Mizuho Short Industry Focus Vol.248
April 15, 2025

Innovative Technology Series*

# Towards the Widespread Adoption of "Artificial Photosynthesis," an Innovative Technology from Japan

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**Summary**

- As movements toward a decarbonized society accelerate, technologies that contribute to this goal are gaining attention. Among these technologies, artificial photosynthesis is considered to contribute to carbon negativity and represents an area where Japan has technological superiority globally. This technology can generate hydrogen and chemicals from carbon dioxide ($CO_2$) and water utilizing sunlight as its energy. In the half-century since its discovery in 1967, numerous research and development efforts have progressed, bringing practical application closer. This paper examines the challenges and potential solutions for its practical application and mass production.

- Challenges and risks in the practical application of artificial photosynthesis include the procurement of photocatalyst raw materials, the explosion hazard of mixed hydrogen and oxygen gases, and the external procurement cost of hydrogen. Addressing these issues requires not only further research and development but also policy measures.

- Regarding the production of artificial photosynthesis equipment, specifications may need to be tailored on a case-by-case basisdepending on factors such as customer budgets, environmental conditions site constraints, and differences in the target chemicals to be produced by customers (chemical manufacturers). For manufacturers of artificial photosynthesis equipment, there are two main strategic directions to consider: guiding customers toward specifications that can be mass-produced, or identifying markets and customers who can accept higher unit prices for the equipment.

- However, Japan has had many bitter experiences where it has been ahead of other countries in the development and practical application stages of a technology, only to be outcompeted by Chinese and Korean rivals at the mass production stage. Therefore, even with artificial photosynthesis, it is necessary to consider differentiation strategies to maintain competitive advantage while anticipating competition with rivals from the current stage. Examples of such strategies include: (1) forming strategic alliances with influential companies at an early stage, and (2) establishing a strong foothold in niche markets.

- While artificial photosynthesis faces multiple challenges, there are many people hoping that Japan will continue to demonstrate its presence with this innovative technology originating from Japan. Policy initiatives, such as subsidies to stimulate interest in business development and regulations like emissions trading systems designed to encourage $CO_2$ emission reductions, are deemed essential. Rule-making that evaluates carbon negativity, a characteristic of artificial photosynthesis, is also expected. It is anticipated that artificial photosynthesis, often regarded as a dream technology, will gain widespread and accurate and correctly recognizedrecognition among the general public and expand through the identification of viable markets for its application.

* A report focusing on technology and innovation areas that could contribute to strengthening the competitiveness of Japanese industry and solving social issues.

## 1. Introduction — History of Research and Development

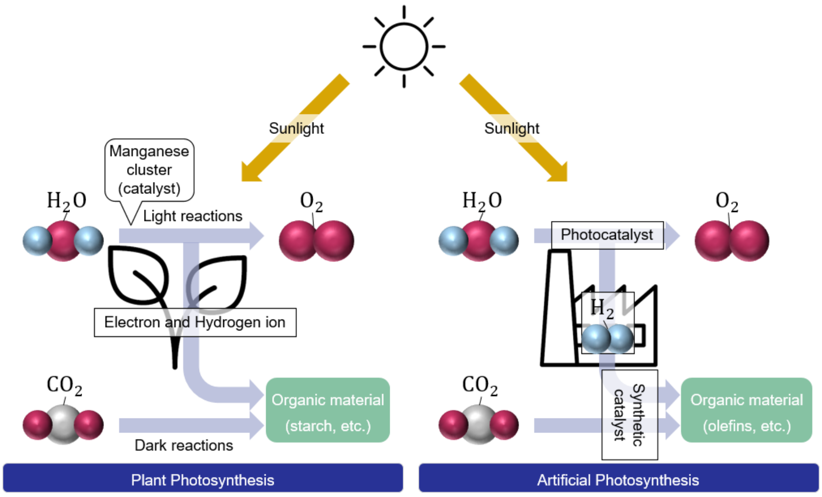
Carbon-free technologies like artificial photosynthesis attract attention

Since then-Prime Minister Suga announced the "2050 Carbon Neutrality Pledge" at the extraordinary Diet session in October 2020, technologies aimed at achieving a decarbonized society have been garnering attention. This paper focuses on artificial photosynthesis, which contributes to carbon negativity and is an area where Japan is said to have technological superiority globally.

Artificial photosynthesis refers to the process of manufacturing organic materials from $CO_2$ and water, or the process up to hydrogen extraction

Photosynthesis is the process in which plants convert $CO_2$ and water into organic compounds and oxygen using solar energy. Artificial photosynthesis is a technology that replicates this process artificially, typically divided into two main stages: (1) a process in which water is decomposed into hydrogen and oxygen by photocatalysts[2] or photoelectrodes[3] that utilize sunlight as an energy source, followed by hydrogen extraction using separation membranes; and (2) the production of olefins—a category of fundamental chemical products such as ethylene and propylene—through the reaction of hydrogen with $CO_2$ using synthetic catalysts ([Figures 1, 2]). The term artificial photosynthesis can refer to both processes (1) and (2) together, or sometimes only to process (1). Artificial photosynthesis is broadly categorized into two types: photocatalyst systems and photoelectrode systems.[4] Hybrid systems (devices) that integrate both approaches are also feasible, such as using electrical energy generated by photoelectrodes to enhance photocatalytic reactions.

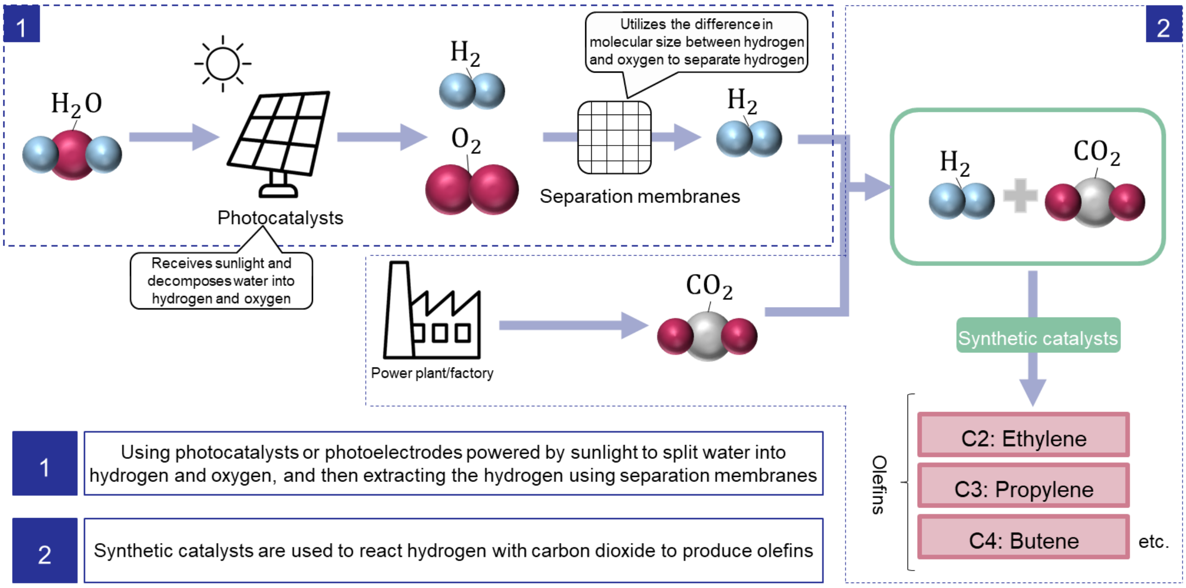
[Figure 1] Comparison Between Plant Photosynthesis and Artificial Photosynthesis




Source: Compiled by Mizuho Bank Industry Research Department based on the Ministry of Economy, Trade and Industry, Agency for Natural Resources and Energy website and Mitsubishi Chemical website.

[2] A substance that absorbs light and, in an activated state, promotes chemical reactions by coming into contact with reactants.
[3] A type of semiconductor that absorbs light energy to generate electric current.
[4] Photocatalyst systems are considered advantageous for mass production and scaling up, while photoelectrode systems are advantageous for efficient solar energy conversion.

[Figure 2] Overview of the Artificial Photosynthesis (Photocatalyst System) Process




Source: Compiled by Mizuho Bank Industry Research Department based on the Ministry of Economy, Trade and Industry, Agency for Natural Resources and Energy website and Mitsubishi Chemical website.

Artificial photosynthesis has continued to develop in research since its discovery in 1967

The concept of artificial photosynthesis date back to 1967. Akira Fujishima, then a graduate student at the University of Tokyo, discovered under the guidance of Assistant Professor Kenichi Honda that titanium dioxide, when irradiated with light, facilitates the decomposition of water into hydrogen and oxygen. This groundbreaking discovery was published in *Nature* in 1972 and later became known as the "Honda-Fujishima Effect" named after its discoverers. However, titanium dioxide, used as a photocatalyst, only absorbs ultraviolet light, which has shorter wavelengths than visible light. Since ultraviolet light constitutes only a small fraction of sunlight, the 'Solar-to-Hydrogen Energy Conversion Efficiency' (STH) for hydrogen production remains below 1%. To achieve commercialization and maximize STH, utilizing visible light and improving the efficiency of absorbed light (specifically photon usage, i.e., quantum efficiency) are essential. This necessity has driven intensified research and development of new photocatalysts and processes since 1980. For commercialization, the STH is generally considered to need to be around 10%. Later, in 2001, Kazunari Domen of Tokyo Institute of Technology (at the time), a leading figure in artificial photosynthesis R&D, and his colleagues demonstrated the existence of photocatalysts that absorb visible light, and, in the same year, the National Institute of Advanced Industrial Science and Technology (AIST) succeeded in the world's first water decomposition using an artificial photosynthesis system with visible light. In 2023, the Japan Technological Research Association of Artificial Photosynthetic Chemical Process (ARPChem)[5] and its collaborators achieved an STH of 10% using a hybrid system. In 2024, US-based SunHydrogen achieved an STH of 10.8% with a demonstration module presumed to be a photoelectrode system of 100 cm². Additionally, although the target product is formic acid rather than hydrogen, Toyota Central R&D Labs achieved a conversion efficiency of 10.5% with what is presumed to be a photoelectrode-based artificial photosynthesis

5 A technology research association formed under the leadership of the Ministry of Economy, Trade and Industry. As of June 20, 2024, the participating companies, universities, and research institutions are as follows:
○ Companies (in Japanese alphabetical order): INPEX, KYOCERA, JX Advanced Metals, Dai Nippon Printing, Dexerials, TORAY INDUSTRIES, TOYOTA MOTOR , NIPPON STEEL , FURUYA METAL, Mitsui Chemicals, Mitsubishi Chemical
○ Universities and Research Institutions (in Japanese alphabetical order): Gifu University, Kyoto University, National Institute of Advanced Industrial Science and Technology, Shinshu University, The University of Tokyo, Tokyo University of Science, Tohoku University, Nagoya University, University of Miyazaki, Yamaguchi University

system in 2021. Regarding timelines for practical application, Toyota Central R&D Labs is targeting around 2030, while Mitsubishi Chemical, a member of ARPChem, aims for around 2035, specifically for practical olefin production ([Figure 3]).

[Figure 3] History of Artificial Photosynthesis Research and Development

| Period | Events |
|---|---|
| Early Research (1970s) | • 1972: Akira Fujishima and Kenichi Honda published their findings on water decomposition reaction using titanium dioxide ($TiO_2$) photocatalyst (Honda-Fujishima Effect) |
| Development Period (1980s-1990s) | • Active research and development of photocatalysts using materials other than titanium dioxide, such as zinc oxide and iron oxide |
| Technological Breakthrough (2000s) | • Photocatalyst research progressed, improving light absorption efficiency and reaction rate. Research on photocatalysts that work under visible light irradiation advanced<br>➢ 2001: National Institute of Advanced Industrial Science and Technology (AIST) succeeded in the world's first complete water decomposition using an artificial photosynthesis system with visible light |
| Modern Research (2010s~) | • Research toward the practical application of artificial photosynthesis accelerated, including $CO_2$ reduction reactions, production of organic compounds, and development of actual systems<br>➢ 2011: Toyota Central R&D Labs succeeded in demonstrating the principle of an artificial photosynthesis system using only water and $CO_2$ as raw materials under sunlight. They achieved a conversion efficiency of 10.5% (photoelectrode system) to formic acid using sunlight in 2021, and are accelerating research and development toward practical application in around 2030<br>➢ 2012: Led by the Ministry of Economy, Trade and Industry, the Japan Technological Research Association of Artificial Photosynthetic Chemical Process (ARPChem) was established with member organizations including Mitsubishi Chemical. In the first phase of activities until fiscal 2021, they succeeded in a large-scale demonstration of artificial photosynthesis for the first time in the world. In the second phase, to be implemented until fiscal 2030, they achieved the STH of 10% (hybrid system) at a practical level in 2023, and are promoting technological development with a view to social implementation |

Source: Compiled by Mizuho Bank Industry Research Department based on "Green Hydrogen Production Using Artificial Photosynthesis Type Photocatalysts," *Chemistry & Education* Vol.70, No.9 (2022), The Chemical Society of Japan, etc.

Artificial photosynthesis is an innovative technology that supports the realization of a decarbonized society

This paper will now calculate the area required to produce hydrogen equivalent to Japan's annual energy consumption in 2023. Assuming the average solar radiation in Tokyo is approximately 1,602 million kWh/km²/year, the estimated area required is approximately 19,900 km². This corresponds to approximately 5.3% of Japan's total area of 377,975 km². If Japan's idle farmland of 2,644 km² in 2023[6] were utilized for artificial photosynthesis, it could theoretically supply approximately 13.3% of Japan's annual energy consumption. In theory, it is possible to further increase hydrogen production through improvement of STH and expansion of the installation area of photocatalyst sheets. Artificial photosynthesis, which emit no $CO_2$ during the hydrogen production process and is a carbon-negative technology utilizing $CO_2$ as a raw material to produce hydrogen and chemicals, represents an innovative solution for achieving a decarbonized society. Additionally, for Japan, which is not an energy resource-rich country, the practical application of artificial photosynthesis is considered a significant technology from the perspective of advancing toward energy self-sufficiency.

6 Sum of the areas of Type 1 idle farmland, farmland that can be reused, and Type 2 idle farmland, based on the "Fiscal Year 2023 Idle Farmland Area" from the Ministry of Agriculture, Forestry and Fisheries.

[Figure 4] Evaluation of Artificial Photosynthesis Potential

a. Japan's annual energy consumption (2023)

$$11{,}476PJ = 11{,}476 \times 10^{15}J$$

b. Energy unit conversion

$$1kWh = 3.6 \times 10^{6}J$$

$$11{,}476PJ = 11{,}476 \times 10^{15}J = \frac{11{,}476 \times 10^{15}J}{h = 3.6 \times 10^{6}J\ /kWh} = 3{,}188 \times 10^{9}kWh$$

c. Photocatalyst efficiency (STH)

$$STH = 10\%$$

d. Required solar energy amount

$$= \frac{b.}{c.} = \frac{3{,}188 \times 10^{9}kWh}{0.1} = 3{,}188 \times 10^{10}kWh$$

e. Annual average solar radiation (Tokyo)

$$4.39kWh/m^{2} \cdot day \times 365 = 1{,}602kWh/m^{2} \cdot year$$

f. Required area

$$= \frac{d.}{e.} = \frac{3{,}188 \times 10^{10}kWh}{1{,}602kWh/m^{2} \cdot year} = 19{,}900{,}124{,}844m^{2} = \mathbf{19{,}900km^{2}}$$

Approximately 5.3% of Japan's total area (377,975 km²)

If Japan's idle farmland (2,644 km²) was utilized for artificial photosynthesis, it could supplement approximately 13.3% of annual energy consumption

Source: Compiled by Mizuho Bank Industry Research Department based on the Ministry of Economy, Trade and Industry Agency for Natural Resources and Energy, the New Energy and Industrial Technology Development Organization "Solar Radiation Database Browsing System" (MONSOLA-20), the Ministry of Agriculture, Forestry and Fisheries "Fiscal Year 2023 Idle Farmland Area," etc.

## 2. Toward Practical Application — Overview of Challenges to Overcome

Examining the challenges for practical application of artificial photosynthesis

There remain challenges to overcome for the practical application of artificial photosynthesis. This chapter examines the challenges in the artificial photosynthesis process, along with directions toward their resolution ([Figure 5]).

[Figure 5] Major Challenges and Risks Toward Practical Application

| Process | Challenges/Risks | Directions Toward Resolution |
|---|---|---|
| Water decomposition | Procurement of photocatalyst raw materials | Strengthening relationships with resource-rich countries, development of photocatalysts using non-critical minerals as raw materials |
| Hydrogen extraction | Explosion hazard of mixed hydrogen and oxygen gases | Development of membranes that safely and efficiently separate hydrogen gas |
| Chemical production | External hydrogen procurement cost | Combined use with water electrolyzers, chemical production at hydrogen production sites |

Source: Compiled by Mizuho Bank Industry Research Department

Potential constraints in procurement of raw material of catalyst

The First challenge lies in the procurement of raw materials for photocatalysts used in the artificial photosynthesis process. For example, in the process of decomposing water into hydrogen and oxygen using photocatalysts, materials such as titanium dioxide, tantalum nitride, and strontium titanate are considered promising from the perspectives of efficient light absorption capability, reaction rate, and crystal structure stability. Critical minerals,[7] including precious and rare metals, are commonly used as raw materials for photocatalysts. However, for Japan, a country that is not rich in resources, there is a possibility of constraints in procuring critical minerals, making it important to strengthen relationships with resource-rich countries and develop photocatalysts with lower dependence on critical minerals. Nevertheless, carious approaches are being explored to address these challenges, including the development of a 'rare-metal-free, high-efficiency water electrolysis oxygen generation catalyst' announced by the Institute of Science Tokyo in December 2024. Continued progress in this area is anticipated.

Separation membrane development becomes important to address explosion hazard of mixed gases

The next challenge involves the explosion risk associated with the mixture of hydrogen and oxygen gases during the separation process. Hydrogen produces water and heat through reaction with oxygen, but due to its high reactivity, the reaction can be initiated even by static electricity or small sparks. Due to the rapid reaction rate, there is a significant risk of substantial heat release, potentially leading to explosions. Therefore, the development of membranes that can safely and efficiently separate hydrogen and oxygen is important, and companies like Mitsubishi Chemical are advancing the development of separation membranes and modules. According to research results reports as of June 2024,[8] researchers have successfully achieved separation with a hydrogen concentration of over 96% and a hydrogen recovery rate of 90%. The separation itself is possible, and improvements in performance such as durability and lifespan of separation membranes and modules are expected.

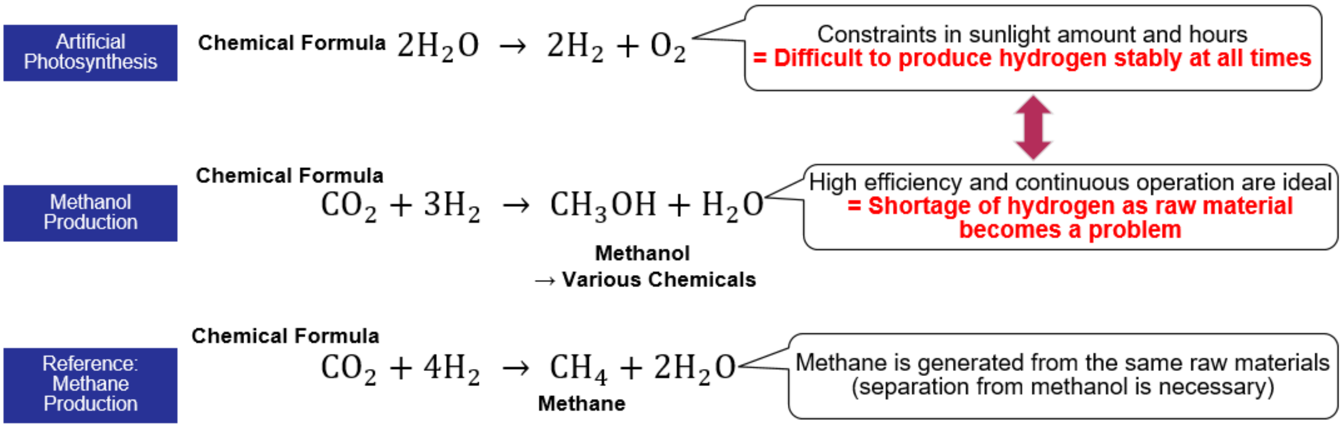
External procurement cost of hydrogen as a raw material becomes a challenge

Finally, a key challenge is the external procurement cost of hydrogen as a raw material in the production process of olefins, achieved by reacting hydrogen with $CO_2$ using synthetic catalysts. Let's consider the case of producing methanol from hydrogen generated by artificial photosynthesis as an example ([Figure 6]).

7 In this paper, this term is defined as a collective term for precious metals and rare metals. For elements belonging to precious metals and rare metals, please refer to "Learning About Mineral Resources Supporting Global Industries" by the Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry.

8 New Energy and Industrial Technology Development Organization (NEDO) "Business Strategy Vision Project Name: Commercial Development of Artificial Photosynthesis-based Chemical Raw Material Production ① Development and Demonstration of Chemical Raw Material Manufacturing Technology from Green Hydrogen (Artificial Photosynthesis), etc. ② Development and Demonstration of Basic Chemical Manufacturing Technology from CO2 (as of June 2024)"

[Figure 6] Challenges in Artificial Photosynthesis and Methanol Production




Source: Compiled by Mizuho Bank Industry Research Department

Need to consider creating an environment for procuring hydrogen at low cost

It should be noted that artificial photosynthesis may not consistently produce hydrogen, as reactions occur only during periods when sunlight is available. When manufacturing chemicals that need to maintain reactions through high-efficiency, continuous operation to increase yield,[9] a hydrogen shortage may become a bottleneck,[10] so it is necessary to prepare means to procure raw material hydrogen from elsewhere. There is a need to consider creating an environment for procuring hydrogen at low cost, such as placing artificial photosynthesis equipment adjacent to water electrolyzer sites, or conducting chemical production in countries and regions where hydrogen procurement costs are low.

Hydrogen price required for competitiveness set at 10 yen/Nm³, an ambitious level

However, low-cost hydrogen procurement is unlikely to be straightforward. According to Mitsubishi Chemical's calculations, the hydrogen price required to achieve an olefin cost of 100 yen/kg--a target equivalent to current basic chemical production methods—would need to be 10 yen/Nm³ or less.[11] The Ministry of Economy, Trade and Industry's target values for hydrogen supply prices (CIF) are 30 yen/Nm³ in 2030 and 20 yen/Nm³ in 2050,[12] highlighting the difficulty of replacing current chemical production methods with artificial photosynthesis. While companies' efforts to lower hydrogen prices are important, policy mechanisms that enable environmentally sustainable chemical production to remain competitive will also critical.

9 The ratio between the amount actually obtained and the amount theoretically assumed to be extractable when obtaining a target substance from raw materials through chemical methods.
10 When manufacturing methanol, it is also necessary to be aware of the possibility that methane may be unintentionally generated, lowering the yield.
11 Mitsubishi Chemical "Commercial Development of Artificial Photosynthesis-based Chemical Raw Material Production"
12 Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry "Overview of Hydrogen Basic Strategy"

## 3. Toward Equipment Production

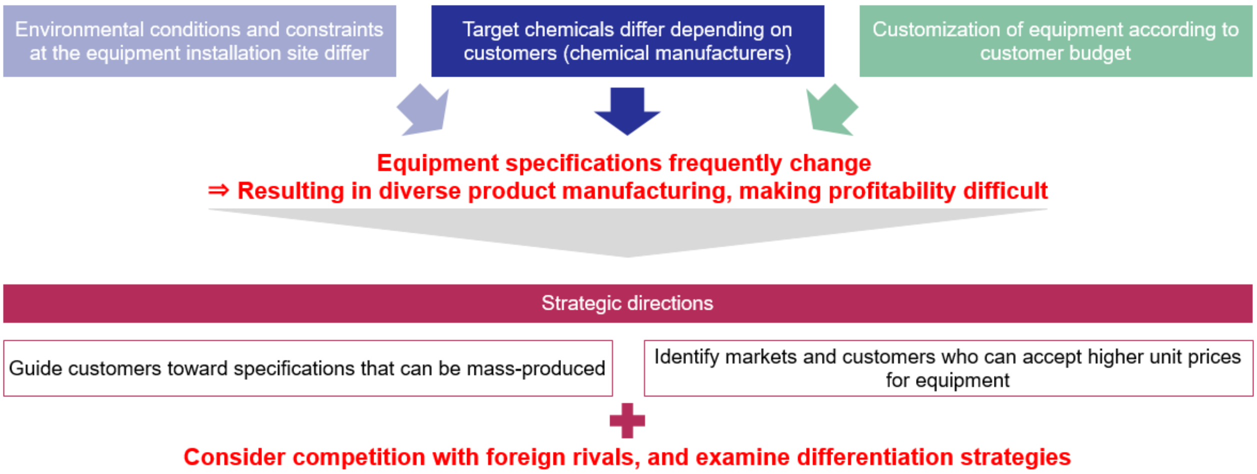
Artificial photosynthesis equipment is likely to be for small to medium-scale diverse production

After achieving practical application, the focus will shift to the mass production stage. However, artificial photosynthesis equipment is likely to emphasize diverse production rather than mass production. This is because the budgets of customers, such as electric power companies and chemical manufacturers, and the environmental conditions and constraints, such as the shape and area of the land where the equipment is to be installed are expected to vary on a case-by-case basis. Additionally, when manufacturing chemicals through artificial photosynthesis, the target chemicals will differ depending on the chemical manufacturer, requiring different photocatalysts and synthetic catalysts to maximize yield. Therefore, it is expected that equipment will be customized each time, and since it will not be possible to mass-produce equipment with identical specifications, the unit price of equipment is likely to increase.

The importance of considering differentiation strategies against Chinese and Korean rivals

For manufacturers of artificial photosynthesis equipment, there are two main strategic directions to consider: guiding customers toward specifications that can be mass-produced,[13] or identifying markets and customers who can accept higher unit prices for the equipment ([Figure 7]). However, in markets where profitability can be secured and significant growth is expected, it is necessary to anticipate competition with rivals such as those from China and Korea, which aim to capture markets with nationwide efforts. Therefore, developing robust differentiation strategies will be crucial.

[Figure 7] Challenges and Strategic Directions for Artificial Photosynthesis Equipment




Source: Compiled by Mizuho Bank Industry Research Department

## 4. Importance of Differentiation Strategies — Strategies Japan Should Implement

Considering strategic directions for differentiation

Japan has faced numerous setbacks where, despite leading other countries in the development and practical application stages of technologies such as solar cells and displays, it was ultimately outcompeted by Chinese and Korean rivals in the mass production phase. In the case of artificial photosynthesis, the challenge lies in differentiating and maintaining competitive advantage while proactively anticipating competition from rivals at the current stage. Therefore, referencing two current approaches adopted by companies, universities, and research institutions in relation to artificial photosynthesis, this section will explore potential directions for differentiation strategies ([Figure 8]).

13 Assuming the target manufactured products are representative chemicals such as methanol and ethylene.

[Figure 8] Directions for Differentiation Strategies

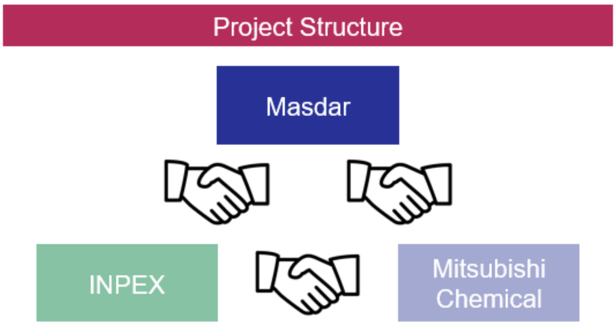
| | Examples of Differentiation Strategies | Explanation | Example Case |
|---|---|---|---|
| 1 | Developing alliances with influential companies from an early stage | • Form alliances with influential entities such as state-owned enterprises from an early stage. Address various challenges by complementing strengths and create entry barriers in specific countries/regions | Masdar × Mitsubishi Chemical Group × INPEX |
| 2 | Early positioning in niche areas (e.g., installation in detached houses) | • Deliberately narrow the target to small-scale demand and develop equipment optimized to meet that demand | Iida Group HD × Osaka Metropolitan University |

Source: Compiled by Mizuho Bank Industry Research Department

First strategic direction: Alliances with influential companies from an early stage

The first strategic direction is exemplified by the "Joint Feasibility Study for Carbon Recycle Chemicals Project" ([Figure 9]) announced in July 2023 by Masdar, Mitsubishi Chemical, and INPEX, which seeks to manufacture chemicals using artificial photosynthesis. This approach focuses on forming alliances with influential companies at an early stage, leveraging their collective knowledge and resources to drive commercialization. Masdar, recognized as a flag-bearer for clean energy development in the UAE, has shareholders including ADNOC (Abu Dhabi's national oil company), TAQA (likewise a national energy company), and Mubadala (Abu Dhabi's sovereign wealth fund). Abu Dhabi offers ideal environmental conditions for artificial photosynthesis powered by sunlight, with annual rainfall ranging from 140 to 200 mm and approximately 12 rainy days per year. The alliance between Mitsubishi Chemical and INPEX (members of ARPChem with technological expertise) and Masdar (with financial resources and influence) establishes a collaborative framework where each participant compensates for the others' weaknesses, effectively addressing various challenges. Since this project can be interpreted as one involving a state-owned enterprise with national prestige at stake, it is expected to create entry barriers within the UAE. Additionally, to generate results within the established timeframe, each company should strive to maximize the deployment of its resources. For artificial photosynthesis, which faces multiple challenges to overcome, such alliances are considered to contribute to advancing in unison, working toward achieving commercialization.

[Figure 9] Key Points of the Alliance Between Masdar, Mitsubishi Chemical, and INPEX




**Key Points**

1. Project in the UAE where ideal environmental conditions are in place
2. Masdar's participation as the flag-bearer for green energy in the UAE and with state-owned enterprises as shareholders
3. Structure where INPEX and Mitsubishi Chemical (with technological capabilities) join with Masdar (with financial power and influence), complementing each other's strengths

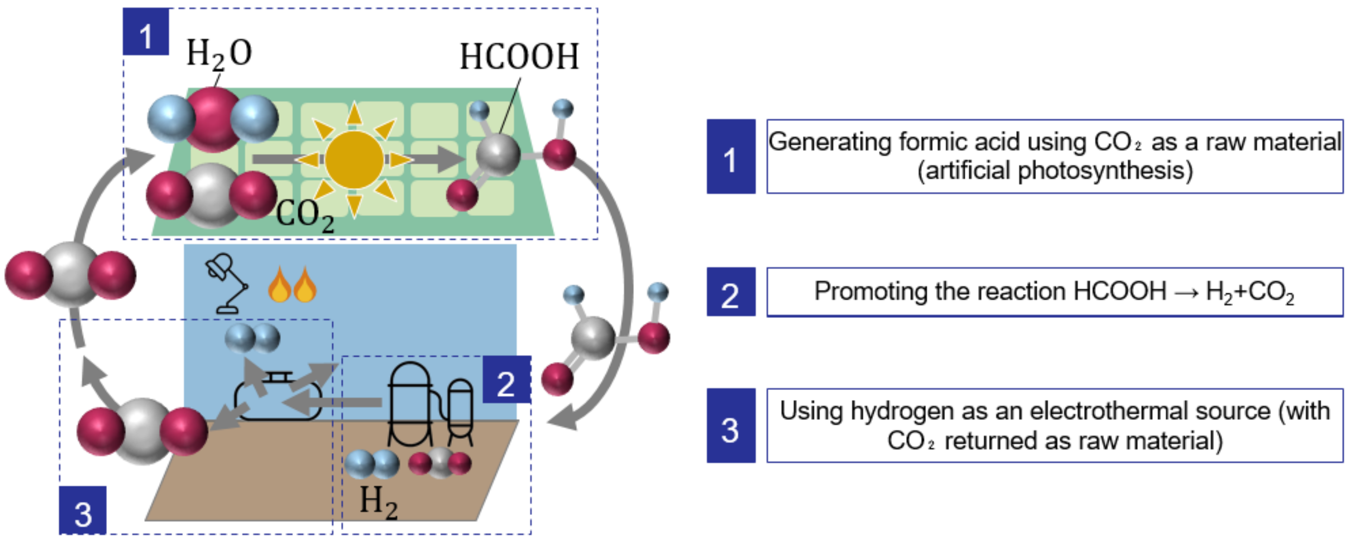
**Contributes to advancing in unison toward solving challenges and completing commercialization**

Source: Compiled by Mizuho Bank Industry Research Department based on materials published by Mitsubishi Chemical, etc.

**Second strategic direction: Early positioning in niche areas**

The second strategic direction can be seen in initiatives like the "Artificial Photosynthesis House" announced in July 2017 by Iida Group Holdings (hereinafter, Iida GHD), a holding company for corporate groups involved in housing sales and construction material manufacturing, and Osaka Metropolitan University. This approach involves early positioning in niche areas where Chinese and Korean rivals have low motivation to enter. Their artificial photosynthesis house adopts a system that circulates between three processes ([Figure 10]): (1) generating formic acid using $CO_2$ as a raw material (artificial photosynthesis), (2) promoting a reaction to obtain hydrogen and $CO_2$ from formic acid, and (3) using hydrogen as an electrothermal source (with $CO_2$ returned to the raw material). This initiative is noteworthy for optimizing equipment (system) specifications with the goal of providing an energy source for detached houses. When using artificial photosynthesis to obtain hydrogen as an energy source, challenges are pointed out from two perspectives: safety (explosion risk) and storage (requiring special containers to prevent hydrogen embrittlement). By manufacturing formic acid, which acts as a hydrogen carrier, as the target product, these concerns can be eliminated ([Figure 11]), making it a specification that considers the residents.

[Figure 10] Overview of the Artificial Photosynthesis House Proposed by Iida GHD × Osaka Metropolitan University




Source: Compiled by Mizuho Bank Industry Research Department based on published materials from Iida GHD and Osaka Metropolitan University.

[Figure 11] Comparison of Hydrogen and Formic Acid from the Perspectives of Safety and Storage

| | Hydrogen | Formic Acid (Hydrogen Carrier) |
|---|---|---|
| Safety | • Risk of explosion | • Possibility of eliminating fire hazard by mixing with water |
| Storage | • Special containers required to prevent hydrogen embrittlement | • Can be stored long-term in glass or polyethylene containers |

Source: Compiled by Mizuho Bank Industry Research Department

Iida GHD and Osaka Metropolitan University focus on the niche characteristics of the domestic housing market, positioning from an early stage

The domestic housing market in Japan has formed a unique ecosystem where prime contractors (house manufacturers) and subcontractors (construction companies) work in close cooperation, making it difficult for foreign companies to enter. Building codes and regulations differ by country, so equipment that can be installed in other countries may not necessarily be installable in Japan, and enlarging equipment may not always be the optimal solution. Iida GHD and Osaka Metropolitan University have focused on these niche characteristics of the market and have positioned themselves from an early stage. While solar power generation exists as a means of energy acquisition for detached houses, and batteries exist as a means of energy storage, it is hoped that artificial photosynthesis will also become widespread as a means that handles both energy acquisition and storage simultaneously.

## 5. Conclusion

Hoping for the widespread adoption of artificial photosynthesis, contributing to a decarbonized society

Artificial photosynthesis is a technology that produces hydrogen and chemicals using water and $CO_2$ as raw materials. Since it does not emit $CO_2$ during the process, it can be considered an innovative technology that contributes to carbon neutrality. Many people express hope that Japan will continue to maintain its strength in this field, as Japanese companies and research institutions have led development and practical implementation efforts. However, numerous challenges still exist on the path to commercialization. To overcome these challenges, we believe both a "carrot" to stimulate Japanese companies' motivation for commercialization and a "stick" to increase the necessity of addressing these issues are required. For the "carrot," support for the commercialization of artificial photosynthesis is already being provided through the framework of the Green Innovation Fund (GI Fund)[14] by the New Energy and Industrial Technology Development Organization (NEDO).[15] For wider adoption, subsidies aimed at stimulating consumer demand could also be considered. Regarding the "stick," regulations that can promote the reduction of $CO_2$ emissions, such as the full-scale introduction of emissions trading systems already pioneered in Europe, are anticipated. Another option could be revising existing systems, such as adding artificial photosynthesis to the framework of Tokyo's solar power installation support and obligation system.[16] Furthermore, compared to other decarbonization technologies, artificial photosynthesis is characterized by its contribution to carbon negativity, and rule-making that evaluates such features is also anticipated.[17] It is our hope that artificial photosynthesis, a dream technology, will become widely and correctly recognized by the public and spread through the discovery of viable markets for its application.

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14 An initiative to support companies and other entities addressing management issues aimed at Japan's "2050 Carbon Neutrality" with research and development, demonstration, and social implementation over a 10-year period.

15 On February 18, 2022, it was announced that Mitsubishi Chemical as the lead company, along with Mitsubishi Gas Chemical and ARPChem, proposed and received approval for "Commercial Development of Artificial Photosynthesis-based Chemical Raw Material Production" in response to the GI Fund's research and development item 4 "Development of technology for producing chemicals from alcohols," an open call from NEDO.

16 From April 2025, a system has been initiated that obliges the installation of solar power generation equipment and ensures insulation and energy conservation performance for new housing.

17 Discussions on rule-making for creating a CDR (Carbon Dioxide Removal) market have already begun, with the Ministry of Economy, Trade and Industry taking the lead.

# [Reference]


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   - ○ Nikkei Inc.(2021), "Zinkou-Kougousei, Tikaduku-Zituyouka Mitubisi-Kemi nado Daikibo-Zissyou-Seikou" [人工光合成、近づく実用化 三菱ケミなど大規模実証成功]
   - ○ Nikkei Inc.(2023), "Zinkou-Kougousei, Mazu ha Jyutaku de Osaka-Kouritu-Daigaku no Amao-Yutaka-Kyouzyu" [人工光合成、まずは住宅で 大阪公立大学の天尾豊教授]
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Mizuho Short Industry Focus／248



Edited/Published by: Industry Research Department, Mizuho Bank

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