and is attracting attention worldwide as a key to achieving carbon neutrality. The Japanese government also intends to provide support focusing on the price gap between existing raw materials and fuels and low-carbon hydrogen[1] along with support for developing bases. This policy is expected to allow first movers with the enthusiasm and commitment to drive the social implementation of hydrogen to achieve large-scale, low-cost hydrogen supply and to ameliorate the current situation, in which consumers are hesitant to use hydrogen.

There are challenges in establishing domestic renewable energy-based and import-based supply chains

For low-carbon hydrogen supply in Japan, green hydrogen production using surplus renewable energy, which is expected to increase with the expanded adoption of renewable energy, will be important from the perspective of effective energy use. However, Japan has relatively low renewable energy potential due to its small land area, making it unlikely to see any large-scale expansion of green hydrogen production. For this reason, low-carbon hydrogen imported from overseas is being considered. On the other hand, establishing an import-based hydrogen supply chain presents challenges in that the location and number of sites that can receive hydrogen supplies are limited, which may result in a regional bias in domestic hydrogen supply along with domestic transport costs to final demand locations, while risks remain from the perspective of Japan's energy security. From this standpoint, technology that can ensure the stable and inexpensive supply of hydrogen on a large scale is necessary.

Turquoise hydrogen production will enable stable hydrogen supply

In regard to this point, Japan's "Basic Hydrogen Strategy," which was revised in June 2023, mentions the need to develop innovative technologies, in particular the production of hydrogen through methane pyrolysis (turquoise hydrogen) (see Fig. 1). Turquoise hydrogen has the potential to stably and inexpensively supply sufficient hydrogen to meet domestic hydrogen demand in each region of Japan. This report will provide an overview of turquoise hydrogen production technology and discuss the potential for introducing it in Japan.

[Fig. 1] Positioning of Turquoise Hydrogen in the Revised Basic Hydrogen Strategy

Basic Hydrogen Strategy
June 6, 2023, The Ministerial Council on Renewable Energy, Hydrogen and Related Issues

3-6. Bring forward innovative technology development
The following innovative hydrogen technologies have to be steadily researched and developed in the areas of production, transportation, storage, and use **through industry-academia-government collaboration** in order to achieve the widespread use of hydrogen over the mid- and long-term periods toward carbon neutrality by 2050. **In addition, it is also important to develop human resources who will lead future industries through research and development activities.** In the context of technology development, **the competent ministries and agencies will take into account international moves, promising seeds from basic research, and the needs of the industrial sector and bridge important scientific achievements made by universities and research and development agencies to companies and enable their social implementation in a concerted manner.**

[Production]
High-efficient, high-durable, and low-cost water electrolysis technology, high-temperature heat sources, such as high-temperature gas reactor, **thermal decomposition of methane**, and photocatalytic **hydrogen production technology**
[Transportation and Storage]
Efficient hydrogen liquefier, transport, and storage technologies, such as hydrogen storage alloys, technologies for reducing hydrogen carrier cost and ammonia cracking
[Use]
Efficient, durable, and low-cost fuel cell technologies, technologies for manufacturing Carbon Recycling products, including e-methane and synthetic fuel (e-fuel)

Source: Compiled by Mizuho Bank Industry Research Department based on The Ministerial Council on Renewable Energy, Hydrogen and Related Issues, *Basic Hydrogen Strategy*

[1] Hydrogen that emits less than a certain volume of CO_2 (carbon intensity) in its production process, etc.

2. Overview of turquoise hydrogen production through thermal decomposition of methane and examples of initiatives

Technology to obtain hydrogen and solid carbon from methane

Thermal decomposition of methane, the technology used to produce turquoise hydrogen, is a process in which heat is applied to methane (CH_4)[2] to obtain hydrogen (H_2) and solid carbon (C) (see Fig. 2). More efficient methods are being developed, such as using catalysts to lower the reaction temperature.

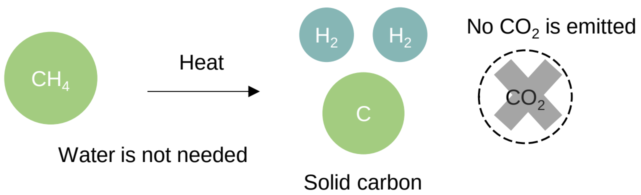
Unlike blue hydrogen, the byproduct is solid carbon instead of CO_2

The difference from blue hydrogen is that the production process does not produce any carbon dioxide (CO_2) from the raw materials, and instead produces solid carbon as a byproduct (see Fig. 3). Because the byproduct is captured as solid carbon when it is produced, unlike a CO_2 gas byproduct, it does not require CCS.[3] In addition, the solid carbon can be obtained as carbon black or carbon nanotubes, etc. Expected applications include the use of carbon black to reinforce car tires, and carbon nanotubes as a conducting agent for lithium-ion batteries and a material for manufacturing concrete.

Unlike green and blue hydrogen, the process does not use water

Furthermore, the fact that water (H_2O) is not needed as a raw material to produce turquoise hydrogen is a feature that differs from green and blue hydrogen. Because the process does not use water, the energy input required to obtain hydrogen is relatively low, only about 20% of that required for green hydrogen.

[Fig. 2] Overview of the Methane Thermal Decomposition Process



Source: Compiled by Mizuho Bank Industry Research Department.

[Fig. 3] Examples and Characteristics of Low-Carbon Hydrogen

Hydrogen Color Code	Overview	Benefits	Drawbacks
Green	• Water electrolysis using renewable energy-derived electricity	• Low carbon intensity	• High energy input • Stable hydrogen production is difficult
Blue	• Combination of hydrogen produced through fossil fuel reforming/gasification and CCS used to sequester the resultant CO_2 emissions	• Low production cost	• CO_2 sequestration via CCS is necessary
Turquoise	• Hydrogen produced through thermal decomposition (pyrolysis) of methane. Carbon is produced as a solid.	• Low energy input • Water is not needed as a raw material • Solid carbon is produced as a byproduct	• Consumes more methane as a feedstock than blue hydrogen does

Note: Hydrogen produced through fossil fuel reforming/gasification without CO_2 sequestration is called gray hydrogen, and is not classified under low-carbon hydrogen.
Source: Compiled by Mizuho Bank Industry Research Department based on various materials.

The maturity of thremal decomposition of methane technology is improving

The International Energy Agency (IEA) places the technological readiness of methane pyrolysis between the early prototype and the first-of-a-kind commercial levels (see Figs. 4 and 5). While less mature than alkali (ALK) or PEM (polymer-electrolyte membrane) technologies of water electrolysis, which are considered to be in the commercial operation in relevant environment stage, it has matured to the next level following, led by plasma pyrolysis. Moreover, Monolith (U.S.), a forerunner in turquoise hydrogen production, rates its technology as being on the same level as alkali- or PEM-based water electrolysis.

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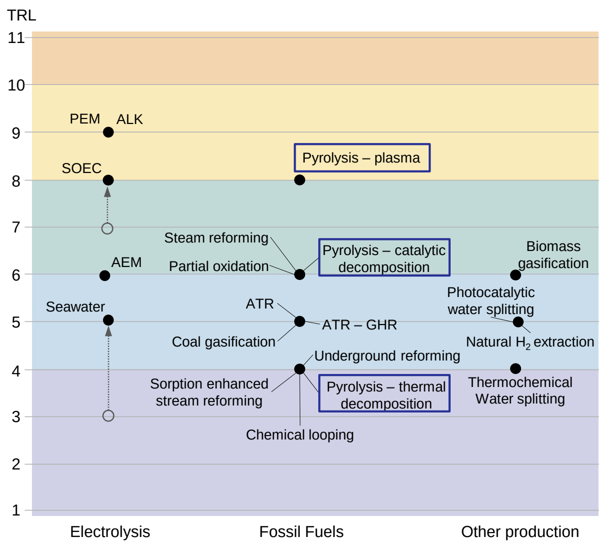
[2] Methane is the main component of natural gas and biogas. LNG is liquefied natural gas by cooling to -162℃.
[3] CCS (Carbon dioxide Capture and Storage) is a technology that captures CO_2 from exhaust gases, etc., transports it to a suitable location, and stores it underground, and requires the necessary equipment for each process.

[Fig. 4] Hydrogen Production Methods and Technology Readiness Levels



Source: Compiled by Mizuho Bank Industry Research Department based on IEA, *Global Hydrogen Review 2023*.

[Fig. 5] Classification of Technology Readiness Levels

Relative Level of Technology Development	Technology Readiness Level	TRL Definition
Early Adoption	TRL9	**Commercial operation in relevant environment** Solution in commercially available, needs evolutionary improvement to stay competitive
Demonstration	TRL8	**First of a kind commercial** Commercial demonstration, full scale deployment in final form
	TRL7	**Pre-commercial demonstration** Solution working in expected conditions
Large Prototype	TRL6	**Full prototype at scale** Prototype proven at scale in conditions to be deployed
	TRL5	**Large prototype** Components proven in conditions to be deployed
Small Prototype	TRL4	**Early prototype** Prototype proven in test conditions
Concept	TRL3	**Concept needs validation** Solution needs to be prototyped and applied
	TRL2	**Application formulated** Concept and application of solution have been formulated
	TRL1	**Initial idea** Basic principles have been defined

Source: Compiled by Mizuho Bank Industry Research Department based on IEA, *Technology readiness level scale applied by the IEA*

Monolith leads the way in the use of plasma. Utilization of byproduct carbon is taking shape

Monolith is the leader in utilizing plasma for methane pyrolysis, and is expanding the scale of production by connecting reactors capable of producing 600kg of hydrogen per hour (see Fig. 6). In addition, Monolith is collaborating with tire manufacturers such as Goodyear Tire and Rubber (U.S.) to utilize the byproduct carbon black as a material for reinforcing car tires.

Pyrolysis using catalysts involves the use of molten salts or metals or of iron ore, etc.

Catalytic decomposition of methane can be classified into two types, one that uses molten metals or salts and one that uses iron ore or other catalysts. The molten metal method is being developed by Palo Alto Research Center (PARC, U.S.) among others, while C-Zero (U.S.) and others use the molten salt method. Hazer (Australia) is working on the method using iron ore catalysts, and is involved in a demonstration project in Australia to produce hydrogen at a scale of 100 tons a year.

Other methane decomposition technologies are being developed

Thermal processes for the decomposition of methane which do not use plasma or catalysts are also being tackled by BASF (Germany), the largest chemical company in Europe, and by emerging companies Modern Hydrogen (U.S.), founded in 2015, and Ekona Power (Canada), founded in 2017.

Support is provided in the U.S. by ARPA-E

In the U.S., in addition to providing support for 8 projects related to methane pyrolysis thus far (see Fig. 7), ARPA-E[4] holds the Methane Pyrolysis Cohort Annual Meeting to share research and development results. In addition, the U.S. Department of Energy committed to a loan guarantee of approximately 1 billion dollars for the installation of methane pyrolysis equipment at Monolith's Oliver Creek facility (see Fig. 8).

Efforts by Japanese companies are also making progress

Efforts by Japanese companies are also progressing. With assistance from the New Energy and Industrial Technology Development Organization (NEDO), Ebara Corporation is working on a specialized plant design to prevent catalyst deactivation (coking) caused by byproduct carbon deposition (see Fig. 9). Toda Kogyo and Air Water Inc. are unique in the fact that they are engaged in hydrogen production utilizing unused natural gas in the Toyotomi Town in Hokkaido. Ihara Industries is developing a method that will reduce the ratio of catalyst

[4] Advanced Research Projects Agency – Energy.

contamination of the byproduct carbon by using a plate-shaped metal catalyst instead of particulate metal catalyst. The Aichi Center for Industry and Science Technology is collaborating with Ihara Industries to develop applications for conductive composite materials using the byproduct carbon obtained. Elsewhere, Microwave Chemical Co. is working with Sumitomo Chemical Company to develop a highly-efficient production process using microwaves.

Moves toward large-scale implementation are also gaining momentum

Using Hazer's technology, Chiyoda Corporation and Chubu Electric Power plan to launch proof-of-concept tests to demonstrate hydrogen production on a scale of 2,500 tons per year in the late 2020s. Sojitz is also considering large-scale hydrogen production through its investment in Finnish startup Hycamite. Meanwhile, along with its investments in Monolith and C-Zero, Mitsubishi Heavy Industries is working on the development of methane pyrolysis technologies at its Nagasaki Carbon Neutral Park, aiming for commercialization in 2026 or beyond.

[Fig. 6] Example of Businesses Working to Develop Turquoise Hydrogen Production Methods and Technologies

Method		Overview	Business Operators, etc.	
			Non-Japanese	Japanese Grey = investor, ( ) = investee, etc.
Plasma pyrolysis [First of a kind commercial]		• Thermal decomposition of methane using plasma • Fast start-up is possible • A challenge is that producing plasma requires a lot of energy	Monolith (U.S.) HiiROC (UK)	Mitsubishi Heavy Industries (Monolith)
Catalytic pyrolysis [Full prototype at scale]	Molten metal or molten salt	• Thermal decomposition of methane by filling the reactor with molten metal or salt • Requires technology for handling molten metals/salts at temperatures of 1,000℃ or above	C-Zero (U.S.) PARC (U.S.)	Mitsubishi Heavy Industries (C-Zero)
	Other	• Thermal decomposition of methane using catalysts loaded with Ni or Fe as the active metal or iron ore, etc. as a catalyst • Deactivation of catalysts due to deposition of solid carbon is a challenge	Hazer (Australia) Hycamite (Finland)	Ebara Corporation, Toda Kogyo, Ihara Industries, Air Water Inc., IHI, Mitsubishi Heavy Industries Chiyoda Corporation (Hazer), Chubu Electric Power, Sojitz (Hycamite)
Thermal pyrolysis [Early prototype]		• Reaction occurs without using plasma or a catalyst	BASF (Germany) Modern Hydrogen (U.S.) Ekona Power (Canada)	Miura Co., Ltd. (Modern Hydrogen) Mitsui & Co. (Ekona Power)

Source: Compiled by Mizuho Bank Industry Research Department based on various materials.

[Fig. 7] Support Provided by U.S. ARPA-E

Project Name	Period	Funding	Operator
Molten-Salt Methane Pyrolysis Optimization Through in-situ Carbon Characterization and Reactor Design	May 2020-Apr. 2022	$1,997,532	C-Zero
Carbon Dioxide-Free Hydrogen and Solid Carbon from Natural Gas via Metal Salt Intermediates	June 2019-Dec. 2023	$3,690,304	Johns Hopkins University
Electrothermal Conversion of Methane into Hydrogen and High-Value Carbon Fibers	May 2020-July 2023	$1,500,000	Johns Hopkins University
CarbonHouse	Mar. 2020-June 2024	$3,726,606	Massachusetts Institute of Technology
High Value Energy Saving Carbon Products and Clean Hydrogen Gas from Methane	Sep. 2019-June 2022	$3,475,124	NanoComp
High-throughput Methane Pyrolysis for Low-cost, Emissions-free Hydrogen	June 2019-Dec. 2022	$3,946,540	Palo Alto Research Center
From Hydrocarbon Feedstock to Recyclable Carbon-Based Automotive Bodies with Positive Hydrogen Output	Sep. 2019-Dec. 2023	$3,447,862	Rice University
Co-Synthesis of Hydrogen and High-Value Carbon Products from Methane Pyrolysis	Apr. 2020-Sep. 2024	$1,877,548	Stanford University

Source: Compiled by Mizuho Bank Industry Research Department based on Advanced Research Projects Agency – Energy, U.S. Department of Energy HP.

[Fig. 8] U.S. National Clean Hydrogen Strategy and Roadmap (Excerpt)

- A third type of natural gas-based production, **methane pyrolysis**, uses high heat to split methane into hydrogen and solid carbon.
- **This can be an attractive option** since the solid carbon can provide a value-added co-product for applications such as industrial rubber and tire manufacturing and for specialty products such as inks, catalysts, plastics, and coatings.
- **The cost of hydrogen from methane pyrolysis pathways are highly dependent on the price of the carbon product sold, thus high value and volume carbon markets for the carbon products are pivotal.**
- In 2021, DOE's LPO announced a conditional commitment for a loan guarantee to Monolith™ Inc. (formerly Monolith Nebraska, LLC) for approximately $1 billion to deploy methane pyrolysis technology at their Olive Creek facility in Hallam, Nebraska.
- Hydrogen produced at this facility will be used to produce ammonia fertilizer. Deployment of this facility is also expected to create approximately 1,000 jobs during construction and 75 high-paying, highly skilled, clean energy jobs to support facility operations.

Source: Compiled by Mizuho Bank Industry Research Department based on U.S. Department of Energy, *U.S. National Clean Hydrogen Strategy and Roadmap*.

[Fig. 9] Examples of Support Provided by NEDO for Turquoise Hydrogen Production

Project Name	Period	Project Operators	Overview of Efforts
Hydrogen production through reaction field separation of methane activation and carbon deposition	Apr. 2021-Mar. 2023	National Institute for Materials Science, Shizuoka University, Taiyo Koko, Tokyo Institute of Technology, Kochi University of Technology, Ebara Corp.	• Conventional direct methane cracking causes deactivation of methane catalysts (coking) due to carbon deposition, but continuous production of high-purity hydrogen is possible by creating an appropriate system for separation
Hydrogen production from methane using gas circulation and carbon dioxide recycling	Oct. 2023-	National Institute for Materials Science, Ebara Corp., Kochi University of Technology, Tokyo Institute of Technology	• Develop a system to extract hydrogen from a mixed gas composed of methane and carbon dioxide and at the same time produce high added-value carbon
Development of hydrogen production technology through direct methane cracking	Apr. 2021-Mar. 2023	Ihara Industries, Tokyo University of Science, Aichi Prefectural Government, Nagoya University, Shizuoka University	• Along with improving the thermal efficiency of methane direct cracking reactors (achieve a hydrogen yield of 60% at a reaction temperature of 700℃), analyze the characteristics of the carbon produced and consider a wide range of utilization methods
Research and development of highly efficient hydrogen production systems with the direct methane reforming (DMR) method using iron-based catalysts	Apr. 2021-Mar. 2023	Toda Kogyo, Air Water Inc.	• Establish a highly efficient hydrogen production system to obtain high-purity (99.99% pure or higher) hydrogen and highly conductive carbon nanotubes in a pilot-scale facility that integrates components from the DMR reactor to a hydrogen purification system
Utilization of unused natural gas in Toyotomi, Hokkaido to build a regional CO_2-free hydrogen supply chain	Aug. 2023-Aug. 2025	Toda Kogyo, Air Water Inc.	• Promote local production of energy for local consumption by utilizing unused natural gas produced incidentally with hot springs in the town of Toyotomi, Hokkaido as hydrogen

Source: Compiled by Mizuho Bank Industry Research Department based on various materials.

3. Potential for adopting thermal decomposition of methane in Japan

Technologies are advancing, mainly for catalytic methane pyrolysis

Japan possesses the catalyst technology, microwave technology, and plant design technology to enable efficient turquoise hydrogen production, and the Japanese government is also providing support for technological development through NEDO projects. Turquoise hydrogen production technology is developing rapidly through efforts by the public and private sector.

Existing gas infrastructure can be used for turquoise hydrogen production

An advantage of turquoise hydrogen is the fact that it can be produced by installing methane pyrolysis facilities to the existing gas infrastructure that have been developed for LNG procurement and as city gas supply infrastructure, whether in coastal or inland areas. Unlike the construction of large-scale-supplying hubs, which would require an integrated regional approach, another advantage is that the installation of hydrogen applications can be realized gradually based on customer needs. To a certain extent, manufacturers and construction contractors of turquoise hydrogen-related equipment are able to avoid constraints on human and material resources. Meanwhile, while blue hydrogen production can also utilize existing LNG and city gas infrastructure, it differs from turquoise hydrogen production in that it requires CCS equipment.

The gas infrastructure in place will accelerate the social implementation of turquoise hydrogen

The transition from small-scale demonstration tests to large-scale social implementation is expected to proceed smoothly and rapidly by maximizing the utilization of the gas infrastructure that is already in place. While green hydrogen demonstration tests are currently under way, turquoise hydrogen has the potential to lead hydrogen production in Japan in the future because of its rapid social implementation. Currently announced projects alone are expected to produce tens of thousands of tons of turquoise hydrogen in Japan around 2030, and there is ample potential for more projects to be set in motion through the latter half of the 2020s.

Government support for turquoise hydrogen is also important

However, at present, public awareness of turquoise hydrogen production is low, and the timing for the launch of large-scale demonstration projects is slower than that of green hydrogen production. There is, therefore, a risk that policy resources such as support for the establishment of supply chains, which are currently being designed by the Japanese government, may not be allocated in a timely and appropriate manner. In this regard, it is desirable that the importance of turquoise hydrogen in Japan be properly recognized and that the necessary policy resources be invested.

Potential to further improve the performance of Japan's technology utilizing hydrogen

In addition, Japan also has a wide variety of hydrogen applications, including power generation technology, boilers, burners, mobility, and water heaters. If hydrogen can be conveniently supplied to users through turquoise hydrogen production, the utilization of these types of technologies should be promoted. Furthermore, the performance of hydrogen applications can be upgraded significantly by rapid increase of hydrogen demand.

Large-scale expansion of existing gas infrastructure is not expected

The large-scale introduction of turquoise hydrogen production does not require a major expansion of the existing gas infrastructure. For example, to produce 4 million tons of low-carbon hydrogen, which represents 30% of the Japanese government's hydrogen demand target for 2040, in a year using turquoise hydrogen would require 16 million tons of LNG (19.5 billion m^3 natural gas equivalent) as the raw material. This is an increase of about 20% compared to Japan's annual LNG import volume of 70 million tons. Conversely, demand for LNG is expected to decline in the future due to a decrease in population, expanded adoption of renewable energy, and other factors.

Issuance of certifications, etc. necessary in anticipation of the introduction of e-methane

However, as the city gas sector has set its sights on increasing the percentage of total gas accounted for by e-methane[5] to 90% by 2050, there may be pros and cons to using e-methane for hydrogen again. In this regard, because the natural gas used for turquoise hydrogen production is expected to be supplied via existing city gas pipelines, appropriate management of natural gas and e-methane will be necessary. For example, it would be necessary to take measures such as issuing certificates indicating that e-methane consumers are consuming e-methane to ensure that they are not deemed to be consuming conventional natural gas.

4. Cost of producing hydrogen via thermal decomposition of methane

Turquoise hydrogen is cost competitive for domestic hydrogen production, and among methane pyrolysis, catalytic method is competitive

In addition to the ability to supply hydrogen on a commercial scale, cost competitiveness is also an essential condition for the social implementation of turquoise hydrogen production. Based on a certain set of assumptions, the cost of domestic production of turquoise hydrogen using imported LNG as the feedstock was estimated to be 353-479 yen/kg-H_2 (see Fig. 10). Looking at the cost breakdown, the raw material (LNG) accounts for the vast majority at 82-88%, whereas production equipment accounts for 12-17% and other costs for around 1%. Compared to blue hydrogen, the raw material cost is higher because the amount of methane doubles, but ultimately there is no significant difference between the two because turquoise hydrogen does not incur costs for CCS. For example, assuming that the cost of CCS is 17,500 yen/t-CO_2 (96 yen/kg-H_2)[6], the blue hydrogen production cost is 330 yen/kg-H_2. Besides, the production cost of green hydrogen derived from renewable energy is 627 yen/kg-H_2. As a result, turquoise hydrogen can be said to have the competitive edge in terms of the cost of hydrogen production in Japan. Moreover, among the various methods for producing turquoise hydrogen, catalytic and other methods of thermal decomposition that do not use electricity have a cost advantage over plasma pyrolysis, which is currently the most technologically mature method.

Hydrogen imported from overseas is cheaper than domestically produced hydrogen

On the other hand, closing the gap in production costs between Japan and resource-producing countries is not realistic. For example, the lowest hydrogen procurement cost is to procure blue hydrogen produced in the Middle East, where natural gas is abundant, and import it to Japan in the form of ammonia, which is just under 290 yen/kg-H_2.[7] However, it should be noted that transportation within Japan is necessary when hydrogen is used in regions other than the import receiving site.

[5] Methane synthesized from hydrogen and CO_2.
[6] Mizuho Bank Industry Research Department, Mizuho Industry Focus Vol. 242, Innovative Technology Series: The Path for the Development of CCS in Japan (2023).
[7] Mizuho Bank Industry Research Department, Mizuho Industry Focus Vol. 237, How Japan Can Win the Global Competition for Hydrogen (February 2023). This report uses an exchange rate of 110 yen to the U.S. dollar for its analysis.

Efforts to reduce the procurement cost of methane used as the raw material are needed

Turquoise hydrogen is the key to realizing a hydrogen-based society in Japan, but the high price of natural gas and LNG is an issue because the raw materials cost constitutes a significant percentage of the production cost. In this regard, the conclusion of large-scale, long-term LNG procurement contracts could offer a solution. Japan has been the world's pioneer in establishing LNG supply chains and is also the world's largest importer (as of 2022). However, with future demand for LNG expected to decline, Japanese companies are unlikely to secure LNG-related interests or enter into long-term procurement contracts. Turquoise hydrogen production could shore up natural gas demand in Japan and provide an incentive for Japanese companies to secure LNG-related interests and conclude long-term contracts.

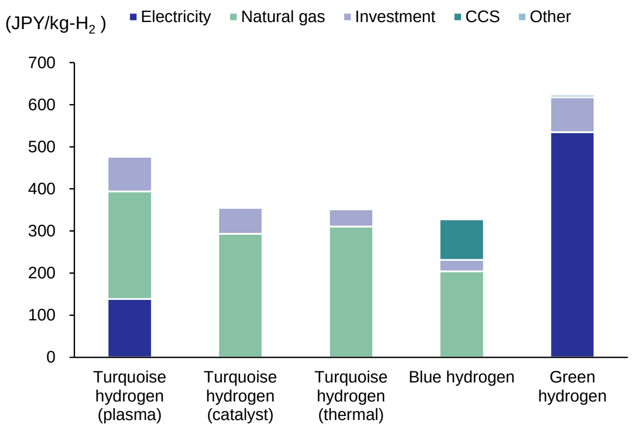
Effective use of byproduct carbon is key. If progress is made in this area, 20 yen/Nm^3 can be achieved

Another way to reduce hydrogen production costs is to utilize the byproduct carbon. As progress is made in the effective utilization of byproduct carbon, the revenue generated from byproduct carbon transactions is expected to lower the real cost of hydrogen production (see Fig. 11). For example, assuming that byproduct carbon has a value equivalent to the unit price per weight of cement, the real cost of hydrogen production would decrease by about 45 yen/kg-H_2 from the aforementioned 353-479 yen/kg-H_2. And if a carbon value more than double this amount is recognized, the Japanese government's 2050 target of 224 yen/kg-H_2 (20 yen/Nm^3-H_2) can be achieved.

Establishing industries with demand for byproduct carbon is important

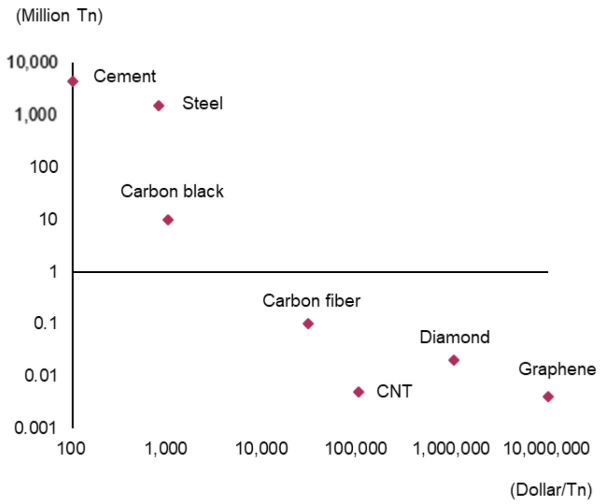
Japan has advantages in carbon technologies. For example, carbon nanotubes were discovered in Japan, and Japanese companies hold the majority of the global market for carbon fiber. One of the reasons for its high share of the carbon fiber market is Japan's high competitiveness in the aerospace and automotive sectors, which have demands for carbon fiber. Therefore, with regard to the utilization of byproduct carbon as well, it will be important for Japan to lead the world in establishing demand for byproduct carbon.

[Fig. 10] Hydrogen Production Cost by Production Method



Note: Natural gas price: $7.6/MMBtu, renewable energy-derived electricity price $0.074/kWh, CCS cost 17,500 yen/t-CO_2, 1 USD=150 JPY.
Source: Compiled by Mizuho Bank Industry Research Department based on various materials.

[Fig. 11] Market Size and Unit Price of Carbon-Related Products



Source: Compiled by Mizuho Bank Industry Research Department based on Advanced Research Projects Agency – Energy, U.S. Department of Energy HP.

Methods for supplying hydrogen vary depending on the region. From the standpoint of resilience, it is also important to establish a multi-layered supply chain

To implement hydrogen in society, it is preferable to achieve stable and large-scale hydrogen supply by combining various methods, taking into account regional characteristics and economic rationality (see Fig. 12). In coastal areas where several large hydrogen consumers are located, such as oil complexes, the lowest hydrogen procurement cost is through large-scale imports, because imported hydrogen can be used without transportation over long distances. Meanwhile, in areas where demand is small and surplus renewable energy is abundant, domestic green hydrogen production using surplus renewable energy in locations close to consumers is an option. However, from an economic standpoint, the ability to use surplus renewable energy at a lower cost than renewables-derived electricity is a prerequisite. Turquoise hydrogen, which utilizes gas infrastructure, can act as a flexible valve for hydrogen demand of varying scales. Moreover, turquoise hydrogen is suitable for establishing a multi-layered supply chain in combination with other production methods, and will contribute to strengthening the resilience of the hydrogen supply chain.

[Fig. 12] Comparison of Low-Carbon Hydrogen Supply Methods and Types

Type			Suitable Locations	Supply Scale	Production Facility Cost	Hydrogen Production Cost
Imported	Large-scale imports		Industrial complexes	Large	–	✔✔ 290 yen/kg-H_2 and up
Domestic production	Green hydrogen production		Surplus power supply location	Small	High	624 yen/kg-H_2*
Domestic production	Blue hydrogen production	CH_4	Gas infrastructure usage location	Large, medium, small	High (includes CCS)	✔✔ 330 yen/kg-H_2
Domestic production	Turquoise hydrogen production	CH_4	Gas infrastructure usage location	Large, medium, small	Low	✔✔ 353-479 yen/kg-H_2

Note: Also dependent on the procurement cost of surplus renewable energy.
Source: Compiled by Mizuho Bank Industry Research Department based on various materials.

5. Roadmap to social implementation in Japan

Social implementation of hydrogen will be achieved when cost-competitive hydrogen is supplied on a commercial scale

Social implementation of turquoise hydrogen production hinges on the ability to supply cost-competitive hydrogen on a commercial scale. And in order for hydrogen to be cost-competitive, it will be necessary to reduce costs related to procurement of raw materials for the feedstock and to effectively utilize the byproduct carbon, as described previously. In addition to using existing infrastructure, the cost of procuring raw materials can be lowered through more large-scale and long-term procurement (see Fig. 13). Furthermore, unlike North America and other regions where natural gas, the feedstock for turquoise hydrogen production, is abundant, Japan needs to import much of its methane feedstock in the form of LNG. Strategies for utilizing hydrogen in a country with scarce natural resources will serve as a guidepost for other countries in similar situations as well as a source of competitiveness for Japan in the hydrogen field.

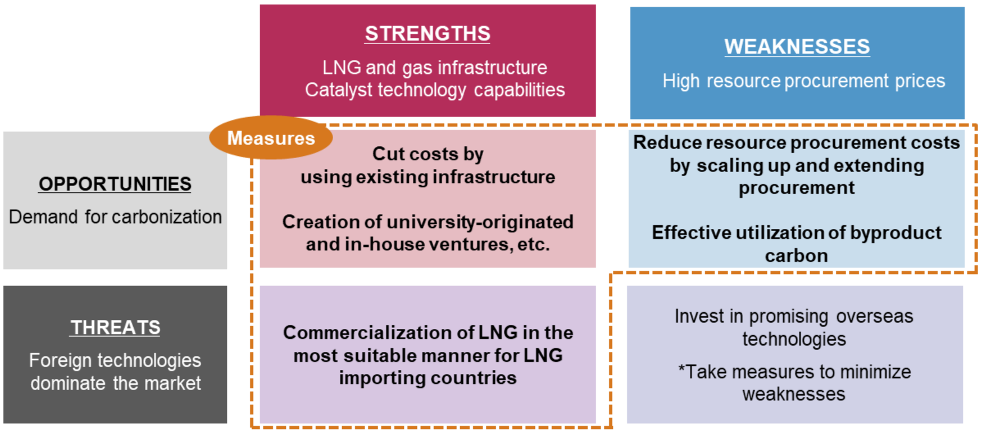
Mechanisms for widely cultivating technology at universities and companies are important

In addition, in order to realize hydrogen production on a commercial scale, it is also important to create an environment in which the requisite funds for the scaling up of production can be raised. It is also necessary to carve out promising Japanese technologies, for example as university-launched or in-house ventures at companies, and to quickly ramp them up into large businesses through the enthusiasm and funding of the relevant stakeholders, without being bound by any existing competitive or affiliated relationships.

Some new companies are catching the eye of domestic and foreign stakeholders

For example, Tsubame BHB, a company launched by the Tokyo Institute of Technology working to commercialize their innovative ammonia production technology, has attracted investment from a wide range of industries, including oil and natural gas development, oil refining, petrochemicals, shipping, logistics, food, finance, and leasing, to support its expansion. The company has also been selected as one of the "2022 APAC Cleantech 25," a list of 25 promising companies in the Asia-Pacific region issued by the Cleantech Group (U.S.), which also selects the Global Cleantech 100, the world's 100 most innovative clean technology companies. It is hoped that such initiatives will become more widespread in the area of hydrogen and ammonia utilization, including turquoise hydrogen production.

[Fig. 13] Measures for the Social Implementation of Turquoise Hydrogen Production Technology



Source: Compiled by Mizuho Bank Industry Research Department.

Setting appropriate KPIs serves as an impetus for popularizing turquoise hydrogen

In addition, we believe that setting appropriate KPIs at the national level is important for the domestic production of price-competitive low-carbon hydrogen (see Fig. 14). For example, as financing is key to achieving fast and large-scale commercial application of innovative technologies, attracting domestic and foreign investors would be an effective means to achieve this. From this perspective, it will also be important to create companies that can be selected for the Global Cleantech 100 (see Fig. 15).

Make turquoise hydrogen the "base hydrogen," with a production target of 4 million tons

In view of the important role that turquoise hydrogen can play in establishing domestic hydrogen demand, positioning turquoise hydrogen as the "base hydrogen" and setting a national-level production target will further increase the predictability of hydrogen being implemented in society. Given that turquoise hydrogen would be the base hydrogen, it is also worth considering setting the target at 4 million tons, which is equivalent to 30% of the Japanese government's hydrogen demand target for 2040.

A phased approach to effective utilization of byproduct carbon is also important

On the other hand, how to handle the 12 million tons of byproduct carbon generated from the 4 million tons of turquoise hydrogen production will be an issue. Even the market size of carbon black, which accounts for a considerable portion of the carbon market, is only 613,000 tons (Japan, 2022). As stated in the U.S. National Clean Hydrogen Strategy and Roadmap, establishing carbon markets is pivotal.

Turquoise hydrogen can also contribute to Asia's energy transition

Furthermore, turquoise hydrogen production is highly compatible not only with Japan but also with other Asian countries such as Malaysia and Singapore that have well-developed LNG and city gas infrastructure. As a real solution to decarbonization, it could also contribute to the energy transition in Asia.

[Fig. 14] Draft KPIs for Japan to Achieve a Competitive Advantage

KPI	Significance
(1) Be selected as one of the Global Cleantech 100	Attract domestic and foreign investors to scale up fast
(2) Produce 4 million tons of hydrogen through thermal decomposition of methane as of 2040 (**30% of the domestic demand target**)	There are limitations in hydrogen production by utilizing surplus renewable energy, which is the key to regional diversification. Possible to establish a social system with large-scale production in mind
(3) Effectively utilize byproduct carbon (**12 million tons of carbon byproducts** when producing 4 million tons of hydrogen)	Contribute to lowering the price of hydrogen
(4) Roll out the business model **to the Asian region**	Contribute to the decarbonization of Asia Quickly build cooperative relationships with Asia premised on collaborative creation

Source: Compiled by Mizuho Bank Industry Research Department.

[Fig. 15] Overview of Companies Selected for the Global Cleantech100 (Turquoise Hydrogen-Related)

Company	Year selected	Overview	Year founded
Monolith (U.S.)	2023 2022	• Produce hydrogen and carbon black using the plasma pyrolysis method. Achieve large-scale production by connecting reactors capable of producing 600kg of hydrogen per hour • Also collaborating with tire manufacturers to utilize the carbon black byproduct as a material to reinforce car tires	2013
Ekona Power (Canada)	2023 2022	• Obtained a patent for catalyst-free pulsed methane pyrolysis technology • Currently running a PoC test to produce 200kg of hydrogen a day, with plans to build a hydrogen plant in Alberta, Canada in 2024 with a daily production capacity of 1,000kg	2017
C-Zero (U.S.)	2022	• Developing a methane pyrolysis process that uses a bubble column reactor with molten salt as a heat medium and catalyst • Plans to operate a pilot plant with a hydrogen production capacity of 400 kg/day and a commercial demonstration plant with a capacity of 6,000 kg/day	2018

Source: Compiled by Mizuho Bank Industry Research Department based on various materials.

6. Initiatives for the utilization of byproduct carbon

Need to increase the value of byproduct carbon to reach a hydrogen cost of 20 yen/Nm^3

Since utilization of byproduct carbon contributes to lowering hydrogen production costs, aiming to effectively use the byproduct carbon will be extremely important. To achieve the Japanese government's target cost of 224 yen/kg-H_2 (20 yen/Nm^3, in 2050), the average value of carbon must be increased to 45,000 yen/ton-C (reducing the hydrogen production cost by 135 yen/kg-H_2), which is equivalent to three times the per-weight unit price of cement.

Utilization in existing applications and development of new applications are both essential

To achieve the 2050 government target hydrogen production cost, it will be important to develop applications that can utilize byproduct carbon on a large scale, such as concrete, for which efforts are under way in the U.S., while at the same time conducting research and development to cultivate markets in high value-added areas (see Fig. 16). Even for existing applications, it is important to make efforts to improve the quality, because if the quality is not improved through the use of byproduct carbon, it is difficult to expect transactions at higher prices than those of existing raw materials.

Potential as an alternative thermal power generation fuel during the energy transition

Another existing application that should be considered is as an alternative fuel for coal until coal-fired power generation is phased out, after appropriate environmental countermeasures such as CCS are taken. Funds allocated to coal imports would be circulated domestically and used as a resource to lower hydrogen production costs. However, this application should be strictly understood as a temporary measure to establish demand for hydrogen during the process of transitioning to carbon neutrality, and should not be implemented after the transition is completed.

[Fig. 16] Volume of Carbon Handled in Japan and Technical Feasibility

Application	Volume Handled	Unit Price	Technical Feasibility
Car tires, etc.	0.6 million Tn (carbon black market)	$1,000/ton-C	△／○
Power generation	100 million Tn (electric utility receipts)	$200/ton-C	△
Concrete	171 million Tn (shipment volume of ready-mixed concrete)	$100/ton-C	○
Advanced fields	TBD (Applications are expected to expand in the future)	TBD	△
Disposal	TBD	—	○

Source: Compiled by Mizuho Bank Industry Research Department based on various materials.

Byproduct carbon is fixated, but actions are necessary if using it for fuel

Byproduct carbon is a solid and unlikely to be released into the atmosphere as carbon dioxide; by its very nature, carbon is fixated (see Fig. 17). However, in the event that byproduct carbon is used for fuel in the future, carbon dioxide will be released into the atmosphere. Therefore, appropriate measures need to be taken in accordance with how byproduct carbon is utilized downstream in the supply chain.

Reporting related to greenhouse gas emissions must be done by the business that uses it as fuel

Specifically, in the case of byproduct carbon used for fuel, the business that uses it as fuel needs to report on greenhouse gas emissions in accordance with laws and regulations, and take appropriate environmental measures such as CCS. Meanwhile, if the byproduct is used as a raw material, it is not expected to result in the immediate release of carbon dioxide into the atmosphere, but this does not rule out the possibility that it could be used as fuel or for other purposes in the future. Therefore, as in the aforementioned case of direct use of the byproduct carbon as fuel, it will be necessary for the business entity that uses it as fuel to implement the necessary measures.

Establishing rules and fostering common understanding are vital for the widespread use of turquoise hydrogen

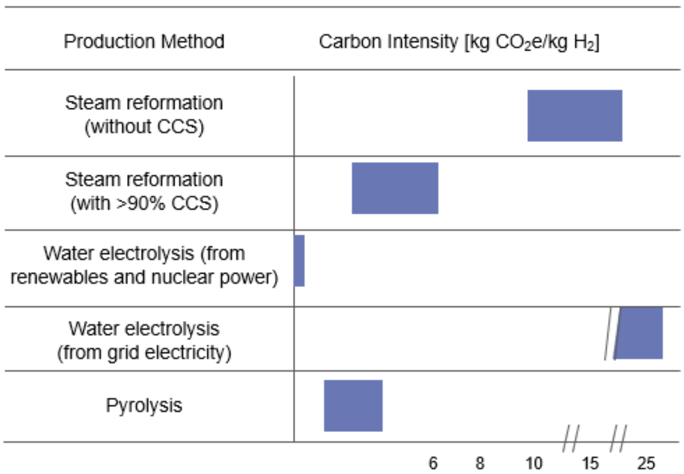
The carbon intensity of turquoise hydrogen should ideally be calculated based on the amount of carbon dioxide generated in the production process of the turquoise hydrogen itself, with the impact of emissions produced by future combustion of byproduct carbon considered separately. This is consistent with the idea that hydrogen should be separated from valuable co-products and by-products when calculating greenhouse gas emissions from hydrogen production. However, it is an issue that discussions on the carbon intensity of turquoise hydrogen are less developed than those pertaining to blue and green hydrogen, and it will be needed to develop the necessary rules and foster a common understanding going forward. In this regard, it is highly significant that the carbon intensity of methane pyrolysis was presented in the U.S. Clean Hydrogen Strategy and Roadmap (see Fig. 18).

[Fig. 17] Draft Conceptual Framework for the Fixation of Byproduct Carbon

Application	Carbon Fixation	Notes
Disposal	○	Not released into the atmosphere
Environmental dispersion	○	Not released into the atmosphere
Use as raw material	○	Not released into the atmosphere, but continuous carbon tracing is necessary
Use as fuel	×	Combustion causes the release of CO_2

Source: Compiled by Mizuho Bank Industry Research Department.

[Fig. 18] Carbon Intensity by Hydrogen Production Technology



Source: Compiled by Mizuho Bank Industry Research Department based on U.S. Department of Energy, *U.S. National Clean Hydrogen Strategy and Roadmap*.

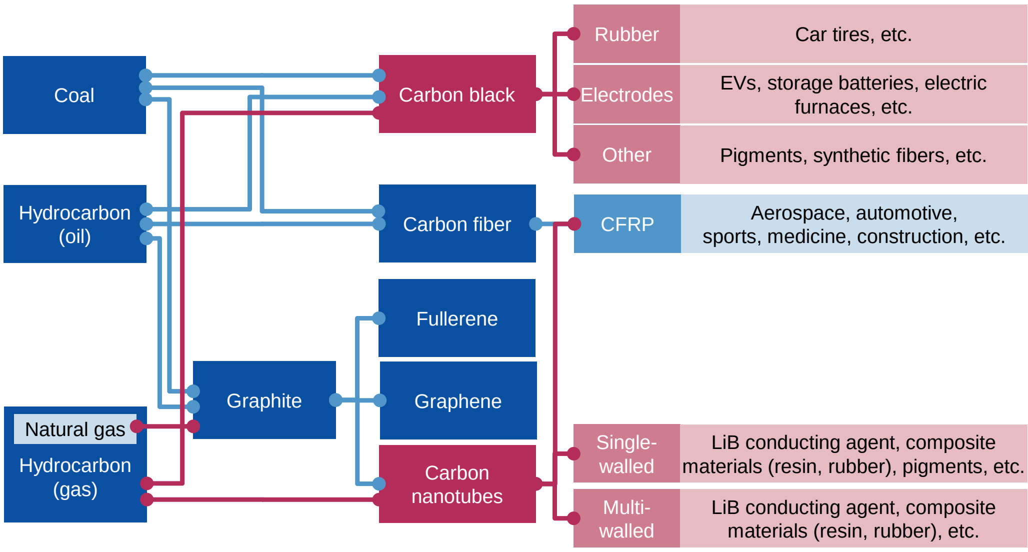
Collaboration among companies is important for developing high value-added applications

High value-added applications are expected to include utilization as a substitute for carbon black used to reinforce car tires and for carbon nanotubes used as a conductivity agent for lithium-ion batteries (see Fig. 19). For example, the Aichi Center for Industry and Science Technology has developed a prototype conductive composite material from byproduct carbon, and is promoting collaboration among companies for its practical application. In the U.S., Rice University and UK oil giant Shell are receiving support from the U.S. Department of Energy to pursue research and development for high-value-added utilization of byproduct carbon.

Efforts to improve the quality of byproduct carbon will also be important

To expand high value-added applications, ensuring the quality of the byproduct carbon will be important. For example, if the byproduct is used as a conductive agent for lithium-ion batteries in place of carbon nanotubes, it needs to be high purity carbon, as any residual metals can generate heat and cause other problems. In this regard, the fact that the carbon byproduct of the catalytic methane pyrolysis process contains trace amounts of metal catalysts may be an issue. Technology to separate metal catalysts from the byproduct carbon and progress with the development and introduction of turquoise hydrogen production technology that does not use catalysts would resolve this problem.

[Fig. 19] High Value-Added Applications of Carbon



Note: Items in red are applications related to byproduct carbon.
Source: Compiled by Mizuho Bank Industry Research Department based on various materials.

7. In conclusion

Turquoise hydrogen is the key to realizing a hydrogen-based society, but there are challenges

Methane pyrolysis is a technology to produce hydrogen and solid carbon by applying heat to methane. Because LNG facilities and city gas infrastructure can be used for the production of turquoise hydrogen, little infrastructure needs to be developed for its social implementation, and hydrogen supply chains can be established quickly and in stages. Dealing with the solid carbon byproducts created in the process of hydrogen production will be vital in order to implement turquoise hydrogen in society. If 4 million tons of hydrogen is produced, which is equivalent to 30% of the Japanese government's demand target for 2040, 12 million tons of solid carbon will be produced as a byproduct.

Expectations for joint public-private efforts to implement turquoise hydrogen in society

Various efforts are currently being undertaken, primarily in the United States, to utilize solid carbon as a raw material for concrete and car tire manufacturing, and in the future, it is expected to be utilized in advanced applications including as a conducting agent for lithium-ion batteries. To effectively utilize this valuable resource, progress in research, development, and proof-of-concept tests along with the system design necessary to utilize byproduct carbon is desirable. We sincerely hope that the importance of turquoise hydrogen, which is the key to the realization of a hydrogen-based society, will be fully recognized, and that the public and private sectors will actively pursue joint efforts to unlock its potential going forward.

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Link to survey

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