CENTER FOR GLOBAL COMMONS

SYSTEMIQ

October 2024

Planet Positive Chemicals in Japan

Unlocking new roles of the Japanese chemical industry in achieving scope 1–3 net zero and safeguarding the Global Commons

One-Sentence Summary

This report presents quantitative pathways for the Japanese chemical industry to achieve net zero emission for scope 1, 2, and 3, offering strategies for a transition that considers Japan's strengths and weaknesses, and proposes a future role for the industry, which may also be applicable to chemical industries in other countries and regions with similar constraints.

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Acknowledgements

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This research was funded by Mitsubishi Chemical Corporation.

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Preface: Reasons for writing this report

Pressure is mounting for the chemical industry in Japan to pursue scope 1, 2, and 3 net zero. Since Prime Minister Suga announced Japan's target to achieve net zero greenhouse gas (GHG) emission by 2050 in 2020, Japan has formulated strategies and established relevant laws. They will support innovation, promote infrastructure and business development, and advance carbon pricing coupled with government transition bonds to drive private sector investments. It may take time for the effectiveness of these policies to become clear, but the government has laid out an initial framework for transition. For the chemical industry in Japan, however, the roadmap for achieving net zero remains unclear. In addition, the industry must address other sustainability issues regarding the Planetary Boundaries[1], without shifting the burden from one category to another. In global business, the requirement for scope 3 net zero, in addition to scope 1 and 2, has become clearer since COP26 in 2021. For example, financial institutions under the GFANZ alliance[2] have started to press their investees to achieve scope 1, 2, and 3 net zero, while brand owners in the downstream of supply chains have started to drive transparency in scope 3 emission under the PACT alliance[3]. Delayed responses by Japanese chemical companies could increase the risk of exclusion from international finance and supply chains, whereas proactive measures will enhance competitiveness.

We aim to provide net zero pathways and insights to bridge the gap between the current state of the chemical industry in Japan and a desired sustainable future. Chemical industry's transition to net zero is known to be challenging. The need to transition carbon-containing raw materials (feedstock), in addition to transitioning energy, highlights this challenge. To address this challenge, our group previously wrote a report[4] and a peer-reviewed academic paper[5] to show quantitative pathways to scope 1, 2, and 3 net zero for the global chemical industry. In this report, based on another recently published peer-reviewed academic paper[6], we focus on Japan to provide quantitative pathways for the chemical industry in Japan to reach scope 1, 2, and 3 net zero, using our established model. In addition, we will shed light on uncertainties (e.g., future demand for net zero chemicals and suitable technologies to produce them) that hinder the Japanese chemical industry's transition to net zero, so that it can move forward amid these uncertainties. Furthermore, we aim to provide insights into competitive strategies and necessary actions by combining information derived from the quantitative pathways with the existing knowledge of the Japanese chemical industry.

We hope that this report will inspire leadership and action to unlock the potential of the Japanese chemical industry to lead the global chemical industry's transition to an economically, socially, and environmentally sustainable future.

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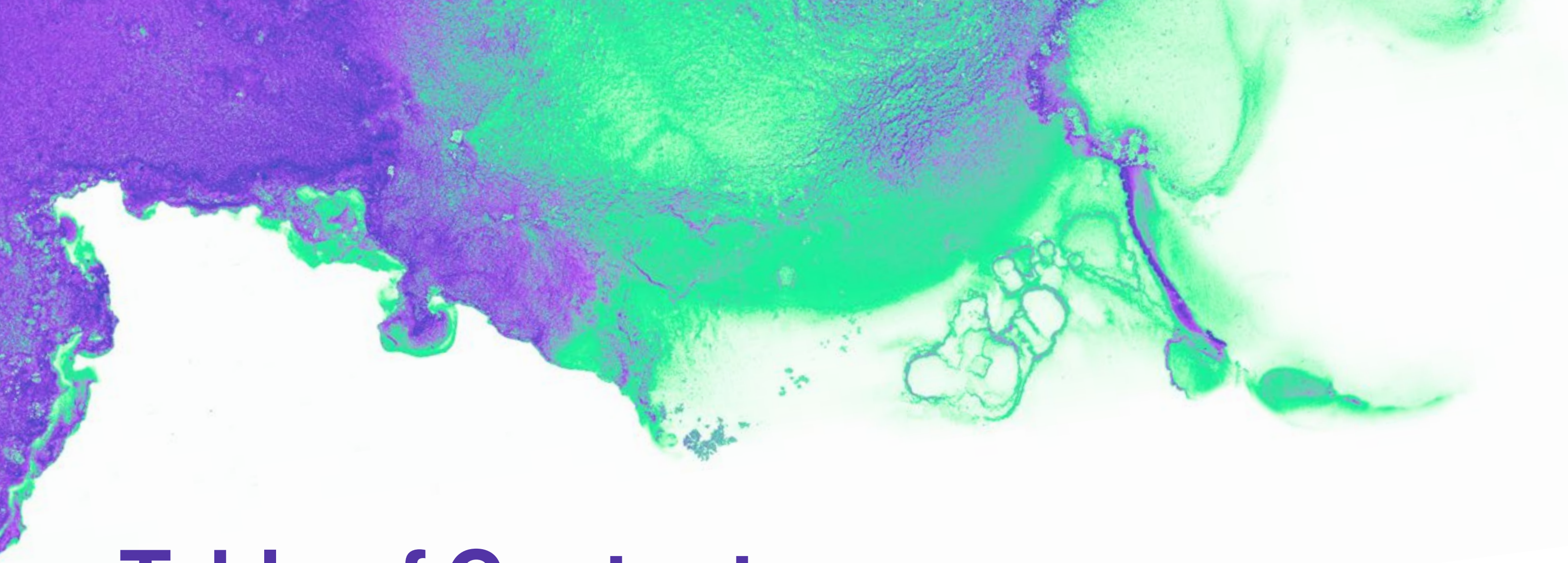
1 Rockström J. et al., Planetary Boundaries: Exploring the Safe Operating Space for Humanity. *Ecology and Society* **14**(2): 32 (2009), https://www.ecologyandsociety.org/vol14/iss2/art32
2 Glasgow Financial Alliance for Net Zero (GFANZ), https://www.gfanzero.com
3 Partnership for Carbon Transparency, https://www.wbcsd.org/news/pathfinder-framework-version-2-0/
4 University of Tokyo and Systemiq, Planet positive chemicals (2022), https://cgc.ifi.u-tokyo.ac.jp/en/research-en/chemistry-industry-en/, https://www.systemiq.earth/systems/circular-materials/planet-positive-chemicals/
5 Meng F. et al., Planet-compatible pathways for transitioning the chemical industry. *Proceedings of the National Academy of Sciences*, **120**, e2218294120 (2023), https://doi.org/10.1073/pnas.2218294120
6 Kanazawa D. et al., Scope 1, 2, and 3 Net Zero Pathways for the Chemical Industry in Japan, *Journal of Chemical Engineering of Japan*, **57**, 2360900 (2024), https://doi.org/10.1080/00219592.2024.2360900



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Executive Summary

1. Introduction

Global business and Japanese political development towards net zero. Since Prime Minister Suga announced Japan's target to achieve net zero by 2050 in 2020, Japan has formulated initial policy frameworks and laws to drive the transition to net zero. These policies and laws[7] enable carbon pricing, business and infrastructure development for hydrogen and CCS, and subsidies to drive innovation. In global business, net zero greenhouse gas (GHG) including scope 3, has become a global business requirement, driven particularly by business alliances and frameworks, such as GFANZ[8], a large alliance of financial institutions; the Partnership for Carbon Transparency (PACT)[9] under WBCSD's leadership to exchange product-level emission data across supply chains, including scope 3; and the International Sustainability Standards Board[10] (ISSB) to develop global baseline of sustainability disclosure standards for investors. In addition, the Science Based Targets initiative[11] (SBTi) is developing sector guidance for the chemical industry, which could "colour-code" chemical companies with credible GHG reduction targets for downstream customers and financial institutions that are not familiar with the details of the chemical industry (see Section 1 for details).

7 Ministry of Economy, Trade and Industry (METI),
Green Growth Strategy (2021), https://www.meti.go.jp/english/policy/energy_environment/global_warming/ggs2050/index.html
Green Innovation Fund (2021), https://www.meti.go.jp/english/policy/energy_environment/global_warming/gifund/index.html
Transition Finance (2021-2023), https://www.meti.go.jp/english/policy/energy_environment/transition_finance/index.html
Green Transformation Basic Policy (2023), https://www.meti.go.jp/english/press/2023/0210_003.html
CCS Business Act (2024), https://www.meti.go.jp/press/2023/02/20240213002/20240213002-6.pdf
Hydrogen Society Promotion Act (2024), https://www.meti.go.jp/press/2023/02/20240213002/20240213002-1.pdf

8 Glasgow Financial Alliance for Net Zero (GFANZ), https://www.gfanzero.com

9 Partnership for Carbon Transparency (PACT), Emissions transparency: Pathfinder Framework provides updated guidance for the accounting and exchange of product life cycle emissions (2023), https://www.wbcsd.org/news/pathfinder-framework-version-2-0/

10 International Sustainability Standards Board (ISSB), https://www.ifrs.org/groups/international-sustainability-standards-board

11 Science Based Targets initiative, Science-based targets for chemicals companies, https://sciencebasedtargets.org/sectors/chemicals

Progress in GHG reduction by the global chemical industry has been limited despite the global pressure, and the Japanese chemical industry is no exception. Although pivotal in the global economy, the chemical industry is recognised as a "hard-to-abate" industry, along with other industries, such as steel, cement, and aviation. The challenges faced by the chemical industry include the following:

1. Most chemical products contain carbon, thus emission abatement is required when they are disposed of, such as upon incineration, for scope 3 net zero.
2. A wide variety of chemical products are used today that require a combination of multiple technologies for net zero with no decisive "silver bullet" technologies.

In addition to net zero, the industry must address plastic pollution and other environmental issues identified in the Planetary Boundaries, ensuring that solutions do not shift the burden from one category to another. These challenges and the resulting uncertainties about the future demand for net zero chemicals, which are likely to be more expensive and about suitable technologies to produce them are major impediments to the industry's transition (see Section 1 for details).

Japanese chemical industry's starting point is shaped by its historical and geographical characteristics. Regarding non-fossil energy sources, despite Japan's rapid growth in solar power in the last ten years, challenges abound in further expanding them (e.g., nuclear power amid uncertain public support after the Fukushima accident, and floating offshore wind power with limited a track record). Domestic opportunities for CCS also appear limited. Although Japan's waste collection system can be considered efficient, it largely depends on incineration today. Furthermore, as the population is expected to decline by 20% by 2050, the chemical industry must identify opportunities for growth. Japanese chemical complexes, which are scattered across Japan, generally have smaller and more aged steam crackers, and thus the industry is more fragmented than its overseas competitors (see Section 1 for details).

2. Aim and Methodology of this Study

In this report, based on the scientific findings from our recent peer-reviewed academic paper[12], we aim to (1) present quantitative pathways for the chemical industry operating in Japan to reach scope 1, 2 and 3 net zero using our established model[13,14], (2) show a way forward, so that the industry can make progress amid uncertainties, and (3) provide insights into competitive strategies and corresponding actions, by combining information derived from the quantitative pathways and existing knowledge of the Japanese chemical industry. Through these analyses, this report aims to serve as a bridge between the industry today and its desired future.

Our quantitative model combines a demand model and a supply model to calculate net zero pathways. The demand model generated two demand scenarios and the supply model generated three supply scenarios. When these demand and supply scenarios are combined, they provide six net zero pathways, of which the four pathways highlighted in green in **Figure 1** which are deemed the most insightful were studied in depth (see Section 1 for details).

12 Kanazawa D. et al., Scope 1, 2, and 3 Net Zero Pathways for the Chemical Industry in Japan, *Journal of Chemical Engineering of Japan*, **57**, 2360900 (2024), https://doi.org/10.1080/00219592.2024.2360900
13 University of Tokyo and Systemiq, Planet positive chemicals (2022), https://cgc.ifi.u-tokyo.ac.jp/en/research-en/chemistry-industry-en/, https://www.systemiq.earth/systems/circular-materials/planet-positive-chemicals/
14 Meng F. et al., Planet-compatible pathways for transitioning the chemical industry. *Proceedings of the National Academy of Sciences*, **120**, e2218294120 (2023), https://doi.org/10.1073/pnas.2218294120

			Supply scenarios		
			Lowest cost	Fastest emission reduction	Fastest emission reduction without CCS
			ME	NFAX	NFAX2
Demand scenarios	Population decline only	BAU	BAU-ME	(BAU-NFAX)	(BAU-NFAX2)
	Population decline and downstream circularity	CE	CE-ME	CE-NFAX	CE-NFAX2

Figure 1: Two demand scenarios, three supply scenarios, and six combined net zero pathways.

Scope of this study. This study considers seven basic chemicals (ethylene, propylene, butadiene, benzene, toluene, xylenes, and methanol) at the beginning of the chemical supply chain. The types of emission considered in the model are as follows: GHG Protocol's scope 1 (direct GHG emission), scope 2 (indirect GHG emission from purchased energy, such as electricity and steam), and scope 3 (other indirect GHG emission) category 1 (purchased goods and services) and category 12 (end-of-life treatment of sold products). Categories 1 and 12 were considered because they represent the largest scope 3 emission from major chemical manufacturers[15]. The GHGs considered in the model are carbon dioxide (CO_2) and methane (CH_4) (see Section 1 for details).

Key advantages of our approach include (1) it combines the strength of the forecasting approach (i.e., continuity from the current state) and that of the backcasting approach (i.e., reaching the target state); and (2) it can highlight and compare (between pathways) the impact of major actions that the chemical industry needs to take (such as securing bio-based feedstock and carbon capture and storage (CCS)). Although our approach does not guarantee that emission would reach precisely net zero in 2050, we consider it sufficient and appropriate for the aim of this study. Note that the results presented in the demand and supply scenarios and the pathways are not forecasts or projections but rather simulations to identify the key elements necessary to implement a transition to net zero. (See Section 1 for detail.)

3. Demand - Supply Scenarios and Net Zero Pathways

Two demand scenarios for olefins and aromatics by 2050. Downstream industries (e.g., brand owners) are under pressure from consumers, NGOs, and financial institutions to reduce emission, for whom scope 3 emission from upstream industries is often the largest[16]. As they pursue circular economy activities to reduce GHG emission, plastic pollution, and costs, the demand for olefins and aromatics to produce chemical products,

15 BASF SE, Scope 3 GHG Inventory Report (2021), https://www.basf.com/dam/jcr:d562fa5f-c658-3bb8-849a-737f2254cd67/BASF_Scope_3_Report_2021.pdf

16 Partnership for Carbon Transparency (PACT), Pathfinder Framework Version 2.0 (2023), Page 7, https://www.wbcsd.org/resources/pathfinder-framework-version-2-0/

such as plastics could decrease more significantly than expected from Japan's future population decline alone. In the BAU (business as usual) demand scenario, we assume a 20% population decline by 2050, flat net exports (i.e., export less import), and no downstream circular economy activities beyond the current level. In the BAU demand scenario, the annual demand for olefins and aromatics will decrease from 25.1 Mt (million ton) in 2020 to 22.7 Mt in 2050. In the CE (circular economy) demand scenario, in addition to the population decline, circular economy activities in the downstream will lead to an annual demand for olefins and aromatics of 14.4 Mt in 2050 (**Figure 2**). Although these scenarios are not forecast, this general trend of demand reduction from downstream industries is not something that the Japanese chemical industry will be able to fight against. Therefore, the sooner it starts seeking different business approaches, including exports, overseas business, and different business models, the better off it will be (see Section 2 for detail).

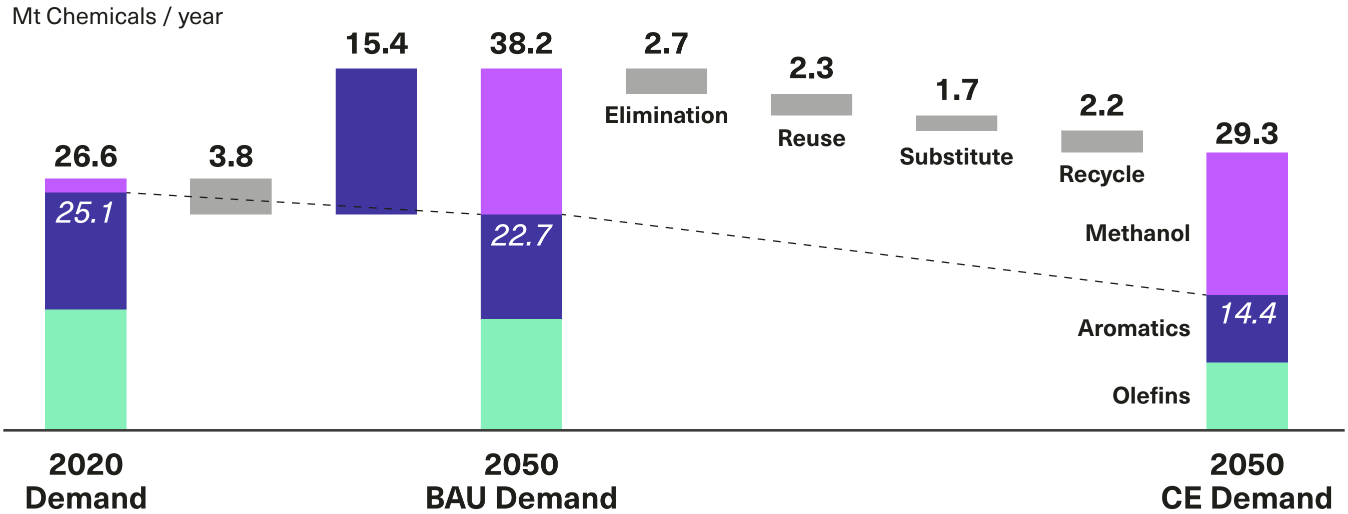
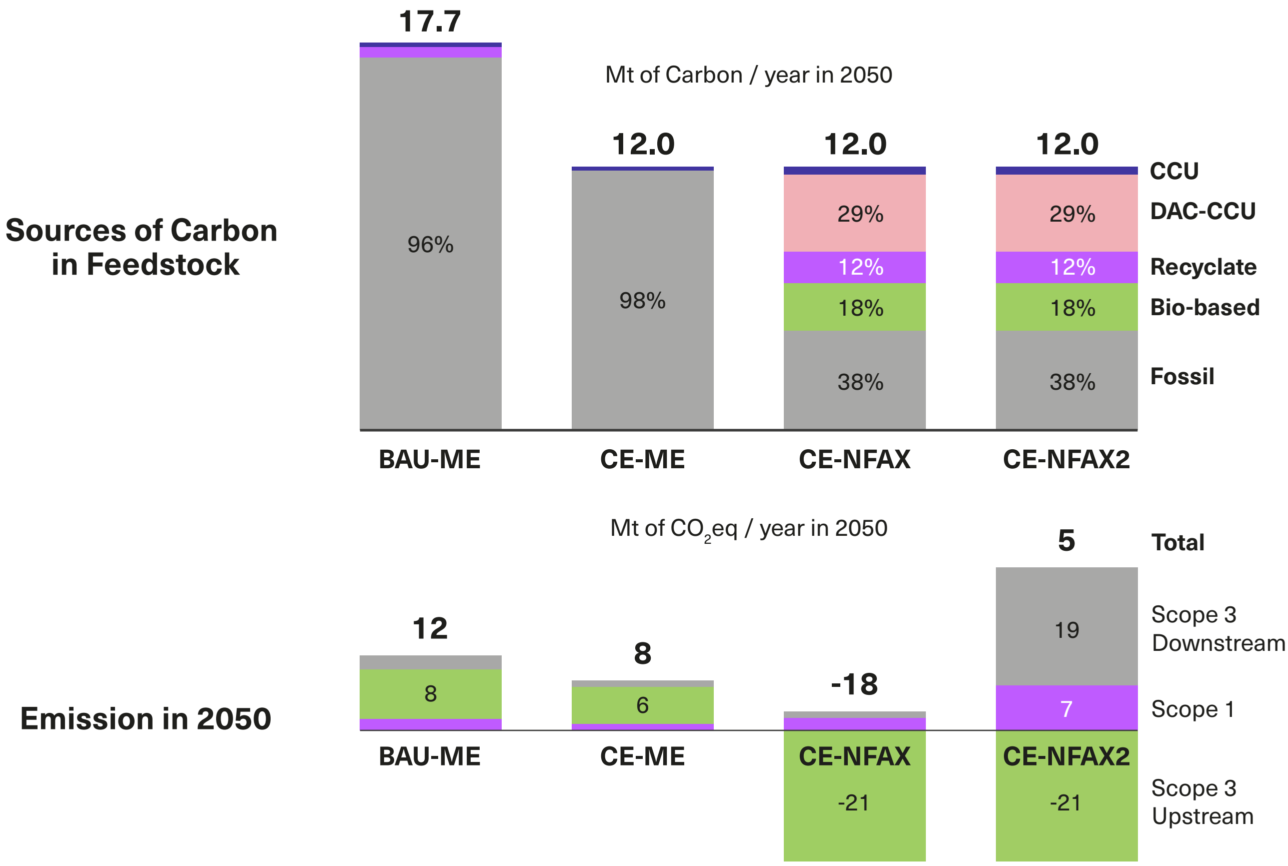


Figure 2: Changes in the demand for olefins, aromatics, and methanol between 2020 and 2050 in Japan. The white type indicates the total demand for olefins and aromatics only.

The Japanese chemical industry can achieve scope 1, 2, and 3 net zero through the combination of three basic strategies: (1) switching from fossil feedstock to alternative feedstocks, (2) switching energy sources, and (3) applying carbon capture, utilisation, and storage (CCUS). In fact, of the four pathways highlighted in **Figure 1**, the BAU-ME and CE-ME pathways mainly use CCS to achieve net zero, in addition to switching to net zero energy sources, while accommodating the respective demand in the two demand scenarios (BAU and CE). The CE-NFAX2 pathway mainly uses alternative feedstocks (e.g., bio-based feedstock, direct air capture with carbon capture and utilisation (DAC-CCU), and recyclates), whereas the CE-NFAX pathway uses both alternative feedstocks and CCS, in addition to switching to net zero energy sources (**Figure 3**) . With Regard to switching energy sources, many zero emission energy options are available for electricity and heat. However, the exact energy sources required for each plant to switch from current fossil fuel are beyond the scope of this study, because of its limited granularity, except for steam crackers (see Section 3 for details).



Amount of CCS in 2050

Mt of CO_2 stored / year in 2050

	BAU-ME	CE-ME	CE-NFAX	CE-NFAX2
CCS from Production	13	8	5	0
CCS from Incinerator	34	18	18	0
Total CCS	**47**	**26**	**23**	**0**

Figure 3: Sources of carbon in feedstocks, emission, and amount of CCS in 2050 for different pathways.

To achieve net zero, olefins, aromatics, and methanol will all undergo significant changes in production processes and feedstock by 2050, resulting in a cost increase that will be uneven across the supply chain. By 2050, olefins will be produced with crackers retrofitted for net zero (e.g., CCS to capture combusted flue gas, or fuelled by H_2/NH_3) using fossil or recycled pyrolysis oil as feedstock, or with the methanol-to-olefins (MTO) process using green or blue methanol depending on the pathway, while some crackers will have to be decommissioned because of the reduced demand. Aromatics production will shift to the methanol-to-aromatics (MTA) process based on our assumption that catalytic reformers that produce gasoline additives and most aromatics today will be decommissioned because of decline in vehicles with internal combustion engines. However, if MTA takes time to reach the commercial scale, catalytic reformers could remain. These infrastructure shifts will require $61–95 billion in cumulative capital expenditures till 2050, depending on pathways. These capital expenditures, together with the increased cost for feedstock, lead to higher unit production cost ($/kg) of net zero olefins and aromatics, which could be twice or more (depending on the chemicals and their transition pathways) in 2050 than today's fossil counterparts. However, the impact on the production costs of consumer products will be limited to an increase of approximately 1% over the next 30 years (i.e., equivalent to 0.03% annually). This uneven impact across the supply chain will be an important clue to breaking out of the "chicken and egg" loop of high cost and low demand of net zero chemical products. Although the cost of olefins and aromatics in 2050 could double, this cost gap would be even greater today than in 2050 because renewable sources will be more expensive today. Thus, the real challenge is to overcome the current cost gap (rather than waiting for 2050), the steps of which are discussed next (see Section 3 for details).

4. Recommendation

Secure access to key resources, as scope 3 net zero imposes a theoretical upper limit to the supply volume of chemical products for a company and a country. Specifically, under scope 3 net zero, access to bio-based/DAC-CCU feedstocks, recyclates, and CCS will determine the maximum possible supply of chemical products, as well as the downstream products that use them. This situation resembles that of the supply chain of electric vehicles, in which the supply of raw materials (e.g., lithium and cobalt) far up in the supply chain could determine the supply limit of finished goods (electric vehicles) all the way down in the supply chain and, as a result, exerts strategic influence across the entire supply chain. Musical chair games have quietly begun, targeting key resources for the chemical industry. Many approaches can expand access to these key resources. For example, the chemical industry in Japan needs to maximise recycling regardless of the pathway and expand the scale of chemical recycling technologies by leveraging Japan's strengths. They include a strong waste collection system backed by the extended producer responsibility (EPR) and generally supportive policies for the industry in a relatively stable political environment, with legislative power centralised at the national level. This will reduce the need for bio-based feedstock and CCS, as well as help reduce plastic pollution. Biomass plays a significant role as a non-fossil feedstock; thus, developing domestic sources is needed to balance imported biomass to ensure stable access. An example would be for the chemical industry to invest in sustainable management and harvesting of domestic woody biomass to unlock Japan's potential. Methanol can serve as a platform chemical (in addition to naphtha) for the production of other basic chemicals, and Japan should pursue both domestic and overseas sources. Domestic methanol can be produced from biomass and waste (recyclate), whereas overseas methanol can be produced from abated fossil sources, biomass, and atmospheric CO_2, for example. The use of methanol would provide flexibility in terms of sources and carbon footprint, as well as the targeted production of olefins and aromatics with less by-products to deal with. Ethanol (bioethanol) also has potential as a platform chemical, but its future availability may be limited due to possible competition for the limited biogenic carbon with transportation fuel (e.g., aviation) which had a head start in signalling future demand and establishing a supply chain, and due to the potential conflict with food production and environmental impact from agriculture. Finally, CCS and CCU must be scaled to mitigate emission from production and incinerators at the end of life in collaboration with the government (see Section 3 for details).

To reach scope 1–3 net zero for the chemical industry in Japan as a whole, alternative feedstocks (e.g., bio-based feedstock) and CCS must be pursued concurrently, while maximising recycling. In other words, Japan should not rely solely on CCS or alternative feedstocks, because relying on one solution would be too risky when Japan has not secured a sufficient amount of either (see Section 4 for details).

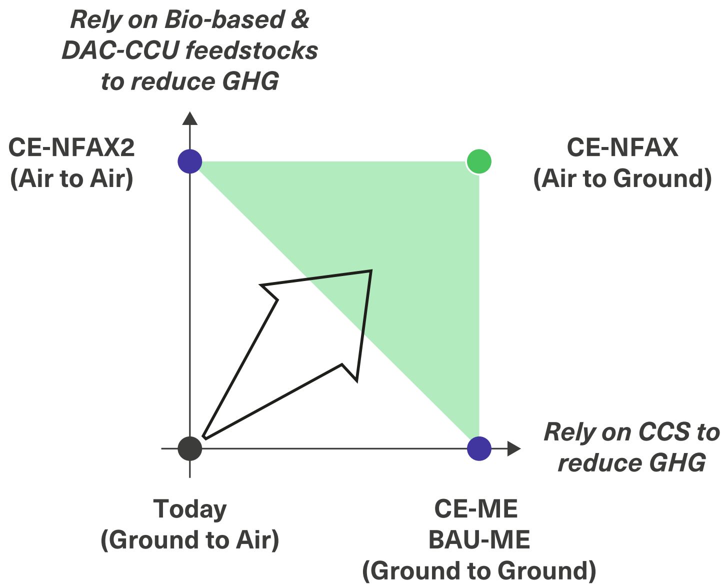


Figure 4: Conceptual map of the direction of GHG reduction. The chemical industry in Japan as a whole should concurrently pursue both alternative feedstocks in the Y-axis (such as bio-based feedstock) and CCS in the X-axis, so that it lands in the green triangle, which indicates net zero or beyond net zero.

To break out of the infinite "chicken and egg" loop of "high cost" and "low demand". A chemical company must first establish new production process technology that uses a new feedstock at a smaller pilot scale. As it advances to invest in a full-scale commercial plant, leadership needs to be demonstrated from a long-term perspective because of the huge investment risk. Leading companies will likely enjoy opportunities ahead of the competition to establish scale (i.e., low cost) and pre-empt prime customers and markets that are more forgiving of the higher costs of net zero chemicals, as well as pre-empt the limited key feedstocks such as recyclates and bio-based feedstock. While such leadership is needed to seize the golden opportunity to turn the commoditised upstream basic chemical business into differentiated products, it must be founded on the prospect of long-term profitability from the current business to enable continued long-term investments. Currently, most major Japanese chemical companies have adopted the corporate structure of a vertically integrated conglomerate, with their corporate strategies focusing on downstream functional chemicals divisions. Given this, an industry reorganisation that integrates upstream (basic chemicals) divisions from conglomerate chemical companies, would streamline the corporate decision-making process and could accelerate the pursuit of a net zero transition. For example, in the semiconductor memory chip industry in the 1990s and the liquid crystal display (LCD) panel industry in the 2000s, large-scale investments were called for to deal with production expansion (i.e., cost reduction) and technology generation changes. Many Japanese electronics manufacturers with a conglomerate-style were slower to make large-scale investment decisions because they were faced with corporate decisions over priorities to justify an immense investment in just one of the many divisions, among other reasons, and ultimately lost business to overseas competitors despite earlier technological and market advantages[17]. Such a reorganisation would also provide economies of scope in a broad sense (in addition to economies of scale) and diversify risks to prepare for an uncertain future. Outside the chemical industry, as a chemical company prepares for a commercial-scale plant, it also needs to secure (1) key resources (e.g., bio-based feedstock and recyclates) by reaching out to non-traditional partners, (2) future demand by participating in the global First Movers Coalition and additionally establishing similar

17 K. Toyama, After all, what did management get wrong? *Toyo Keizai*, May 27, 2017.
M. Taguchi, Learning from past failures, earlier spin-off and consolidation of power semiconductors are needed, *Nikkei XTech*, Nov 29, 2021.
Y. Nakata, Japanese Competitiveness in Liquid Crystal Display Industry, Research Institute of Economy, Trade and Industry, Discussion paper (Apr 2007)

coalitions in Japan, and (3) supportive regulations. Domestic demand-supply coalitions are needed because not all companies are international players, and because of the need to deal with local supply chain specifics. Local coalitions will also be more effective in accelerating initial market growth. In the past in the solar panel, light-emitting diode (LED) lighting, and lithium-ion battery markets, for example, Japanese companies lost market share despite the initial lead in technology and commercialisation. Among other reasons, this was because of insufficient demand-supply coordination and policy support to jump-start the demand and drive market growth for fledgling "green" products which tend to be more expensive than conventional products in the initial stage. For example, Japan's global solar panel market share was 55% in 2002[18], but China surpassed it later. By the time the installation of solar panels skyrocketed in Japan after the introduction of feed-in tariff (FIT) in 2012, Japanese solar panel manufacturers had already lost their competitiveness and subsequently withdrew from the market. Such a demand-supply interaction will be slower and more difficult on a global scale. Thus, the chemical industry in Japan should utilise local coalitions under Japan's large country economy, in addition to the global version (see Section 4 for details).

The future role of the chemical industry could be reshaped by three major trends in sustainability, in which the chemical industry will have a greater role to play: (1) mitigation of climate change, in which the chemical industry has two roles, one to reduce its own and supply chain emission, and the other to support the emission reduction of other industries; (2) adaptation to climate change, in which chemical products support agriculture, access to water, and disaster control, among others, to deal with the changing climate; and (3) prevention of plastic pollution, which could call for simpler formulations and more transparency in ingredients to enhance recycling. Furthermore, the traditional customer base of the chemical industry (e.g., the automotive and electronics industries) now seeks to add more value through software than through hardware, in which chemical products are often used. Given this transition, the chemical industry will likely need to shift its focus to a lower carbon footprint and better recyclability in most hardware products, and away from pursuing higher chemical performance as hardware at the expense of sustainability. As a result, a major shift in the value proposition for both the upstream (basic chemicals) and downstream (functional chemicals) chemical industry towards sustainability is expected (see Section 4 for details).

18 Nemet G. F., How solar Energy Became Cheap, Routledge (2019)

Section 1: Introduction

Challenges for the Japanese chemical industry in achieving net zero emission and safeguarding the Global Commons

Section Summary

Achieving scope 1, 2, and 3 net zero greenhouse gas (GHG) emission has become a global mandate for businesses. Amid the intensifying global pressure to mitigate GHG emission, the Japanese government has laid out initial policy frameworks to drive the transition. Despite these efforts, Japan's actions have so far remained fragmented.

The chemical industry, although pivotal in the global economy, is recognised as a "hard-to-abate" industry, facing significant challenges in achieving net zero. The Japanese chemical industry, shaped by unique historical and geographical characteristics, is no exception. In addition to net zero, the industry must address plastic pollution and other environmental issues identified in the Planetary Boundaries, ensuring that solutions do not shift the burden from one category to another. These challenges and the resulting uncertainties are major impediments to the industry's transition.

This report will present quantitative net zero pathways for the Japanese chemical industry and provide strategic business insights aimed at helping business leaders move toward net zero, amid the uncertainties about future demand, technology, and pathways.

1.1 Political and business context of climate change globally and in Japan

Net zero GHG, including scope 3, has become a global business requirement. To achieve the goals of the Paris Agreement, COP26 in Glasgow in 2021 prompted a number of countries and businesses to make net zero pledges, while key business alliances and frameworks were launched. They include GFANZ[19], a huge alliance of financial institutions that require scope 1, 2, and 3 net zero for investees; the Pathfinder Framework (now PACT) under WBCSD[20] to exchange product-level emission data, including scope 3, across supply chains; and the International Sustainability Standards Board[21] (ISSB) to develop a global baseline of sustainability disclosure standards for investors. Thus, GHG reduction towards net zero, including scope 3, is rapidly becoming a global business requirement after COP26. As such, failure or delay in reaching this goal could mean exclusion from global financing and supply chains. In addition, the Science Based Targets initiative (SBTi) recently developed draft sector guidance for the chemical industry for consultation[22]. Once finalised, it could "colour-code" chemical companies (between those with credible SBTi-validated GHG reduction targets and not) for downstream customers and financial institutions, not familiar with the detail of the chemical industry.

Global pressure to reduce GHG is mounting. Parties to the Paris Agreement are required to submit their Nationally Determined Contribution (NDC) in 2025, which includes the GHG target for 2035. This updated target is expected to take into account the findings in the AR6 Synthesis Report[23] in 2023 by the Intergovernmental Panel on Climate Change (IPCC), in which it stated that a 65% reduction in CO_2 emission (compared to 2019) is needed by 2035 to keep the global warming within 1.5°C from the pre-industrial level. The pressure will increase with more specific and aggressive plans to reach this target and will intensify soon in Japan and elsewhere.

Japanese government has laid out initial policy frameworks for the transition to net zero. Since Prime Minister Suga announced Japan's target to achieve net zero by 2050 in 2020, the Japanese government has formulated initial policy frameworks to drive the transition. It began with the Green Growth Strategy[24] in June 2021, which included two trillion-yen subsidies for innovation under the Green Innovation Fund[25]. Starting in 2021, it has developed technology roadmaps[26] for key industries to promote transition finance, including a roadmap for the chemical industry. More recently, it established the Green Transformation Basic Policy[27] in February 2023, and the Green Transformation Promotion Act was enacted in May 2023. This Act will enable measures such as carbon pricing coupled with transition government bonds to be used to drive private-sector investments in GHG reduction. More recently, the Hydrogen Society Promotion Act[28] and the CCS Business Act[29] were passed in May 2024 to accelerate business and infrastructure development.

However, actions in Japan have so far been uncoordinated, and the outlook is uncertain. For example, the introduction of a compulsory carbon tax (levy) and auctioned allowances will not start until 2028 and 2033, respectively, and it remains uncertain whether

19 Glasgow Financial Alliance for Net Zero (GFANZ), https://www.gfanzero.com
20 Partnership for Carbon Transparency (PACT), Emissions transparency: Pathfinder Framework provides updated guidance for the accounting and exchange of product life cycle emissions (2023), https://www.wbcsd.org/news/pathfinder-framework-version-2-0/
21 International Sustainability Standards Board (ISSB), https://www.ifrs.org/groups/international-sustainability-standards-board
22 Science Based Targets initiative, Science-based targets for chemicals companies ,https://sciencebasedtargets.org/sectors/chemicals
23 IPCC AR6 Synthesis Report: Climate Change 2023, Summary for policy makers, page 21, https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf
24 Ministry of Economy, Trade and Industry (METI), Green Growth Strategy (2021), https://www.meti.go.jp/english/policy/energy_environment/global_warming/ggs2050/index.html
25 Ministry of Economy, Trade and Industry (METI), Green Innovation Fund (2021), https://www.meti.go.jp/english/policy/energy_environment/global_warming/gifund/index.html
26 Ministry of Economy, Trade and Industry (METI), Transition Finance (2021-2023), https://www.meti.go.jp/english/policy/energy_environment/transition_finance/index.html
27 Ministry of Economy, Trade and Industry (METI), Green Transformation Basic Policy (2023), https://www.meti.go.jp/english/press/2023/0210_003.html
28 Ministry of Economy, Trade and Industry (METI), Hydrogen Society Promotion Act (2024), https://www.meti.go.jp/press/2023/02/20240213002/20240213002-1.pdf
29 Ministry of Economy, Trade and Industry (METI), CCS Business Act (2024), https://www.meti.go.jp/press/2023/02/20240213002/20240213002-6.pdf

they are sufficient to trigger behavioural change in consumers. Meanwhile, reverse carbon pricing (e.g., subsidies for gasoline) is currently ongoing. The Sixth Strategic Energy Plan[30], approved in 2021, relies heavily on solar and nuclear power as zero emission energies by 2030. However, solar power has begun to face criticism for its overdevelopment, and the public acceptance of nuclear power has been questionable, particularly after the Fukushima accident. Although subsidies are being granted to drive private investments in GHG reduction, there has been little quantitative assurance that these government and industry measures will be sufficient to reach net zero; this situation also applies to the Japanese chemical industry.

1.2 Current state of the chemical industry regarding GHG reduction and other environmental issues

Chemical industry is a hard-to-abate industry.
GHG reduction in hard-to-abate industries, including chemical, steel, cement, aviation, marine shipping and heavy-duty road transportation industries, is known to be challenging, because their GHG reduction involves more than switching to renewable electricity. While each industry has its own difficulties, the chemical industry's challenges include the following:

1. Most chemical products contain carbon; thus, emission abatement is required when they are disposed of, such as upon incineration, for scope 3 net zero.
2. A wide variety of chemical products are used today in a wide range of applications, and they require a combination of multiple technologies (such as bio-based feedstock, mechanical and chemical recycling, CCU and CCS, electrification, etc.), with no decisive "silver bullet" technologies that could take care of most, if not all, of the products and applications.
3. High temperature chemical reactions that are difficult and/or costly to electrify.
4. Manufacturing processes that emit CO_2 as a by-product.
5. Long-life heavy asset industry.

As **Figure 5** shows, different industries are expected to require different lead times before reaching a tipping point at which low-emission technologies are adopted in the mass market to replace conventional technologies. The chemical industry is ranked at the bottom of all hard-to-abate industries. This exemplifies the challenges faced by chemical companies, both globally and in Japan.

30 Ministry of Economy, Trade and Industry (METI), Sixth Strategic Energy Plan (2021), https://www.meti.go.jp/english/press/2021/1022_002.html

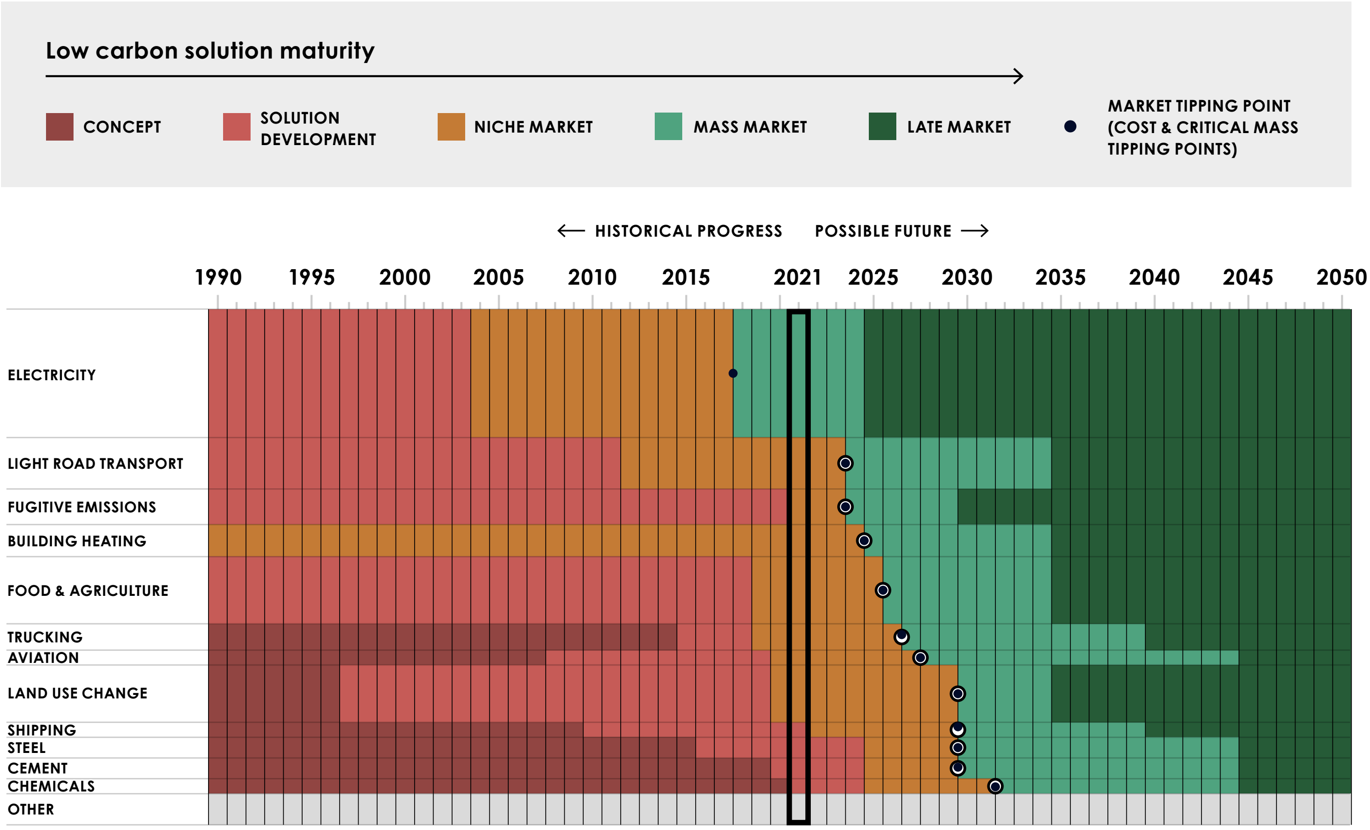


Figure 5: Market tipping point by industry[31]**.** When low emission solutions are expected to out-compete conventional solutions.

Dealing with uncertainties. Specifically, the five challenges mentioned above introduce the following three uncertainties that have slowed down the chemical industry's transition to net zero globally and in Japan:

- Uncertainty in future demand: How to secure future demand for net zero chemicals when cost increase is likely.
- Uncertainty in technologies to produce net zero chemicals: Which technologies to choose from, such as bio-based feedstock, recycling and CCS.
- Uncertainty in possible pathways to achieve scope 1–3 net zero: Which pathway to follow and what measures will be quantitatively sufficient for net zero.

Although these uncertainties cannot be eliminated, this report aims to show a way forward for the Japanese chemical industry even in the face of these uncertainties.

Planetary Boundaries provide a comprehensive environmental perspective. In addition to climate change, the chemical industry is also relevant to other issues in the Planetary Boundaries. Planetary Boundaries[32] describe certain limits, or guardrails (represented by dotted lines in **Figure 6**), for the nine interconnected processes that maintain Earth's stability. If we go over these guardrails, we risk triggering severe and irreversible environmental changes. Therefore, it is recommended that all economic activities be conducted within these limits. Examples of processes that have already exceeded these limits include climate change, biogeochemical flows (e.g., nitrogen and phosphorus runoff from fertilisers), novel entities (e.g., pollution from plastics), and loss of biodiversity. These issues are broadly related to the chemical industry and release of chemicals (such as CO_2) into the environment. As such, the chemical industry has a duty to address these issues, while solving them can also be viewed as business opportunities.

31 Systemiq, The Paris Effect: COP26 edition (2021), https://www.systemiq.earth/the-paris-effect-cop26-edition

32 Rockström J. et al., Planetary Boundaries: Exploring the Safe Operating Space for Humanity. *Ecology and Society* **14**(2): 32 (2009), https://www.ecologyandsociety.org/vol14/iss2/art32
Rockström, J. et al. A safe operating space for humanity. *Nature* **461**, 472–475 (2009), https://doi.org/10.1038/461472a
W. Steffen, et al., Planetary boundaries: Guiding human development on a changing planet, *Science* **347**, 1259855 (2015), https://www.science.org/doi/10.1126/science.1259855

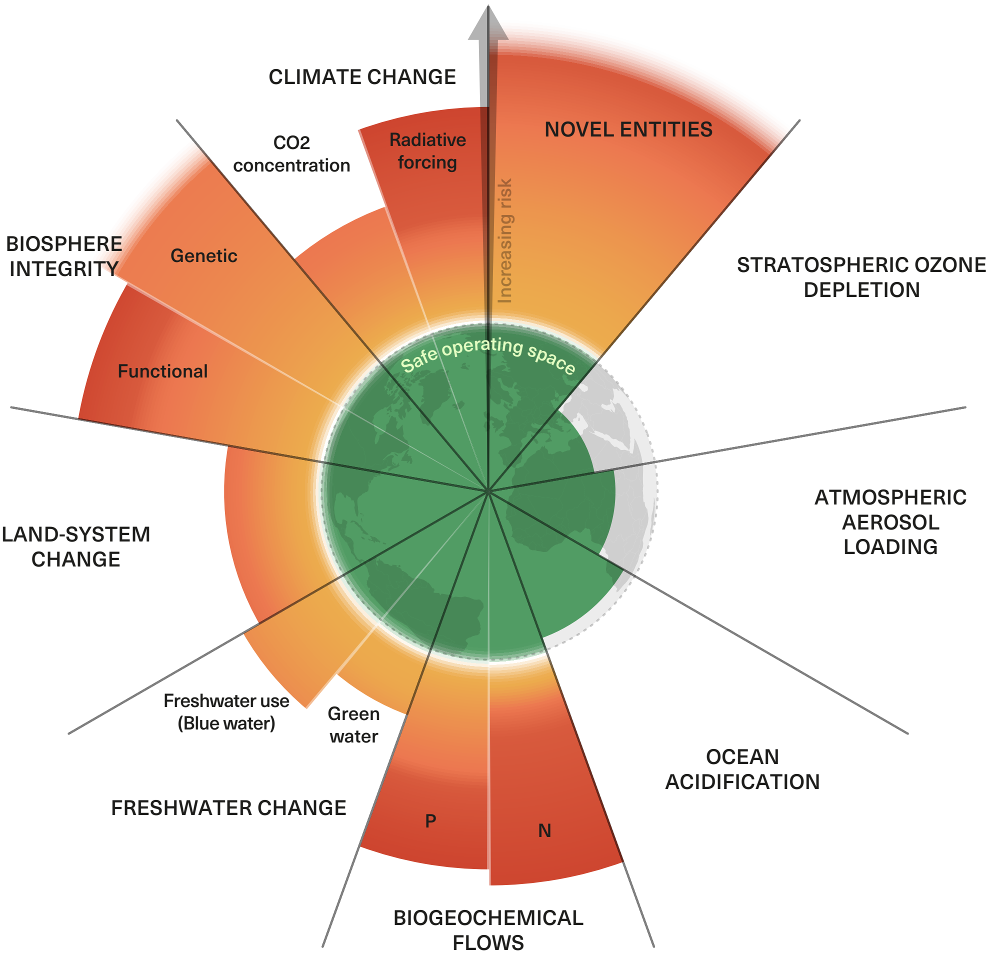


Figure 6: Planetary Boundaries[33]**.** Dotted line around the green circle in the centre indicates safe operating space for humanity.

33 Azote for Stockholm Resilience Centre, based on analysis in Richardson et al. (2023), https://www.stockholmresilience.org/research/planetary-boundaries.html

Plastic pollution prevention and GHG reduction together could reshape the future chemical industry. Prevention of plastic pollution is being actively negotiated towards an internationally legally binding instrument, following the resolution of the UN Environment Assembly (UNEA-5.2) in March 2022[34]. Countermeasures negotiated in the 4th session of the Intergovernmental Negotiating Committee (INC) in April 2024 included a cap on the global production of primary plastics, enhanced regulation and transparency of chemicals (e.g., additives) and polymers of concern, and enhanced collection and recycling of plastic waste. These actions, together with those for GHG reduction towards net zero, will strongly affect the business strategy of the future chemical industry. Conversely, the chemical industry's licence to operate could be at risk if it continues to pursue its current business model of producing and disposing of a greater volume and variety of chemicals and their mixtures.

Prevent burden-shifting. Due to the interlinkages between planetary boundary processes, solutions to climate change must not be isolated. In other words, identifying planetary boundary trade-offs is essential for preventing the burden from shifting from climate change to other issues. For example, the expansion of bio-based feedstock usage and renewable energy capacity must be planned by considering the biosphere integrity and land system changes. Fertiliser usage must be mindful of biogeochemical flows and freshwater use.

1.3 Japan has its own starting point in its journey to net zero because of its unique historical and geographical characteristics

Despite rapid growth in solar power, challenges abound in further expanding non-fossil power sources. In 2021, Japan formulated the Sixth Strategic Energy Plan[35], in which it set forth a policy plan towards 2030 with a view to net zero in 2050. The plan includes the 2030 electricity mix, which consists of renewable energy 36–38% (solar 14–16%, hydro 11%, wind 5%, biomass 5%, and geothermal 1%), hydrogen and ammonia 1%, nuclear 20–22%, LNG 20%, coal 19%, and oil etc. 2%. In line with this plan, Japan accelerated the introduction of renewable energy. The renewable energy supply has grown from 107 TWh (10% of the total electricity) in 2012 to 219 TWh (22%) in 2022[36], supported in part by a feed-in-tariff. Specifically, the recent growth in renewable energy supply has disproportionately depended on solar power, whose supply has increased from 7 TWh in 2012 to 93 TWh in 2022, to the extent that Japan's installed capacity for solar power ranked third in the world after China and the USA in 2021 despite Japan's small land area[37]. However, its rapid introduction has resulted in environmental, landscape, and safety issues. As such, the future introduction of solar power will likely leverage underexplored opportunities, such as rooftops, accelerated by new technologies such as perovskite solar cells. Meanwhile, the mass introduction of wind power has just begun with a focus on onshore and fixed-bottom offshore opportunities. However, because of Japan's mountainous terrain and deep coastal waters, after the low-hanging fruits are exhausted, Japan will have to venture into more technologically and economically challenging floating offshore wind power. Public support for nuclear power has remained uncertain since the Fukushima accident. As a result, it represented only 6% of electricity in 2022, whereas the 2030 target is 20–22%. As a volcanic country, the potential for geothermal power in Japan ranks third in

34 United Nations Environment Programme (UNEP), Intergovernmental Negotiating Committee on Plastic Pollution, https://www.unep.org/inc-plastic-pollution
35 Ministry of Economy, Trade and Industry (METI), Sixth Strategic Energy Plan (2021), https://www.meti.go.jp/english/press/2021/1022_002.html
36 Agency for Natural Resources and Energy, Comprehensive Energy Statistics (2024), https://www.enecho.meti.go.jp/statistics/total_energy/results.html#headline7
https://www.enecho.meti.go.jp/statistics/total_energy/xls/stte/stte_jikeiretu2022fykaku.xlsx
37 Agency for Natural Resources and Energy, Renewable Energy (2024), https://www.enecho.meti.go.jp/about/pamphlet/energy2023/07.html

the world[38], but its development has not been pursued as aggressively as other energy sources.

Focusing on importing hydrogen and its derivatives. Because of the challenges of expanding opportunities for low-cost renewable energy sources, Japan has been developing technologies for importing green and blue hydrogen (and their derivatives) from countries where hydrogen production is less expensive. For example, Japan is developing different forms of ocean transportation, such as liquefied hydrogen, methyl cyclohexane (MCH), and ammonia, with the goal of repeating the history of successfully starting to import liquefied natural gas approximately 50 years ago. One of the main uses is in ammonia-fuelled power plants, which can maintain inertia in AC power generation while being capable of storing ammonia as fuel. Although hydrogen is a versatile form of low-emission energy, it is known to be less energy-efficient; thus, it could be more costly than directly using energy in the original format because of losses through energy conversion. This situation resembles that of a Swiss army knife, which is versatile, but not as useful as a specialised tool[39].

Seeking overseas CCS under limited domestic opportunities. Geological storage sites for CO_2 in Japan are considered limited due to the lack of depleted oil/gas fields and the higher risk of leakage upon earthquakes and natural disasters (e.g., volcanic activities). As a result, opportunities for overseas transportation and sequestration are being pursued, in addition to domestic offshore options. The Japanese government developed a long-term roadmap for CCS in 2023[40], and the CCS Business Act[41], which established the basic business framework necessary for initiating CCS projects, was enacted in May 2024.

Efficient, but incineration-based waste management system. Japan's waste management system can be considered efficient. For example, the recycling rate of PET bottles (i.e., recycled amount / amount sold) was 86% in 2021, as opposed to 43% in Europe for the same statistics[42]. In general, the utilisation rate of plastic waste (for recycling or energy recovery) with respect to discharged plastic waste was 87% in 2021[43]. Plastic recycling has been supported by the Containers and Packaging Recycling Law (a form of extend producer responsibility) since 2000 and by the general environmental policy to avoid landfill due to a lack of available land. However, 71% of the plastic waste utilisation above was in general in the form of incineration with energy recovery in 2021. Today's use of plastic waste for energy recovery (e.g., for power generation and cement production) is likely to be replaced by less emissive sources of energy, as power generation and cement production pursue net zero. This implies that the existing collection system will be a powerful infrastructure for recycling plastic waste, if accompanied by a capable sorting system and chemical recycling technologies.

Declining population. Japan is facing a population decline of approximately 20% by 2050[44], leading to a decrease in domestic demand, assuming flat per-capita consumption. The chemical industry will face contraction unless it seeks overseas opportunities or new business models that do not rely on sales volume.

38 Agency for Natural Resources and Energy (2022), https://www.enecho.meti.go.jp/about/special/johoteikyo/energykihonkeikaku2021_kaisetu04.html
39 Liebreich Associates, The Clean Hydrogen Ladder (2021), https://www.liebreich.com/the-clean-hydrogen-ladder-now-updated-to-v4-1
40 Ministry of Economy, Trade and Industry (2023), https://www.meti.go.jp/shingikai/energy_environment/ccs_choki_roadmap/index.html
41 Ministry of Economy, Trade and Industry (2024), https://www.meti.go.jp/press/2023/02/20240213002/20240213002-6.pdf
42 The Council for PET Bottle Recycling, https://www.petbottle-rec.gr.jp/data/comparison.html
43 Plastic Waste Management Institute, Material Flow of Plastics for 2021 (2022), https://www.pwmi.or.jp/flow_pdf/flow2021.pdf (Plastic waste discharged 8.24Mt, Recycled 2.06Mt, Incinerated with energy recovery 5.10Mt, Incinerated without energy recovery 0.63Mt, Landfill 0.45Mt for 2021) The derivation of 87% and 71% is as follows: 87% = (2.06 + 5.10) / 8.24, 71% = 5.10 / (2.06 + 5.10).
44 United Nations, Department of Economic and Social Affairs, Population Division. 2022. World Population Prospects: The 2022 Revision.

1.4 Japanese chemical industry also has its own starting point

Smaller and more aged chemical complexes distributed across Japan. Chemical complexes in Japan generally have smaller and more aged steam crackers in their centre than those in other Asian countries[45]. These smaller complexes are scattered across Japan, and their locations are optimised for imported crude oil and naphtha. Furthermore, each complex consists of production facilities belonging to multiple companies[46], leveraging the strengths of diverse chemical companies, while at the same time making concerted transitions more difficult. These chemical facilities are among the world's leaders in energy efficiency[47], largely to counter the higher costs of imported fossil fuels.

Competition and industry organisation. Japan's basic chemicals business is under cost competition mainly with mainland China, Taiwan, and South Korea's larger and newer plants running with naphtha as feedstock, as well as with Middle Eastern and US plants running with gas as feedstock. Although Japanese chemical companies have focused on functional chemicals (i.e., downstream chemical industry) rather than on basic chemicals (i.e., upstream chemical industry), the competitiveness of the latter has been a challenge. Moreover, Japan's basic chemicals businesses are fragmented compared to overseas competition, as mentioned above. This industrial organisation has been possible partly because chemical companies have remained profitable thus far by shrinking their production capacity and running at a higher operational rate, while avoiding major mergers and restructuring. This is in contrast to the Japanese refinery industry, which has undergone a number of mergers and has restructured into fewer and more competitive companies.

1.5 Aim of this study

In this report, we aim to

- Provide quantitative pathways for the chemical industry operating in Japan to reach scope 1, 2, and 3 net zero, using our established model (Sections 2 and 3).
- Show a way forward for the industry to make progress amid uncertainties (Sections 3 and 4).
- Provide insights into competitive strategies and their corresponding actions, by combining information derived from the quantitative pathways and the existing knowledge of the Japanese chemical industry (Section 4).

1.6 Approach of this study

Demand scenarios and supply scenarios. Our quantitative model combines a demand model and a supply model. The demand model generated two demand scenarios, and the supply model generated three supply scenarios. The two demand scenarios are called BAU and CE, in which the BAU (business as usual) scenario assumes Japan's population decline only, whereas the CE (circular economy) scenario

45 Key petrochemical plants in the world (2019), https://warp.da.ndl.go.jp/info:ndljp/pid/12546205/www.meti.go.jp/policy/mono_info_service/mono/chemistry/downloadfiles/03_2019plant.pdf
Japan Petrochemical Industry Association, Petrochemical complexes in Japan, https://www.jpca.or.jp/trends/plants.html
New Era of Petrochemical Complexes (2018), K. Inaba, et al.
46 Japan Petrochemical Industry Association, Diagram of complexes in Japan https://www.jpca.or.jp/files/trends/kakusha.pdf
47 Japan Chemical Industry Association, https://www.nikkakyo.org/sites/default/files/GlobalWarmingInitiatives/CN/CN_FollowupReport.pdf

additionally assumes a strong circular economy in the downstream of the supply chain that reduces chemical demands. Further details regarding the demand scenarios are discussed in Section 2. The three supply scenarios are called ME, NFAX and NFAX2, in which ME uses the lowest-cost production technologies (i.e., feedstocks and production processes) to achieve net zero, whereas NFAX uses the greatest abatement solutions, regardless of the cost. NFAX2 is the same as NFAX except that NFAX2 does not use any CCS, to simulate a situation in which Japan is unable to identify any CCS destinations. All three supply scenarios pursue net zero and incorporate a GHG reduction mechanism, in which a fixed portion of the capacity is forced to be replaced with less emissive production technologies every year to drive the industry's emission towards net zero. Further details regarding the supply scenarios are provided in Section 3.

Net zero pathways (i.e., combinations of demand and supply scenarios). By combining the two demand scenarios and the three supply scenarios, six net zero pathways were generated. Of the six pathways, four pathways (BAU-ME, CE-ME, CE-NFAX, and CE-NFAX2) were deemed the most insightful and will be discussed in detail in Section 3. A brief description of these four pathways is provided below.

- BAU-ME (Business-as-usual demand is fulfilled using the lowest-cost production technologies)
- CE-ME (Reduced demand due to circular economy is fulfilled using the lowest-cost production technologies)
- CE-NFAX (Reduced demand due to circular economy is fulfilled using the fastest emission reduction technologies regardless of the cost)
- CE-NFAX2 (Reduced demand due to circular economy is fulfilled using the fastest emission reduction technologies regardless of cost, but without using CCS).

			Supply scenarios		
			Lowest cost	Fastest emission reduction	Fastest emission reduction without CCS
			ME	NFAX	NFAX2
Demand scenarios	Population decline only	BAU	BAU-ME	(BAU-NFAX)	(BAU-NFAX2)
	Population decline and downstream circularity	CE	CE-ME	CE-NFAX	CE-NFAX2

Figure 7: Two demand scenarios, three supply scenarios, and six combined net zero pathways. Repeated from **Figure 1**.

Strengths of our approach. Our approach combines the demand model, which describes the yearly demand between 2020 and 2050, and the supply model, which describes the yearly mix of production technologies to meet the yearly demand for the same period. This combined approach provides continuous transition pathways from 2020 to 2050 in terms of total production capacity and the mix of production technologies. This approach has multiple advantages: (1) It combines the strength of the forecasting approach (continuity from the current state) and that of the backcasting approach (reaching the target state), and (2) It can highlight and compare (between pathways) the impacts of major actions that the chemical industry needs to take (such as securing bio-based feedstock and CCS). Thus, although using a fixed yearly rate in the forced replacement mechanism in the supply model does not guarantee that emission will reach precisely net zero in 2050, we consider this approach to be sufficient and appropriate for the aim of this study. Refer to the accompanying academic papers for detailed modelling methodology[48] as well as the Python program used in the modelling. Note that the results presented in the demand and supply scenarios and the pathways are not forecasts or projections but rather simulations to identify the key elements necessary to implement a transition to net zero.

Scope of this study. This study considers seven basic chemicals (ethylene, propylene, butadiene, benzene, toluene, xylenes, and methanol) at the beginning of the chemical supply chain. The types of emission considered in the model are as follows: GHG Protocol's scope 1 (direct GHG emission), scope 2 (indirect GHG emission from purchased energy, such as electricity and steam), and scope 3 (other indirect GHG emission) category 1 (purchased goods and services) and category 12 (end-of-life treatment of sold products). Categories 1 and 12 were considered because they represent the largest scope 3 emission from major chemical manufacturers[49]. The GHGs considered in the model are carbon dioxide (CO_2) and methane (CH_4). The Python program for the model can be found on our GitHub site[50].

48 Scope 1, 2, and 3 Net Zero Pathways for the Chemical Industry in Japan, https://doi.org/10.1080/00219592.2024.2360900
Planet-compatible pathways for transitioning the chemical industry, https://doi.org/10.1073/pnas.2218294120
49 BASF SE, Scope 3 GHG Inventory Report (2021), https://www.basf.com/dam/jcr:d562fa5f-c658-3bb8-849a-737f2254cd67/BASF_Scope_3_Report_2021.pdf
50 https://github.com/systemiqofficial/Pathways-Chemical-Industry-Japan

Section 2: Demand

The Japanese chemical industry must adapt to future demand reduction due to population decline and the circular economy in downstream industries

Section Summary

Today's Japanese chemical industry and its supply chain are predominantly linear and emission intensive. As a result, downstream customers of the chemical industry will likely enhance activities in circular economy in their pursuit of scope 1, 2, and 3 net zero, prevention of plastic pollution, and cost reduction. This will result in demand reduction for chemical products, which will be in addition to Japan's projected decline in the domestic population.

Two demand scenarios were built, in which one (BAU) assumed Japan's future population reduction only, whereas the other (CE) additionally assumed downstream circularity, accounting for various circular economy activities such as elimination, reuse, and recycling. In the BAU demand scenario, the annual demand for olefins and aromatics will decrease from 25.1 Mt in 2020 to 22.7 Mt in 2050, which will be further reduced to 14.4 Mt in 2050 in the CE scenario. These scenarios were used to build the net zero pathways in combination with the supply scenarios discussed in Section 3.

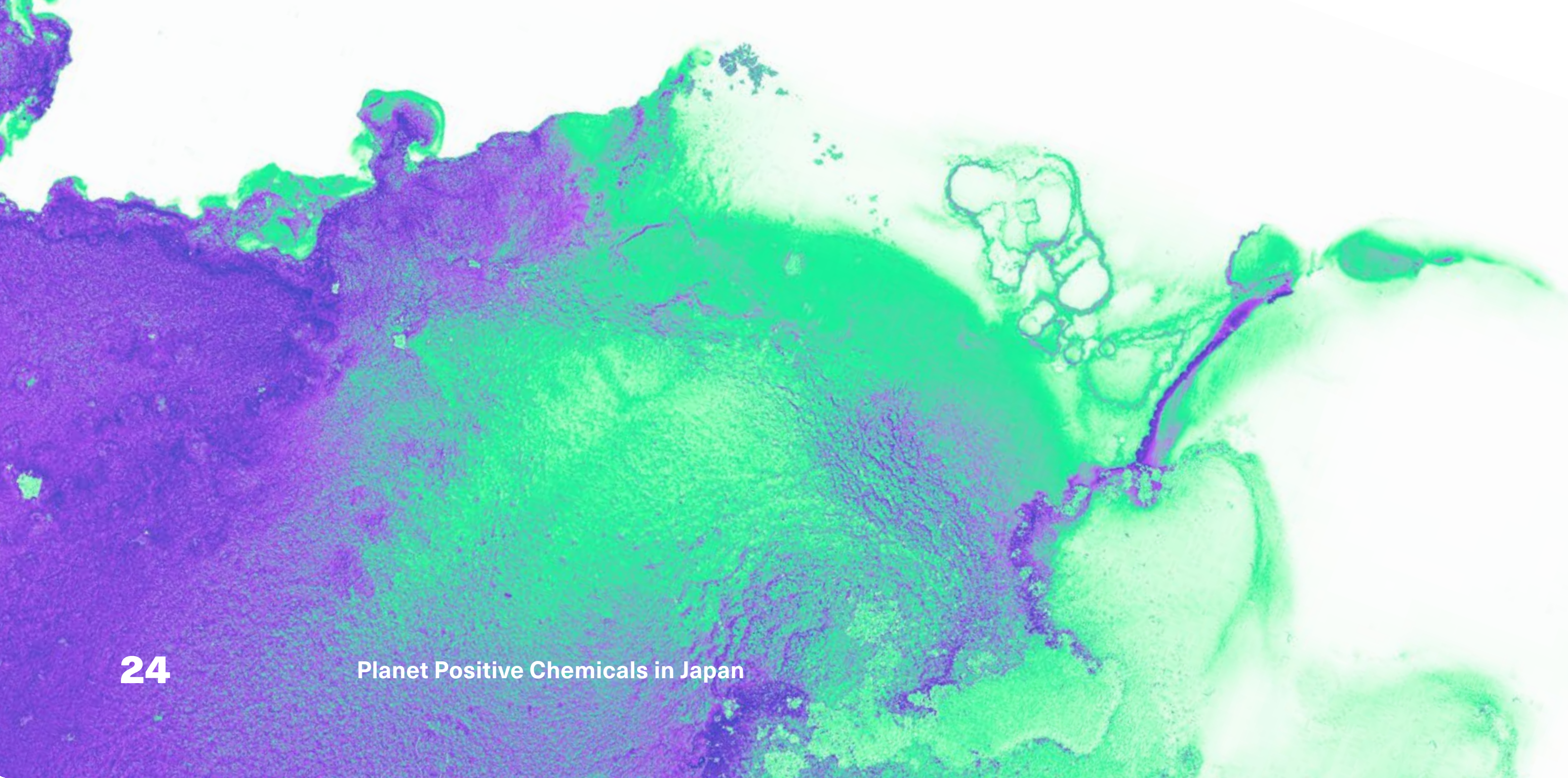
Given these possible long-term demand trends, the sooner the chemical industry prepares to integrate circularity into business to support downstream customers, the better off it will be, although these scenarios are not forecasts.

2.1 Managing scope 3 emission, in addition to scope 1 and 2, is imperative

The Japanese chemical industry and its supply chain are emission-intensive based on a linear model. Chemical products in Japan today are made almost exclusively from fossil feedstock (e.g., naphtha), and most of the collected plastic waste is incinerated at the end of life, with low recycling rates for discharged plastics (25% in Japan in 2021[51]). At the global level, this linear model creates growing externalities, and the industry's licence to operate is being questioned. Additionally, this model is not compatible with the Japanese government's target of net zero by 2050, let alone the scope 3 requirements from GFANZ and brand owners, which may threaten the industry's core business value if no action is taken.

- **From the perspective of emission,** scope 1 and 2 emission from the production of the chemicals in the scope of this study (methanol, ethylene, propylene, butadiene, benzene, toluene, and xylenes) was estimated at 23 Mt of CO_{2eq} in 2020, and 65 Mt of CO_{2eq} when adding scope 3 emission (**Figure 8**)[52,53]. This corresponds to 2.0% and 5.7% of Japan's total emission (1.142 Gt CO_{2eq} in 2020)[54], respectively. The lion's share of scope 1, 2, and 3 emission (42 Mt of 65 Mt, or 65%) comes from upstream feedstock extraction and end-of-life treatment downstream, both of which are somewhat out of control for the chemical industry today. Furthermore, the scope 1, 2, and 3 emission could be nearly twice (120 Mt of CO_{2eq} , or 11% of Japan's emission), if fugitive methane emission in the upstream were properly accounted for, as proposed by Hmiel[55], and if all chemicals produced were incinerated at the end of life, presenting a greater risk to the industry.
- **From the perspective of waste,** although Japan benefits from its efficient waste management system, it is commonly understood that leakage still occurs on land and at sea and typically accounts for 0.5–2% of the total waste generated[56]. However, the risk of waste for the Japanese chemical industry comes mainly from overseas sources, given the amount of exports. Leakage from countries with poor waste management systems can indirectly expose the industry to environmental leakage and its consequences.

51 Plastic Waste Management Institute, Material Flow of Plastics for 2021 (2022), https://www.pwmi.or.jp/flow_pdf/flow2021.pdf (cf. 25% = 2.06 / 8.24) See footnote 43 for detail.
52 In this report, scope 3 emission refers to emission from feedstock sourcing as well as end-of-life emission (categories 1 and 12 from the GHG protocol)
53 Note that scope 3 emission is not necessarily occuring in Japan (e.g., for chemical exported overseas).
54 National Institute for Environmental Studies, https://www.nies.go.jp/gio/archive/ghgdata/index.html
55 Hmiel, B. et al., *Nature* **578**, 409–412 (2020), https://doi.org/10.1038/s41586-020-1991-8
56 The Pew Charitable Trusts and Systemiq, Breaking the Plastics Wave (2020), https://www.systemiq.earth/breakingtheplasticwave/



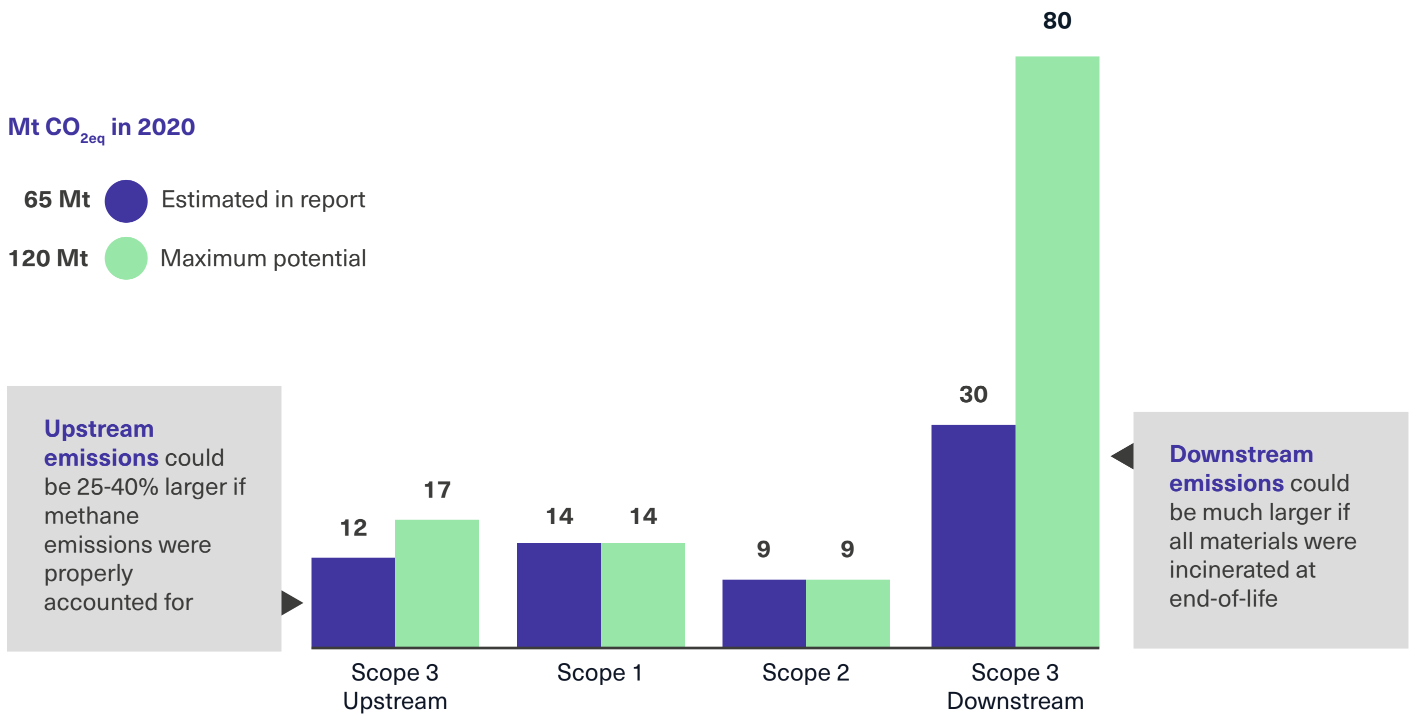


Figure 8: Estimated annual scope 1, 2, and 3 emission of the 7 primary chemicals in scope for Japan in 2020.

2.2 Demand reduction pressure could come from downstream industries that implement circularity to reduce their scope 3 emission

Two demand reduction scenarios for olefins and aromatics by 2050. Downstream industries (e.g., brand owners) are under pressure from consumers, NGOs, and financial institutions to reduce emission, for whom upstream scope 3 emission is often the greatest[57]. As they pursue circular economy to reduce GHG emission, plastic pollution, and costs, the demand for olefins and aromatics to produce chemical products, such as plastics, could decrease more significantly than expected from Japan's future population decline alone. As explained in Section 1, this study used two demand scenarios (BAU and CE). In the BAU (business as usual) demand scenario, which assumes a 20% population decline by 2050 and no downstream circular economy activities beyond today's levels, the annual demand for olefins and aromatics will decrease from 25.1 Mt in 2020 to 22.7 Mt in 2050, indicating that population decline alone will lead to a 10% demand reduction[58] by 2050. In addition to the population decline, circular economy activities in the downstream could lead to an annual demand for olefins and aromatics of 14.4 Mt in 2050 (Figure 9), which is represented in the CE (circular economy) demand scenario. These demand scenarios were estimated through the four main industrial outlets of plastics: packaging and household goods, transportation, building and construction, and textiles. Note that these scenarios should not be regarded as forecasts but as simulations to identify key actions that are necessary to achieve net zero. In reality, future demand reduction could be accelerated or decelerated by the level of targeted policies (e.g., ban on single use plastics and level of recycled content mandates) and downstream industry pledges (e.g., net

57 Partnership for Carbon Transparency (PACT), Pathfinder Framework Version 2.0 (2023), Page 7, https://www.wbcsd.org/resources/pathfinder-framework-version-2-0/

58 Our analysis used the following assumption: (1) net export (i.e., export less import) of olefins and aromatics as well as their derivatives is assumed to remain constant in volume till 2050, (2) domestic consumption decline is proportional to the population decline (20%) projected by the United Nations by 2050, and (3) the demand scenarios in 2050 include an incremental demand for the chemical industry in supporting the energy sector to achieve net zero, such as additional ethylene demand for solar panel components, amounting to 1.1 Mt in 2050.

zero, recycling, and avoidance of plastics) influenced by increasing scrutiny from consumers and NGOs. The future demand will also be influenced by the level of net exports. This general trend of demand reduction from downstream industries is not something that the Japanese chemical industry will be able to fight against. Therefore, the sooner a company begins seeking different business approaches, the better off it will be.

Demand reduction will be driven by four circular economy levers in the downstream of the supply chain. The four circular economy levers were elimination, reuse, substitution, and recycling. Elimination will be the largest lever (reducing 2.7 Mt of annual olefins, aromatics and methanol demand in 2050), followed by reuse (2.3 Mt), recycling (2.2 Mt)[59], and substitution (1.7 Mt).

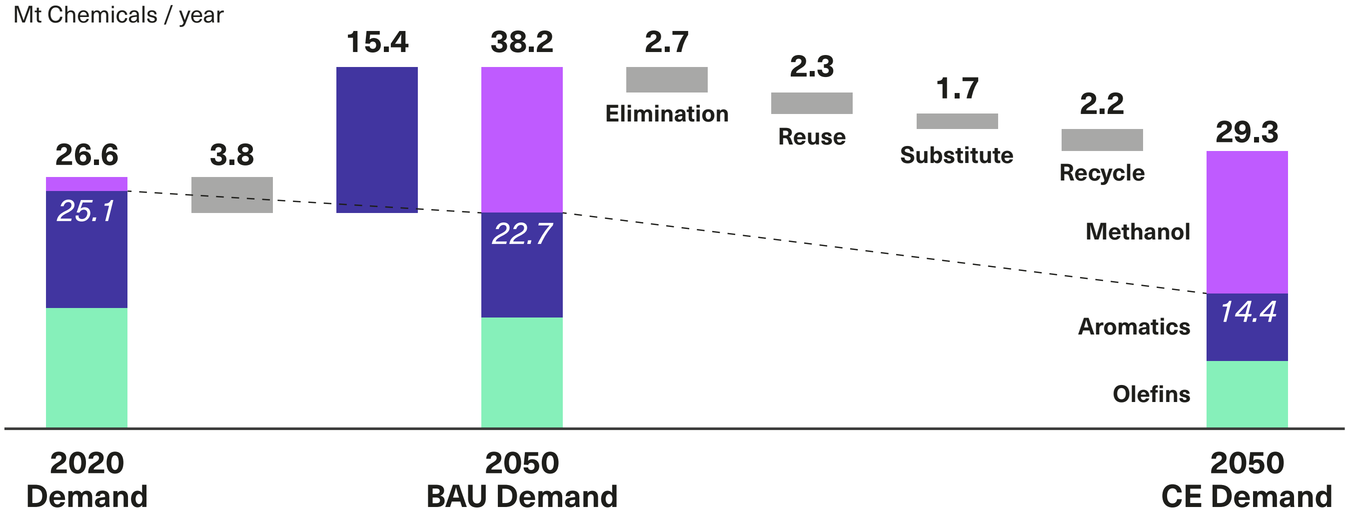


Figure 9: Changes in the demand for olefins, aromatics, and methanol between 2020 and 2050 in Japan. Repeated from **Figure 2**. White type indicates the total demand for olefins and aromatics only.

Elimination is the most significant lever accounting for annually reducing 2.7 Mt of olefins, aromatics and methanol demand in 2050 in the CE demand scenario. Elimination is defined where an entire product or a share of it is no longer required to deliver the same service to society. All downstream industries are expected to act on this lever, because elimination is the most efficient from the circular economy principles, and because they can take advantage of cost reduction as well. For example, reducing unnecessary plastic packaging (0.7 Mt/y) can be achieved by light-weighting packaging, regulating bags and other small-mass items (e.g., straws), and eliminating flexible packaging such as sachets (e.g., consumer care industry, condiments) or business-to-business pallet wrappers. Elimination also includes a sustainable transition towards more efficient building and floor area usage (0.6 Mt/y) requiring fewer overall resources. The transition away from fossil fuels in the transportation sector will lead to the elimination of aromatics and other olefin-derived fuel additives (0.4 Mt/y). Continued vehicle life extension (0.4 Mt/y) will reduce the production need for new vehicles.

Reuse business models are expanding rapidly and represent 2.3 Mt of annual demand reduction in 2050 in the CE demand scenario. It encompasses new business models in which the product utility is still valued but its delivery requires less material for the same output, such as mobility-as-a-service and a closed-loop food packaging and delivery. It is based on economic and environmental benefits, but it also requires new supply chains, business models and partnerships which have been a bottleneck. Service

59 Including mechanical recycling, depolymerization and solvent-based technologies, but excluding pyrolysis and gasification which are accounted for in the supply model as they produce chemical feedstock.

business models are being developed in a number of industries including the chemical industry, with the concept of chemical-as-a-service. The packaging and household goods industry is most likely to benefit from this new paradigm, for example, with the new packaging and delivery models for food (e.g., beverages and seasoning) and consumer products (e.g., shampoo and detergents) as well as business-to-business packaging (e.g., reusable crates), reducing the need for 1.5 Mt/y of plastics by 2050. In the transportation sector, mobility-as-a-service will also progressively lead to a reduced fleet size, with a reduction in demand of 0.7 Mt/y.

Substitution accounts for 1.7 Mt of annual demand reduction in 2050 mostly driven by the packaging industry in the CE demand scenario. This includes all levers where utility is substituted by a material not produced by the chemical industry within the scope of this project. Material substitution requires a clear GHG benefit and a thorough life cycle assessment to avoid unintended consequences in other impact categories (e.g., deforestation and biodiversity loss). Substitution could also be a relevant lever to consider for chemical products with high leakage potential into the environment[60]. Substitution to date seems to be most promising in the packaging and household goods sector with the increasing use of paper and paper coating (e.g., fruits and vegetables punnets, display trays, polystyrene foam substitute, food service items) as well as alternative materials (e.g., compostables for takeaway food, ready meal trays, pouches) displacing 1.3 Mt/y in 2050. The building and construction industry will also likely see a shift towards more bio-based materials (e.g., wood timber and wood panels for interior), displacing another 0.2 Mt/y.

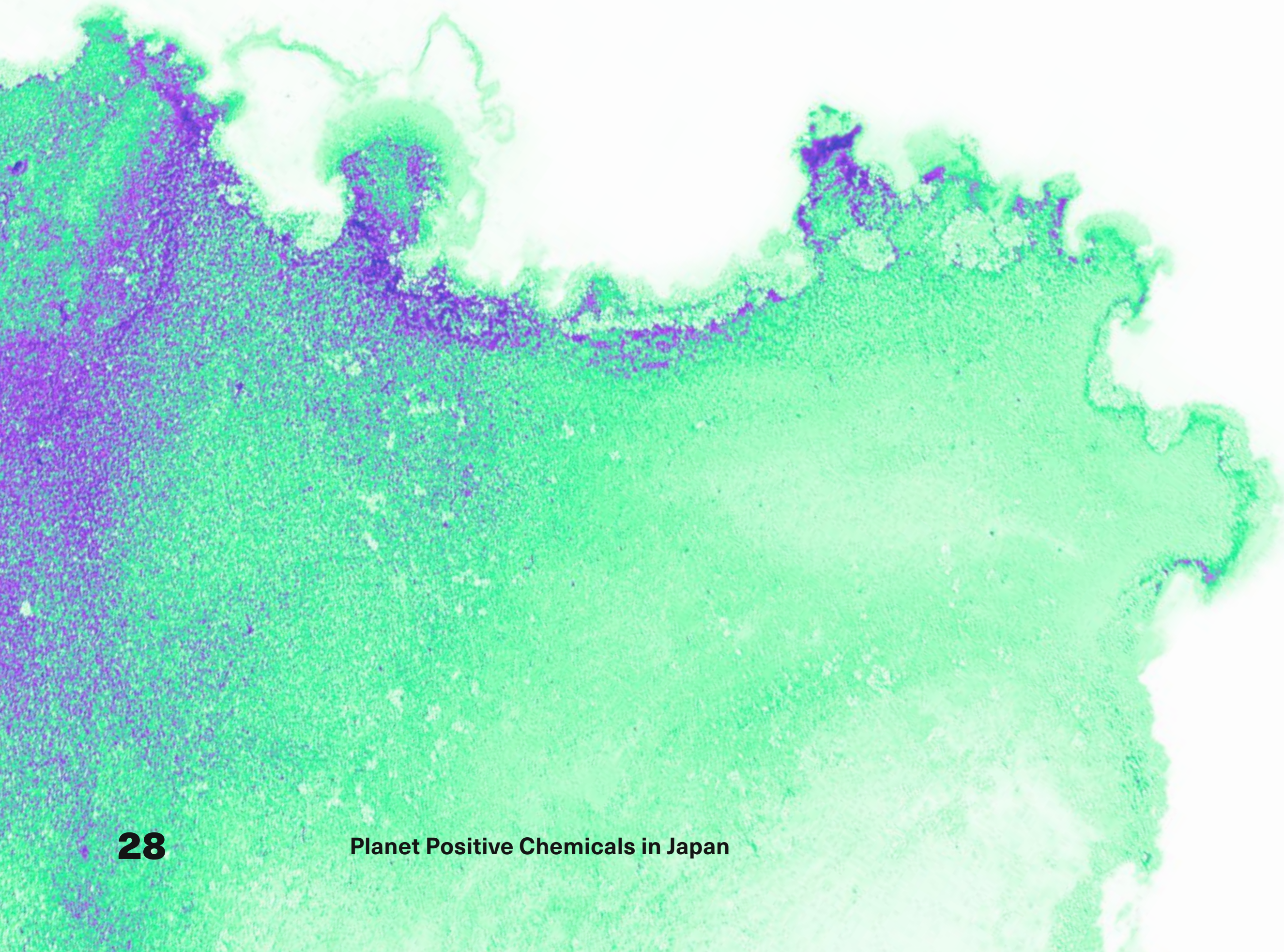
Recycling will be a key reduction lever, but it only accounts for 2.2 Mt of annual demand reduction in the CE demand scenario, due to inherent availability limitations. Two types of recycling are considered in this section: mechanical recycling and downstream chemical recycling technologies (e.g., depolymerisation and solvent-based recycling), because they reduce the demand for the seven chemicals in scope of this study. In contrast, feedstock recycling technologies (e.g., pyrolysis and gasification) are excluded from recycling and are covered later as feedstock for basic chemicals (e.g., olefins and aromatics) because they do not affect the demand for the seven chemicals.

- **Expand mechanical recycling[61] aggressively to reach the Japanese government's plastic packaging target** of 60% reuse/recycling of packaging by 2030[62]. Mechanical recycling is considered the most effective form of recycling in emission reduction. It will translate to 1.8 Mt/y of additional demand reduction by 2050. This scenario assumes continued innovation and technological development, including better product design for recycling, better sorting supported by labelling and sorting technologies (including digital watermarks), better mechanical recycling equipment, and introduction of new decontamination steps to improve purity of waste streams, along with the development of new additives to compensate for physical property loss. All downstream sectors are expected to embrace mechanical recycling.

- **Chemical recycling, such as depolymerisation and solvent-based recycling, will also scale to reach 0.4 Mt/y of demand reduction in 2050.** These chemical recycling technologies, which recycle plastics into monomers and clean polymers, bypass the production of basic chemicals (i.e., olefins and aromatics) and constitute the basis for a new recycling industry to complement mechanical recycling and produce high-quality recyclates for additional applications that mechanical recycling cannot cover.

60 Chemicals with high leakage potential have use cases with easier routes of dissipation into the environment (e.g., paint, tire abrasion) especially if water soluble and non-biodegradable.
61 Mechanical recycling constitutes the recycling of polymers without altering their chemical structure or without the use of subsequent chemical intermediaries. Quality of the output product is typically lower than primary polymer due to the mixing of polymer grades and their related additives.
62 Ministry of the Environment, Plastics Resource Circulation Strategy (2019), https://www.env.go.jp/press/106866.html

Prepare for future demand reduction by enhancing recycling to support downstream circularity.
Demand reduction is not the preferred situation for the chemical industry. However, downstream industries in the supply chain will become increasingly active in the circular economy in their pursuit of reducing scope 3 emission, plastic pollution, and costs. In addition, the ongoing intergovernmental negotiations to end plastic pollution could accelerate recycling and/or reduce production of primary plastics. Because it is unlikely that the Japanese chemical industry will be able to fight against this trend, the sooner it prepares to depart from today's volume-based linear business and pursue technologies that enable the recycling of broader chemical products, or combine such recycling technologies with closed-loop service-based business models to support downstream circularity, the better off it will be.



Section 3: Supply

Scope 1, 2, and 3 net zero for the Japanese chemical industry and its implications

Section Summary

The Japanese chemical industry can achieve scope 1, 2, and 3 net zero through the combination of three basic strategies: (1) switching from fossil feedstock to alternative feedstocks, (2) switching energy sources, and (3) applying CCUS. In fact, multiple pathways exist for the Japanese chemical industry to reach net zero by 2050, which combine these three basic strategies. For example, the BAU-ME and CE-ME pathways use CCS to achieve net zero, in addition to switching to net zero energy sources, while accommodating demand in the respective demand scenarios (BAU and CE). The CE-NFAX2 pathway uses alternative feedstocks (e.g., bio-based feedstock and recyclates), and the CE-NFAX pathway uses both alternative feedstocks and CCS, in addition to switching to net zero energy sources. Regarding switching energy sources, many zero emission energy options are available for electricity and heat. However, the exact energy sources for each plant to switch from today's fossil energy sources are beyond the scope of this study, because of the limited granularity, except for steam crackers.

To achieve net zero, olefins, aromatics, and methanol will all undergo significant change in production process and feedstock by 2050. Olefins will be produced with crackers retrofitted for net zero using fossil or recycled pyrolysis oil as feedstock, or with the methanol-to-olefins (MTO) process using green or blue methanol depending on the pathway, while some crackers will have to be decommissioned because of the reduced demand. Aromatics production will shift to the methanol-to-aromatics (MTA) process based on our assumption that catalytic reformers that produce gasoline additives and most of aromatics today will be decommissioned because of the decline in vehicles with internal combustion engines. However, if MTA takes time to reach the commercial scale, catalytic reformers could remain. These infrastructure shifts in Japan require $61–95 billion in cumulative capital expenditures. Because of this and the increased cost of feedstock, net zero olefins and aromatics could cost twice or more in 2050 than today's fossil counterparts; however the impact on the production cost of consumer products will be limited. This cost gap is greater today than in 2050; thus, the greatest challenge is to overcome the cost gap today (rather than waiting for 2050), which is discussed in Section 4.

Scope 3 net zero imposes a theoretical upper limit to the supply volume of chemical products for a company and country. As a result, access to bio-based/DAC-CCU feedstocks, recyclates, and CCS determines the maximum supply. Specifically, recycling needs to be maximised regardless of the pathway, by leveraging Japan's strengths to scale chemical recycling technologies. Biomass plays a significant role as a non-fossil feedstock; thus, developing domestic sources to balance imported biomass is needed. Methanol can become a platform chemical (in addition to naphtha) to produce basic chemicals, and Japan should pursue both domestic and international sources. Ethanol also has the potential as a platform chemical; however, the future availability of bioethanol may be limited. Finally, CCUS needs to be scaled to mitigate emission from production and incineration at the end of life.

3.1 Japanese chemical industry can achieve net zero through a combination of three basic strategies: (1) switching feedstocks, (2) switching energy sources, and (3) applying CCUS

The chemical industry in Japan can achieve scope 1, 2, and 3 net zero by deploying a combination of the following three basic strategies (Figure 10).

1. **Switching from fossil feedstock to alternative feedstocks.** Alternative feedstocks are needed because part of the feedstock is used as energy in the production process (e.g., cracker off-gases subsequently used as fuel on-site), generating scope 1 emission, and because scope 3 emission from fugitive methane (during extraction and distribution) and from incineration at the end of life need to be abated. The mix of alternative feedstocks needs to be balanced across the available pool, which includes sustainably sourced biomass, waste (recyclate), and CCU, including DAC-CCU, which is energy intensive.
2. **Switching the energy sources so production processes are powered by zero emission energy.** Energy substitution with zero emission sources (e.g., renewable and nuclear electricity, hydrogen, including ammonia and e-methane, and biomass, including bio-methane) will be the key, including the electricity to produce green hydrogen.
3. **Capturing emission so that carbon dioxide from chemical production processes and end-of-life incineration is captured** and permanently stored underground or used as feedstock.

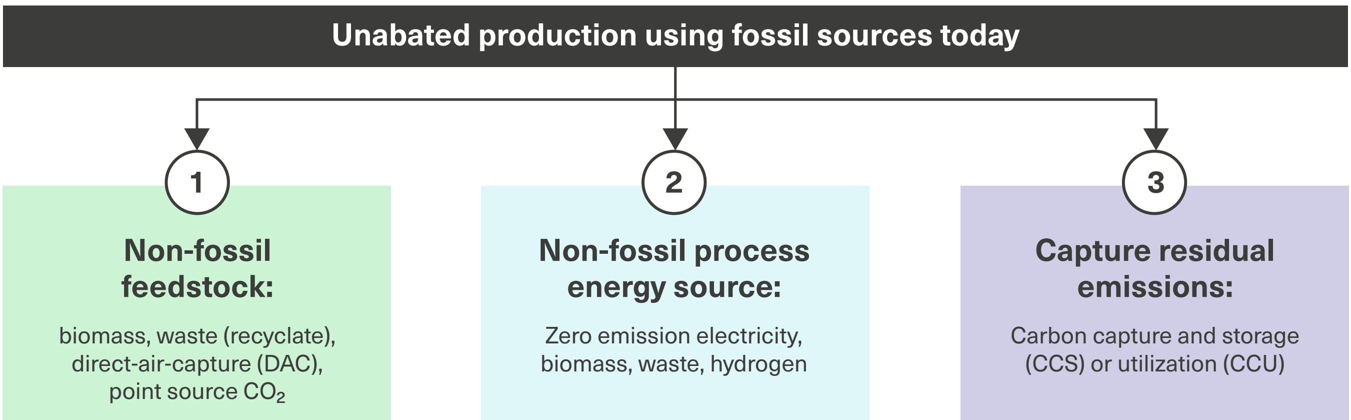


Figure10: Three basic strategies to abate scope 1, 2, and 3 emission in the chemical industry.

3.2 Multiple pathways exist for the Japanese chemical industry to reach scope 1, 2, and 3 net zero by 2050

As explained at the end of Section 1, this study presents three supply scenarios (ME, NFAX, and NFAX2) to reach net zero. Each supply scenario mixes the above three strategies at different ratios. Furthermore, combining these three supply scenarios with the two demand scenarios (BAU and CE) described in Section 2 provides six pathways to net zero (**Figure 11**). Of the six pathways to 2050, the following four pathways (BAU-ME, CE-ME, CE-NFAX, and CE-NFAX2) are considered the most insightful for the Japanese chemical industry and are discussed further. These four pathways can take the Japanese chemical industry to near net zero or beyond, using different combinations of the three basic strategies.

			Supply scenarios		
			Lowest cost	Fastest emission reduction	Fastest emission reduction without CCS
			ME	NFAX	NFAX2
Demand scenarios	Population decline only	BAU	BAU-ME	(BAU-NFAX)	(BAU-NFAX2)
	Population decline and downstream circularity	CE	CE-ME	CE-NFAX	CE-NFAX2

Figure11: Two demand scenarios, three supply scenarios, and six combined net zero pathways. Repeated from **Figure 1.**

BAU-ME and CE-ME pathways achieve near net zero at the lowest possible cost for the respective demand scenarios (BAU and CE). These pathways rely on the development of abundant and affordable CCS capacity and on the continued use of fossil feedstock (see **Figure 12**).

- Fossil feedstock, specifically naphtha and natural gas, will remain the main carbon source, representing 96–98% of the feedstock mix in 2050.
- These pathways will rely on the large deployment of CCS (47 Mt and 26 Mt of CO_2 annually for BAU-ME and CE-ME, respectively, in 2050) to mitigate scope 1 and 3 emission from processes that use fossil feedstock (e.g., crackers, methanol production via steam methane reforming) and from incinerators.
- Net zero for scope 1, 2 and 3 is achievable in these pathways, but it is an approximation to net zero, because the remaining emission from CCS capture inefficiencies (leakage) and fugitive methane from fossil extraction amount to 12 Mt and 8 Mt of CO_{2eq} annually in 2050 for BAU-ME and CE-ME respectively.
- The BAU-ME and CE-ME pathways are cost-effective and seemingly attractive pathways to reach near net zero. However, they heavily depend on the successful deployment of abundant and inexpensive CCS, which involves vast uncertainties, the failure of which would mean a failure for the Japanese chemical industry to reach net zero, with serious consequences of losing international competitiveness and possibly the licence to operate.

CE-NFAX pathway goes beyond net zero and achieves negative emission using diversified feedstocks and CCS.

A large share (62%) of fossil feedstock is replaced by alternative feedstocks. For example, direct-air-capture (DAC-CCU) represents 29% of the carbon source in 2050, and biomass and recycling represent 18% and 12% of the carbon source, respectively. A large amount of green hydrogen of up to 5.5 Mt by 2050 will be needed for DAC-CCU and to adjust the carbon / hydrogen ratio in bio-based feedstock and waste.

- As a result of DAC-CCU and green hydrogen development, electricity consumption increases by 4-fold compared to CE-ME, with DAC expected to consume 0.1 EJ and green hydrogen production 0.3 EJ.

- CCS is used to abate the emission from cracker fuel gas, for example, when recycled pyrolysis oil is used as a new feedstock. Together with the CCS to deal with end-of-life incineration, the requirement for CCS will be 23 Mt of CO_2 annually in 2050.

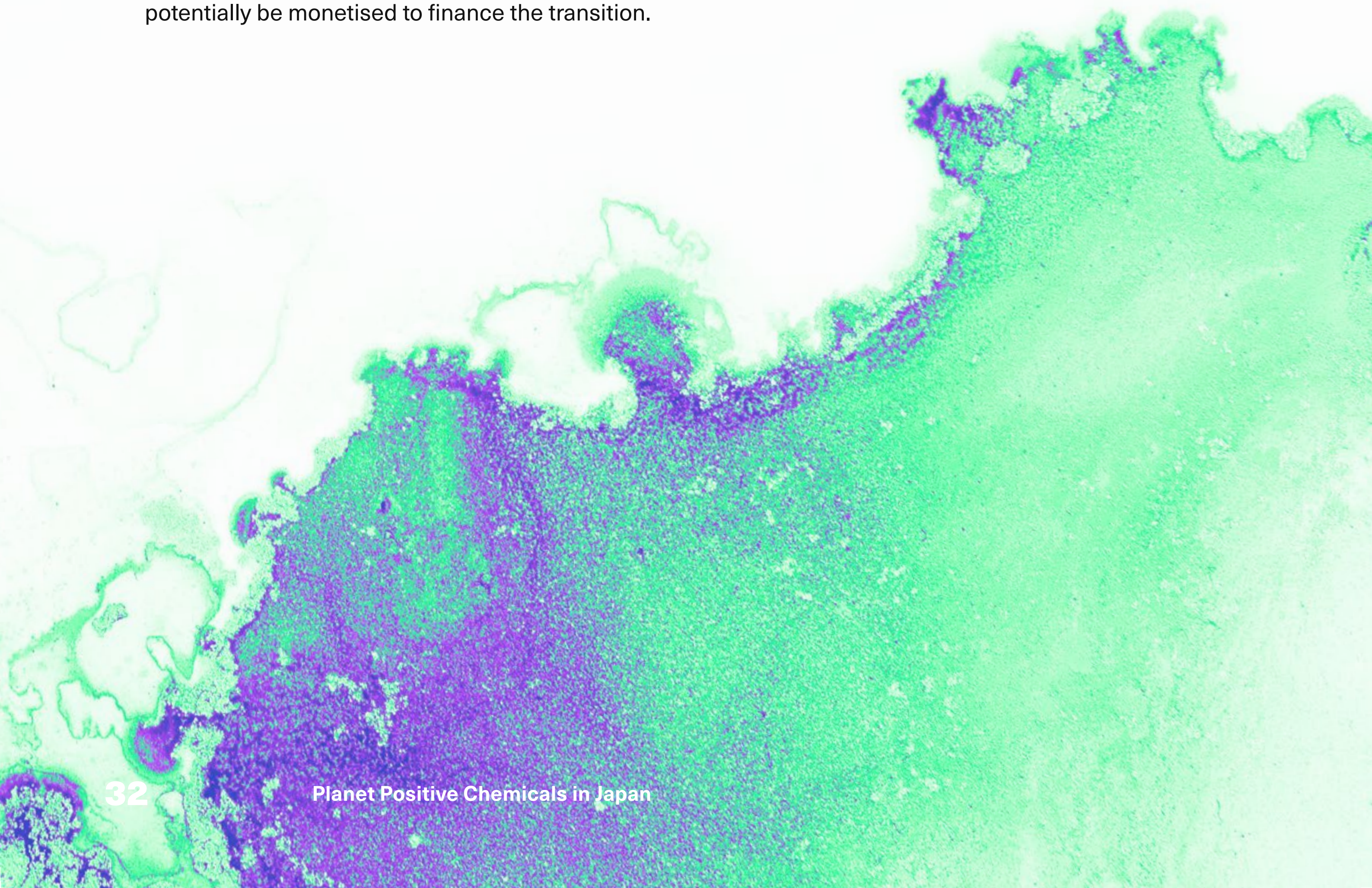
- This pathway will allow the industry and its supply chain to become carbon negative by 2050, with 18 Mt of annual negative CO_{2eq} emission, which could potentially be monetised to finance the transition.

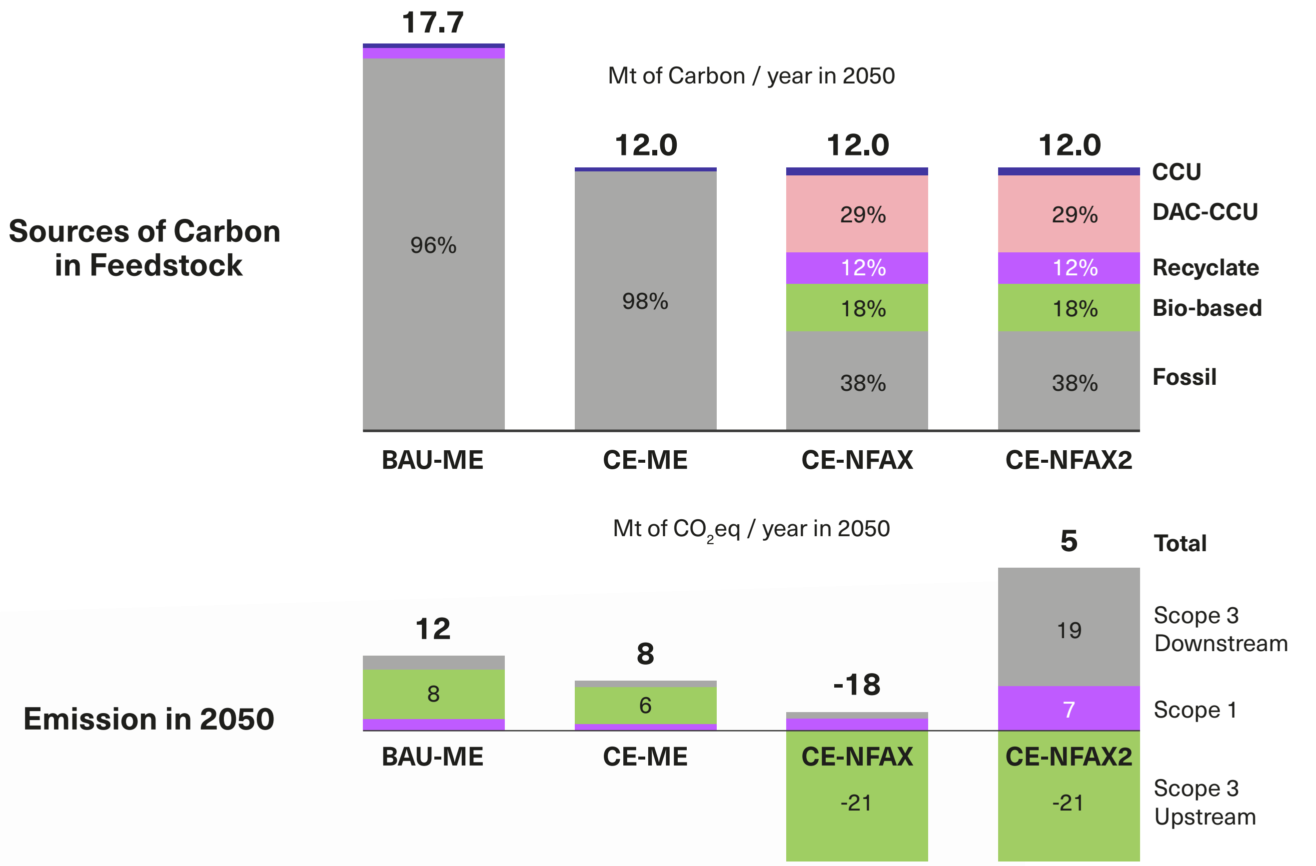
- The CE-NFAX pathway is attractive because it achieves negative emission from the chemical industry. However, this pathway relies heavily on bio-based and DAC-CCU feedstocks, which have not yet been proven at scale in Japan. In addition, CE-NFAX depends on CCS, albeit to a lesser degree than BAU-ME and CE-ME.

CE-NFAX2 pathway achieves near net zero without using CCS while using diversified feedstocks.

- This pathway is the same as CE-NFAX with respect to the mix of production technologies and feedstocks, except that it uses no CCS to reach net zero. This pathway relies on recyclate, as well as bio-based and DAC-CCU feedstocks, which absorb CO_2 from the atmosphere when they are produced.

- This pathway represents a scenario in which Japan is unable secure CCS sites with meaningful capacity, indicating that the Japanese chemical industry will need to use recyclates, bio-based and DAC-CCU feedstocks, which have not been proven at scale in Japan, to reach scope 1, 2, and 3 net zero.





Amount of CCS in 2050

Mt of CO_2 stored / year in 2050

	BAU-ME	CE-ME	CE-NFAX	CE-NFAX2
CCS from Production	13	8	5	0
CCS from Incinerator	34	18	18	0
Total CCS	**47**	**26**	**23**	**0**

Figure 12: Sources of carbon in feedstocks, emission, and amount of CCS in 2050 for different pathways. Repeated from **Figure 3**.

3.3 Energy sources

Many zero emission energy options are available, but the conversion strategy for each plant will be situation-dependent. Figure 13 shows the total energy and feedstock demands in 2050. While BAU-ME requires more energy and feedstock than CE-ME to accommodate the greater demand, CE-NFAX requires more energy than CE-ME for the same demand because of the additional net zero energy needed for processes that involve hydrogen, biomass and recyclates compared to fossil sources. The electricity and heat required by the chemical industry in the production processes (except for steam crackers, which are discussed separately) were assumed to reach net zero by 2050 utilising net zero energy sources such as renewable and nuclear electricity, net zero hydrogen (including ammonia and e-methane), biomass including bio-methane, and abated fossil fuels. The exact net zero energy sources to be utilised in each plant to switch from today's fossil energy sources are beyond the scope of this study, because of the limited granularity.

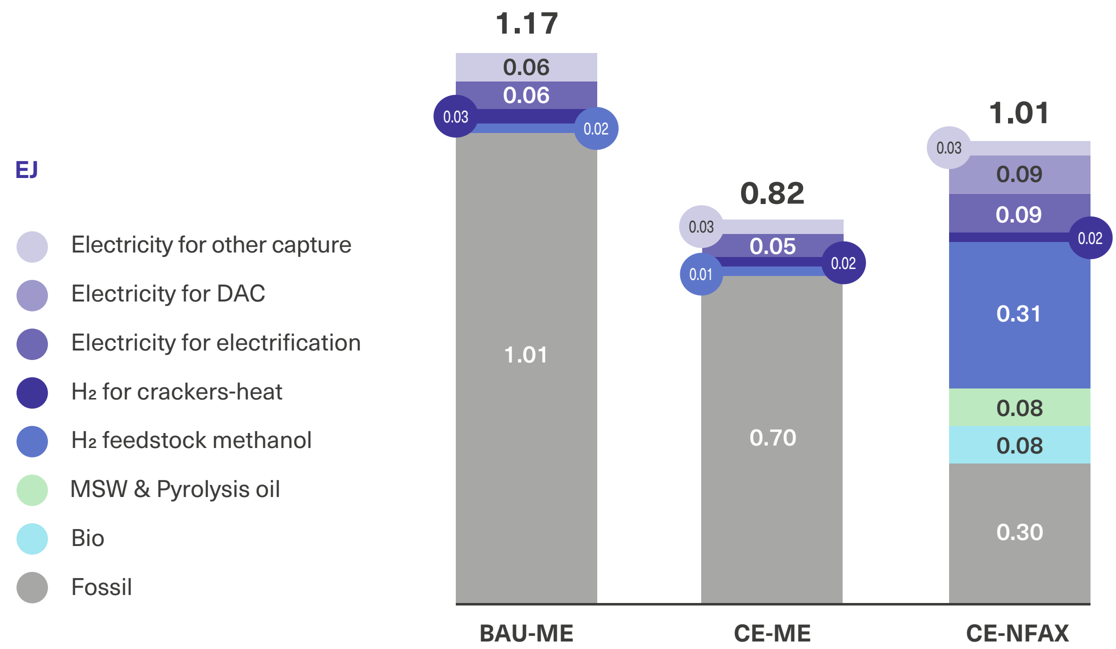


Figure 13: Total energy and feedstock required in 2050.

3.4 Olefins, aromatics, and methanol will all undergo significant changes in the production process and feedstock to reach net zero by 2050

Olefins will be produced with crackers retrofitted for net zero or with the methanol-to-olefins (MTO) process. Currently in Japan, olefins are produced with naphtha crackers using fossil feedstock in Japan. However, by 2050, in the BAU-ME and CE-ME pathways, they will be produced mainly with crackers retrofitted with CCS and those fuelled by hydrogen or ammonia, as well as by the MTO process, while some crackers will have to be decommissioned due to the decline in demand by 2050. In the CE-NFAX pathway, in addition to hydrogen/ammonia-fuelled crackers, electric crackers and crackers using recycled pyrolysis oil with CCS will be used to achieve greater abatement in our analysis.

Aromatics production will shift to the methanol-to-aromatics (MTA) process. Today, aromatics are produced mainly by catalytic reforming and supplemented by naphtha cracking. In particular, the catalytic reforming process is used today in refineries to produce additives to upgrade transportation fuel, as well as to produce aromatics. By 2050, we assume that catalytic reformers will mostly be decommissioned because of decline in vehicles with internal combustion engines. As a result, by 2050 in the BAU-ME and CE-ME pathways, aromatics will be produced mainly by the MTA process using methanol produced via natural gas reforming, which requires CCS to abate the end-of-life emission to achieve net zero. In the CE-NFAX and CE-NFAX2 pathways, CCU, DAC-CCU, or biomass gasification will be used instead of natural gas to produce methanol, which then will be used to produce aromatics via the MTA process. Although we assume that catalytic reformers will be phased down, if MTA takes time to reach the commercial scale, catalytic reformers could remain.

Different pathways require different production processes for net zero olefins and aromatics, but robust commonality exists. Figure 14 shows a breakdown of the production technologies (i.e., production process and feedstock) for olefins, aromatics, and methanol. It shows that, regardless of the pathways to net zero, some crackers will remain and will be retrofitted to produce net zero olefins, while other crackers will be replaced by MTO, and yet others will be decommissioned due to demand reduction. In contrast, net zero aromatics production will require a major shift to the methanol-to-aromatics process regardless of the pathways to net zero, while supplemented by the output from abated crackers. Note that these results are not forecasts, but a simulation derived by prioritising the least cost or fastest emission reduction.

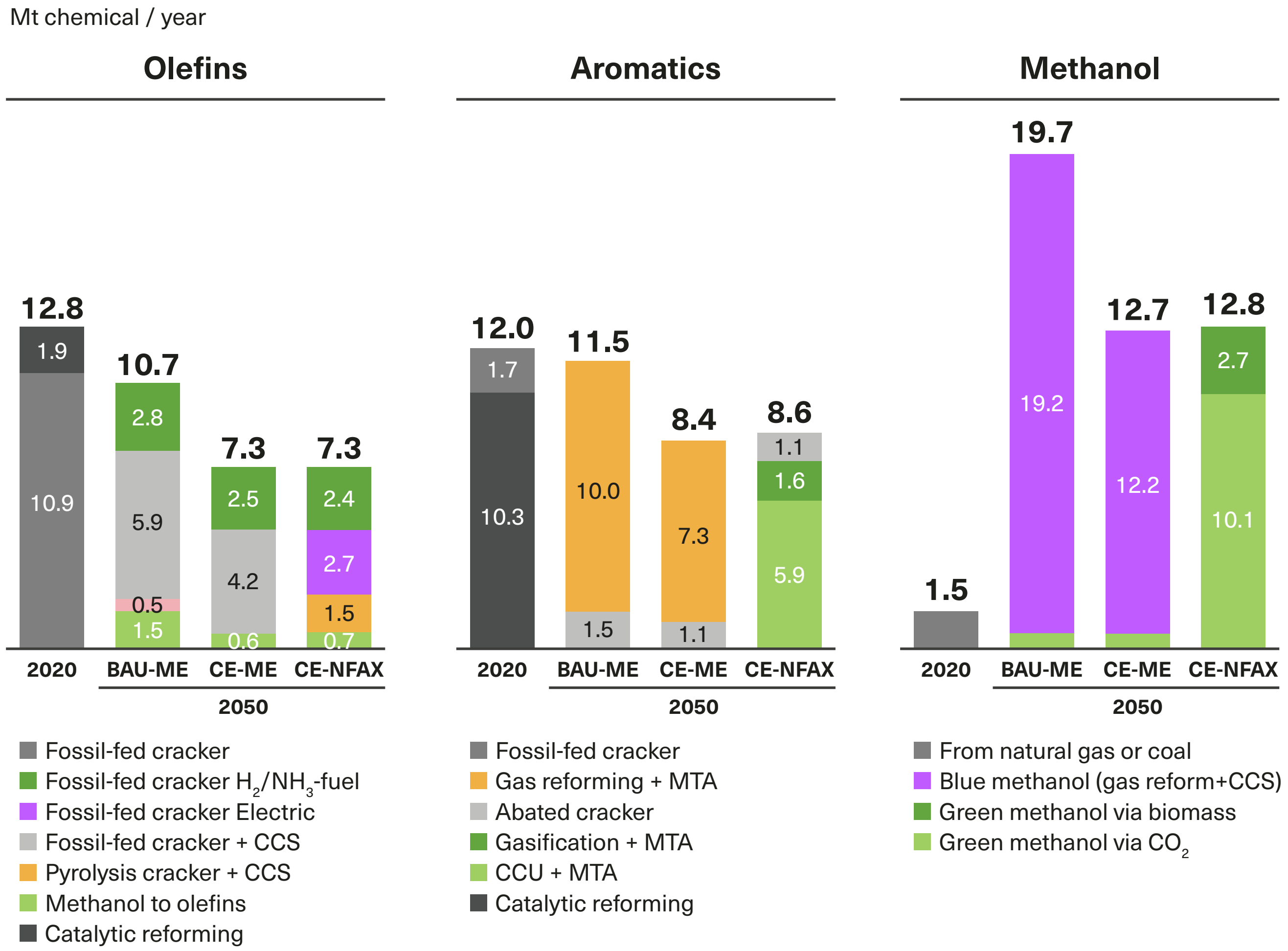


Figure 14: Breakdown of production technologies to produce olefins, aromatics and methanol for different pathways. The technology mix for the CE-NFAX2 pathway is the same as that for CE-NFAX.

3.5 Scope 3 net zero imposes a theoretical upper limit on the supply volume of chemical products

Access to bio-based/DAC-CCU feedstocks, recyclates, and CCS will determine the maximum supply for a country or a company. Scope 3 category 12 deals with emission from end-of-life treatment. Under the constraint that scope 3 category 12 is net zero, it can be theoretically derived that *(A)* = *(E)*, *(B)* = *(F)*, and *(C)* = *(G)* in **Figure 15** (see footnote[63] for a detailed derivation and assumptions). Therefore, it can be shown that *(D)* = *(C)* + *(E)* + *(F)*. In other words, *(D)*, which represents the total supply of carbon in chemical products for a country or company, is limited to the sum of the carbon in the bio-based and DAC-CCU feedstocks *(C)*, sequestered carbon *(E)*, and recycled carbon *(F)*, where each component is limited in availability. For example, because the supply of sustainably sourced bio-based feedstock is limited, the amount of *(C)* is limited unless costly DAC-CCU is widely deployed. The amount of sequestration *(E)* is likely limited because of the time required to develop CCS sites before 2050, as well as the limited availability of managed landfill sites. Finally, the amount of recyclate *(F)* is limited because of the imperfect waste collection and limitations in the recycling process yield.

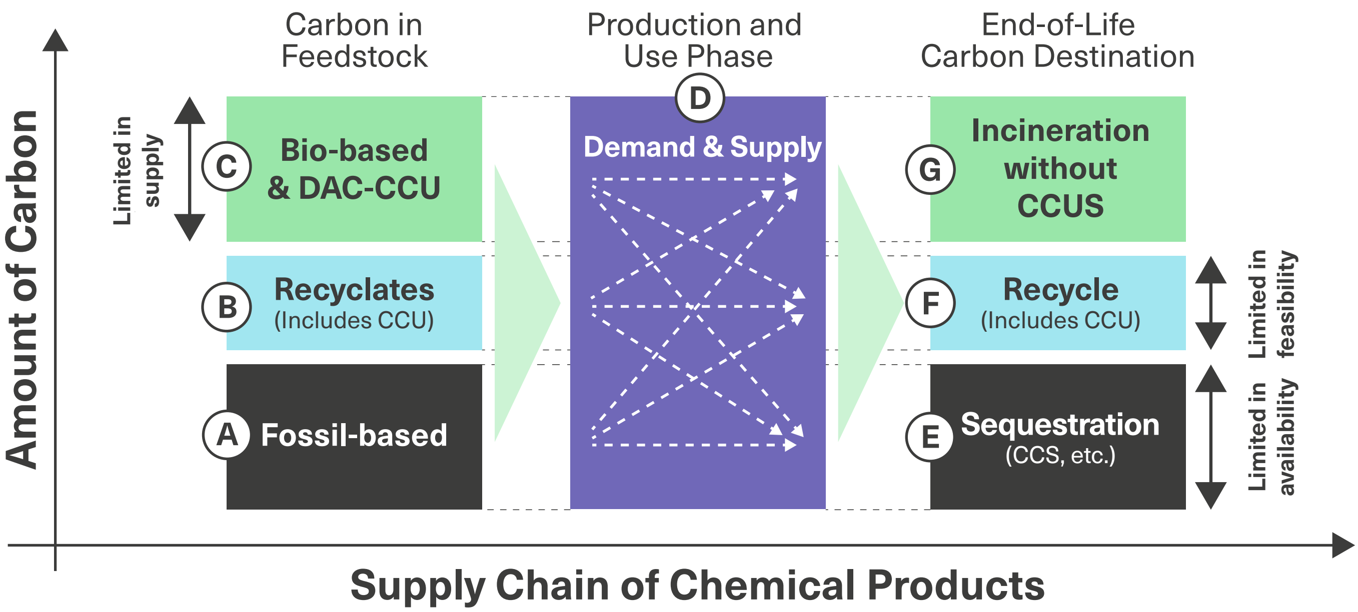


Figure 15: Carbon balance in chemical supply chain. Carbon balance and scope 3 (category 12) net zero together require *(A)* = *(E)*, *(B)* = *(F)*, and *(C)* = *(G)*. As long as these equations hold true, fossil feedstock, for example, can reach any of the three destinations to be scope 3 (category 12) net zero, as indicated by the dotted arrow in the Production and Use Phase. These equations also indicate *(D)* = *(C)* + *(E)* + *(F)*, the strategic implications of which are detailed in the text. The proportion of *(A)* : *(B)* : *(C)* or *(E)* : *(F)* : *(G)* is for illustrative purposes only.

63 Carbon accounting of embedded carbon in chemical products can be complex because of recycling and feedstocks with a negative carbon footprint. This simplified model analyses the relationship in the amount of carbon atoms embedded in feedstocks, chemical products, and end-of-life destinations. It assumes the upstream CO_2 and CH_4 emission from fossil extraction and the CH_4 emission from landfill to be net zero. It also assumes that direct and indirect emission (scope 1 and 2) from chemical processing will be net zero. It further assumes that the annual demand is at a steady level, resulting in a steady level of embedded carbon in the stock of chemical products in the economy, and that the recycling of carbon takes place only within the chemical industry's supply chain.
Under these assumptions, carbon balance requires *(A)* + *(B)* + *(C)* = *(D)* = *(E)* + *(F)* + *(G)*, where *(A)* through *(G)* mean the amount of carbon embedded in each. By definition, *(B)* = *(F)*, where recycling loss is included in *(E)* or *(G)*, therefore *(A)* + *(C)* = *(E)* + *(G)*. Further, net zero requires *(C)* = *(G)*; therefore, *(A)* = *(E)*, and therefore, *(D)* = *(E)* + *(F)* + *(G)* = *(C)* + *(E)* + *(F)*.
Thus, the boxes with the same colour on the feedstock (left) and end-of-life (right) sides must have the same carbon amount, in order to become net zero. It is important to note that not all fossil-based feedstock *(A)* needs to be sequestered *(E)*, and not all bio-based and DAC-CCU feedstocks *(C)* needs be incinerated without CCUS *(G)* to be net zero. As indicated by the dotted arrows, some fossil-based feedstock *(A)* can indeed be incinerated without CCUS *(G)*, and some bio-based and DAC-CCU feedstocks *(C)* can be sequestered *(E)*, and still the system can remain net zero, as long as the equations *(A) = (E), (B) = (F), and (C) = (G)* hold true.

Secure access to the strategic resources. To expand the supply or the capability to accommodate the demand for a company or country under scope 3 net zero, a logical consequence is to expand access to *(C)* bio-based and DAC-CCU feedstocks, *(E)* CCS, and *(F)* recyclates. In other words, bio-based and DAC-CCU feedstocks, CCS, and recyclates will likely become bottlenecks in the supply chain (similar to lithium and cobalt in the supply chain for electric vehicles), and securing access to these will provide a strategic business advantage. This limitation comes only from scope 3 category 12 net zero. If we consider other emission, such as emission from other categories of scope 3 and GHGs other than CO_2, a tighter restriction could be placed on the demand that the chemical industry or a chemical company can accommodate.

The carbon balance and the four net zero pathways lead to the same conclusion. For example, the BAU-ME and CE-ME pathways highlight the importance of *(E)* or CCS; the CE-NFAX2 pathway shows the importance of *(C)* or bio-based and DAC-CCU feedstocks and *(F)* or recycling; and the CE-NFAX pathway features the importance of all of *(C)*, *(E)*, and *(F).*

3.6 Specific strategies and recommendations for net zero enabling technologies for the Japanese chemical industry

3.6.1 Recycling

Recycling needs to be maximised in Japan regardless of the pathways. Our model showed that recycling plays a reasonably important role as an alternative feedstock in the CE-NFAX and CE-NFAX2 pathways, but its usage is minimal in the BAU-ME and CE-ME pathways. The waste utilisation by recycling (including plastic waste for pyrolysis) in 2050 in our analysis was 0 EJ for BAU-ME and CE-ME, and 0.08 EJ for CE-NFAX and CE-NFAX2, which corresponds to approximately 4 Mt/y of plastic waste. The amount of chemical recycling will be limited by waste availability, sorting capabilities, and mechanical recycling capabilities. As a result, we estimated that approximately 1 Mt/y of mixed plastic waste will be available for pyrolysis by 2050. However, this level of recycling is not as high as expected. This is because the combination of fossil feedstock and CCS is more economical than recycling, which the ME supply scenarios prioritise, and bio-based feedstock has lower emission than recycling, which the NFAX and NFAX2 supply scenarios prioritise. In other words, recycling fell into the chasm between ME (lowest cost) and NFAX (lowest emission) in our analysis. It is important to reiterate that pathways are not forecasts but are simulations to discuss necessary actions to implement a transition to net zero. In reality, maximising recycling is vital for the Japanese chemical industry, regardless of the pathway. Given Japan's limited access to bio-based and DAC-CCU feedstocks and CCS (discussed later), greater usage of recyclates will help reduce the requirement for these resources under the restriction of scope 3 category 12 net zero, as shown in **Figure 15** and the accompanying text.

Japan has a well-established waste collection system, but most collected plastic waste is incinerated today. The collection of plastic packaging waste in Japan is promoted by the Containers and Packaging Recycling Law, a form of extended producer responsibility (EPR). This places Japan in a favourable position to utilise plastic waste as a feedstock. However, 70% of the discharged plastic waste are incinerated today (with or without energy recovery)[64]. As the entire economy pursues net zero, the practice of using plastic waste as fuel today (such as in power generation and cement production) is likely to be replaced by less emissive sources of energy, which could leave mixed plastic waste nowhere to go. As a result, chemical recycling technology for mixed plastic waste will become essential for GHG emission reduction in addition to plastic pollution prevention.

64 Plastic Waste Management Institute, Material Flow of Plastics for 2021 (2022), https://www.pwmi.or.jp/flow_pdf/flow2021.pdf (cf. 70% = (5.10 + 0.63) / 8.24) See footnote 43 for detail.

Recommendation: Leverage Japan's strengths to develop and scale chemical recycling technologies. Different countries have different strengths and weaknesses. In large economies outside Japan, waste management and environmental protection are often regulated by complex combinations of regulations at multiple government levels. Depending on the country, only a limited number of areas have an EPR for plastics[65], making the collection, sorting, and recycling of plastic waste challenging. In contrast, Japan has a strong waste collection system supported by the EPR, and policies and the public are generally more supportive of industries in a relatively stable political environment. Compared to other G7 countries, it appears less likely in Japan for politics and societal division to drive the agenda for GHG reduction in the chemical industry, making Japan an ideal location to advance technologies such as chemical recycling that are considered necessary[66]. Despite its limited access to renewable energy compared to other countries[67], the chemical industry in Japan does have its own advantages. However, the Japanese chemical industry should not take this support for granted and must not assume silence by the public to mean support. Rather, it needs to be transparent, for example, regarding GHG emission reduction, energy requirements, yield (e.g., for pyrolysis oil and fuel), and handling of waste from the process, including future improvement expectations, despite the inclination to keep everything confidential. The chemical industry in Japan should consider the trust that chemical plants have established so far with the local community and governments to be the industry's strength and should communicate with them as it develops and expands chemical recycling. Although chemical recycling is considered necessary for the recycling of mixed plastic waste, transparent communication with stakeholders remains essential. The same applies to the introduction of the mass balance approach.

3.6.2 Biomass

Biomass plays a significant role in CE-NFAX and CE-NFAX2 pathways as an alternative (non-fossil) feedstock. Biomass absorbs CO_2 as it grows and carries a negative carbon footprint as a feedstock. Thus, even if chemical products made from biomass are incinerated at the end of life, the resulting emission is not considered to cause a net increase in the atmospheric GHG, because the emission is cancelled by absorption during the growth stage of the biomass. If such chemical products are recycled, the biogenic carbon will stay longer in the economy to delay the ultimate end-of-life emission to return from the negative footprint to net zero. Therefore, using biomass as a chemical material could be considered more beneficial than using it as a fuel which results in immediate emission. Biomass consumption in our analysis ranged from 0 EJ (BAU-ME and CE-ME) to 0.08 EJ (CE-NFAX and CE-NFAX2). In our analysis, we assumed 0.5 EJ per year of sustainably sourced biomass is available in Japan for the chemical industry from abandoned farmland and surplus wood and ensured that the biomass use in the model does not exceed this amount to prevent impacts on biodiversity and land use. This amount was estimated by starting with the technical potential availability of biomass in Japan (3.72 EJ per year in 2050)[68], which was scaled down to account for sustainable sourcing[69], and for the fact that biomass would serve the increasing demand from other industries as well, such as power generation, aviation fuel, and construction. The fact that biomass use in CE-NFAX and CE-NFAX2 was well below the cap indicates that there is a fair chance

65 Trellis, Plastics recycling is coming: How companies should prepare (2024), https://trellis.net/article/plastics-recycling-is-coming-how-companies-should-prepare/
66 Beyond Plastics, Chemical Recycling: A Dangerous Deception (2023), https://www.beyondplastics.org/publications/chemical-recycling
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67 Carbon Tracker Initiative, The sky's the limit (2021), https://carbontracker.org/reports/the-skys-the-limit-solar-wind/
68 Wu W. et al., Assessment of bioenergy potential and associated costs in Japan for the 21st century. *Renewable Energy*, **162**:308–321 (2020), https://doi.org/10.1016/j.renene.2020.08.015
69 Wu W. et al., Global advanced bioenergy potential under environmental protection policies and societal transformation measures. *GCB Bioenergy*, **11**:1041–1055 (2019), https://doi.org/10.1111/gcbb.12614

that biomass requirements can be sourced in Japan. The use of more biomass as a feedstock will help reduce the reliance on the more expensive DAC-CCU feedstock, which also carries a negative carbon footprint.

Domestic biomass sources are needed in the portfolio to mitigate risks in imported biomass. Sustainably sourcing a large amount of bio-based feedstock is considered a major challenge[70], because of the rising demand for securing food for the growing global population and the accelerating movement to safeguard biodiversity, among other reasons. Relying on imported biomass for pulp production and biomass power generation is widespread in Japan today, because of its lower cost and easier access to large volumes compared to domestic sources. However, imported biomass may pose significant risks to supply chain management. They may include biodiversity loss, eutrophication due to excessive use of fertilisers, competition with food, groundwater depletion, and false certifications, for which importers could be held responsible up to the very beginning of the supply chain, which is often difficult to trace. These risks are in addition to economic security, currency exchange risks, and possible competition with other demands for biomass, such as sustainable aviation fuel (SAF). Moreover, the chemical industry needs to be aware that aviation fuels, which are joint products of naphtha today in fossil-based petrochemical refineries, could become competitors that seek limited biogenic carbon as the entire economy pursues net zero. Although it is reasonable to import fossil-based feedstock because of the lack of fossil resources in Japan, importing bio-based feedstock should not be an automatic extension of importing fossil-based feedstock, given the rich potential for biomass in Japan.

Recommendation: Invest in and develop domestic sources to balance the imported biomass. As discussed earlier, bio-based feedstock is a key feedstock that determines the supply capability of a company and country under scope 3 net zero. To secure stable access to sustainably sourced biomass, it is recommended that the chemical industry in Japan make long-term investments in securing domestic sources, in addition to sourcing from overseas because the chemical industry needs a stable supply of sustainably sourced bio-based feedstock. Such an investment is needed to unlock the rich but often underexplored domestic potential. A rare opportunity for a stable domestic source for the chemical industry is woody biomass. Woody biomass is abundant in Japan, where nearly two-thirds of the land is covered with forests but is often left unmanaged and grown above the harvesting age. Woody biomass can be locally converted into methanol or ethanol through gasification or fermentation, which can then be transported to chemical complexes scattered across Japan to produce olefins and aromatics (as opposed to transporting biomass over a long distance). This system could turn Japan's smaller and more geographically dispersed chemical complexes into a strength. Meanwhile, biomass also has a potential to produce functional chemicals in a targeted manner through metabolic designs, for example. However, drop-in replacement by bio-based basic chemicals (e.g., olefins and aromatics) will be an important means to achieve the government's roadmap of reaching 2 million tons of bio-based plastics by 2030[71]. To ensure secure access, the chemical industry will specifically need to invest directly or indirectly in forest roads and automation to enhance productivity, with sustainable long-term management of the forest in mind. In addition, the chemical industry could serve as an alternative demand side after the feed-in tariff (FIT) for biomass power generation expires 20 years after the launch. Without such a long-term domestic investment, access to domestic bio-based feedstock will remain uncertain despite the rich potential.

70 Energy Transitions Commission, Bioresources within a Net-Zero Emissions Economy (2021), https://www.energy-transitions.org/publications/bioresources-within-a-net-zero-economy/

71 Ministry of the Environment, Roadmap for Bioplastics Introduction (2021), https://www.env.go.jp/recycle/plastic/bio/roadmap_for_bioplastics_introduction.html

3.6.3 Methanol-based platform and hydrogen

Methanol as a platform chemical. All four pathways featured in this report require the development of methanol-to-olefins (MTO) and methanol-to-aromatics (MTA) production capacities. In fact, methanol has been known to have potential to become a platform chemical, just like naphtha, from which the chemical industry could produce olefins and aromatics[72]. However, the historical abundance of fossil feedstock and the need to valorise by-products from naphtha cracking has prevented methanol from playing a platform role. Compared to naphtha, the use of methanol as a platform could broaden the variety of feedstock ranging from conventional to "blue methanol" and "green methanol" (see next paragraph for detail), and from domestically sourced to globally sourced, while producing conventional olefins and aromatics in a more targeted manner, reducing the need to deal with by-products. The use of the mass balance approach for the input material will also add flexibility. While the MTO process (including methanol-to-propylene) has been in commercial operations for some time, particularly in China, the MTA process will still require investment before it can be proven on a commercial scale. Although we assume that catalytic reformers that currently produce transportation fuel additives and aromatics in refineries are to be phased down, triggered by the shift away from internal combustion engines, if MTA takes time to reach the commercial scale, catalytic reformers could remain.

Green methanol and blue methanol. For hydrogen, depending on the production process, energy, and feedstock, different colours, such as green and blue, have been assigned. Although the definition of each colour for hydrogen is generally agreed upon[73], that for methanol is less established. According to IRENA's proposed classification[74], green methanol refers to the methanol produced from biomass (through syngas), or from green hydrogen (i.e., hydrogen produced from water electrolysis powered by renewable energy sources) and CO_2 captured from renewable sources (e.g., biomass power plant and atmosphere). Thus, even if chemical products derived from green methanol are incinerated at the end of life, the emission is considered net zero because of the earlier absorption of CO_2 from the atmosphere. In contrast, according to IRENA, blue methanol is produced from blue hydrogen (i.e., hydrogen produced from steam methane reforming with CCUS) and renewable or non-renewable CO_2. Thus, if chemical products derived from blue methanol are incinerated at the end of life, the resulting emission may need to be abated by CCUS to become net zero if the carbon is fossil-based. Blue methanol can also be produced from gasification of waste, such as mixed plastic waste that does not fit pyrolysis, and from captured CO_2 flue gas from industries.

Demand for methanol and hydrogen. Sourcing hydrogen will be critical for Japan for securing the supply of methanol for MTO and MTA. Hydrogen demand for methanol production and for energy sources in olefins production (e.g., hydrogen/ammonia-fuelled crackers) will depend on pathways, with very different needs between the CE-ME and CE-NFAX pathways. In the CE-ME pathway that uses blue methanol, the industry will only need approximately 1 Mt per year of hydrogen in 2050. However, in the CE-NFAX or CE-NFAX2 pathway that uses green methanol, a larger amount of green hydrogen of up to 5.5 Mt/y will be needed in 2050.

Japan must pursue both domestic and overseas supply of methanol. While the calculation in our model assumes domestic production of hydrogen and methanol, Japan has the option to import hydrogen, blue methanol, and/or green methanol from regions with lower costs. Therefore, Japan should explore all possible routes to source methanol, ranging from importing blue and green methanol to producing them domestically, to balance the cost, volume access, and supply chain security/stability. Among these options, large-scale domestic methanol production from DAC-CCU feedstock is unlikely given the limited availability of low-cost renewable energy in Japan. Therefore, to expand its trade partners, the chemical industry

72 Olah G. et al., Beyond Oil and Gas: The Methanol Economy, Wiley-VCH (2018)
73 Incer-Valverde J. et al., "Colors" of hydrogen: Definitions and carbon intensity, *Energy Conversion and Management*, **291** (2023) 117294, https://doi.org/10.1016/j.enconman.2023.117294
74 IRENA and Methanol Institute, Innovation Outlook: Renewable Methanol (2021), https://www.irena.org/publications/2021/Jan/Innovation-Outlook-Renewable-Methanol

in Japan needs to strengthen ties with countries and regions with abundant and low-cost access to renewable energy. It must demonstrate its future demand to these countries as a potential for off-take agreements, create commodity markets, and establish a system for stable procurement.

Domestic methanol production. Japan also has opportunities to produce methanol domestically from waste and biomass. Because waste and biomass are usually generated in a decentralised manner across broad areas, methanol should also be produced locally in a decentralised manner and transported to centralised MTO/MTA process sites in complexes rather than transporting bulky biomass and waste to central methanol production sites.

Taking advantage of methanol's flexibility. With no current methanol production capacity in Japan, a reasonable step would be to start by importing conventional or blue methanol to build an MTO/MTA process and supply chain. Because the carbon in blue methanol is fossil-based, CCUS will be required at the end of life to become scope 3 net zero. To eliminate the need for end-of-life CCUS, the next step is to import green methanol, as well as to establish domestic production of green methanol, which could be produced, for example, from domestic biomass mentioned above, to diversify sources to deal with supply chain risks. Such a transition from conventional to blue and green methanol could be made using the mass balance approach to respond to demand in a flexible manner as society transitions to net zero.

Strategic choices. The import of green methanol to domestically produce olefins and aromatics could replace the current imports of crude oil and naphtha. In this approach, the existing network within the chemical complexes in Japan can be utilised to produce derivatives of olefins and aromatics, as well as downstream chemicals. However, it may be more cost-competitive to produce downstream chemicals in countries that produce green methanol. It is up to the strategic decisions of individual companies as to where they produce chemical products made from feedstocks that carry negative carbon footprints (e.g., green methanol), in which the products have two types of added value (i.e., low carbon footprint and functionality of chemical products). Factors such as the location of and relationship with key downstream customers and technological competitiveness, as well as global marketing and organizational management capabilities affect such decisions.

International carbon accounting rules are needed to build a source of new added value. One of the fundamental assumptions here is that the added value of chemical products (methanol or downstream chemicals) that carry a negative carbon footprint is properly distinguished from conventional chemical products and carried across the international supply chain. As CO_2 is absorbed from the atmosphere and embedded into a chemical product in one country, which is converted into a different chemical in another country, and may reach the end-of-life in yet another country to become CO_2 again, the added value of the negative carbon footprint needs to be passed along with the product itself. This "credit" may be defined as a part of implementation of Article 6 of the Paris Agreement, in which corresponding adjustment is taken care of, or an alternative arrangement may be needed.

3.6.4 Ethanol

Ethanol's potential as a platform chemical. Ethanol dehydration to produce ethylene may be a relevant solution if ethanol is produced from sustainably sourced biomass. However, our analysis did not feature it in any of the pathways because it is more expensive or because its emission abatement potential is lower than that of the alternative in our analysis. Converting atmospheric CO_2 into ethanol involves agricultural processes, such as growing and harvesting energy crops, followed by fermentation, which could add costs and pose potential risks to food production, freshwater usage, nitrogen and phosphorus run off from unabsorbed fertiliser, land use change, and biodiversity loss. If ethanol can be sourced in a cost-effective and sustainable manner, it also has the potential to become a platform chemical, similar to methanol.

Bioethanol is available today but limited in volume. The existing supply chain of bioethanol today is a strength of the ethanol-based solution, and the chemical industry's future access to bioethanol may expand if the current use in automotive fuels is replaced by electric vehicles. However, the chemical industry may not have sufficient access because of the demand from other industries. For example, in the airline industry, the International Civil Aviation Organization (ICAO) has developed the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and set future emission goals[75]. Following this, individual airlines have already created a clear future demand signal for SAF. Today, bioethanol is produced in large quantities as a fuel in countries such as the USA and Brazil; therefore, it is relatively easy to import and start using it to produce ethylene. Approximately 100 million kilolitre (28 billion gallons) per year of bioethanol are produced globally today[76]. However, because the chemical industry could be in competition to source bioethanol with SAF and possibly automotive fuels, this situation will make large-scale and stable procurement of bioethanol challenging. For example, today's (pre-pandemic) entire annual demand for global jet fuel is 464 million kilolitre (8 million barrel per day)[77]. As an extreme scenario, if all jet fuels become neat SAF made from bioethanol (through alcohol-to-jet technology with 100% yield), this demand is already far greater than the entire global bioethanol production today. Moreover, the demand for air travel is expected to double by 2040[78], while growth in bioethanol production may be constrained by the need for sustainable agriculture and competition with food production. As mentioned above, the aviation industry has taken a head start in setting regulations and specifications to communicate future demands. As a result, the SAF market is taking off using, for example, used cooking oil, and the supply chains are being established ahead of the chemical industry. For chemical production, the entire global demand for carbon is currently approximately 390 million tons today annually[79], which would correspond to approximately 930 million kilolitre of bioethanol annually (if all carbon were sourced from bioethanol). As such, bioethanol could play a role in the chemical industry; however, its availability and the role could be limited both globally and in Japan.

3.6.5 Carbon capture, utilization and storage (CCUS)

Scale CCS to mitigate production and end-of-life emission. The chemical industry in Japan will need 23–47 Mt of annual CCS capacity in 2050 (**Figure 12**) in the BAU-ME, CE-ME, and CE-NFAX pathways. Although the CE-NFAX2 pathway shows that near net zero is possible without CCS (if significant amount of alternative feedstocks is introduced), CCS will be a cornerstone technology to deal with the emission

75 International Civil Aviation Organization (ICAO), https://www.icao.int/Newsroom/Pages/States-adopts-netzero-2050-aspirational-goal-for-international-flight-operations.aspx
76 Renewable Fuels Association, https://ethanolrfa.org/markets-and-statistics/annual-ethanol-production
77 S&P Global Commodity Insights, https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/oil/051923-global-jet-fuel-recovery-lags-air-travel-as-flights-return-to-pre-pandemic-levels
78 International Air Transport Association (IATA), Global Outlook for Air Transport (2023), https://www.iata.org/en/iata-repository/publications/economic-reports/global-outlook-for-air-transport----june-2023/
79 Meng F. et al., Planet-compatible pathways for transitioning the chemical industry. *Proceedings of the National Academy of Sciences*, **120**, e2218294120 (2023), https://doi.org/10.1073/pnas.2218294120

from retrofitted crackers and end-of-life emission from a large number of incinerators in Japan. The need for CCS comes from other industries (e.g., steel and cement) as well and will require long-term commitments and infrastructure planning. Japan has recently set relevant laws for CCS as a business[80] and is currently exploring storage sites along its coast as well as the export of CO_2. Given the uncertain demand-supply balance in the access to CCS capacity and the long timeline required to build large and economically feasible CCS sites, Japan should continue to explore domestic and overseas options in parallel to ensure access. Specifically, Japan must partner with climate-ambitious countries that have high CCS capabilities to reach this scale. Therefore, ensuring a strong national strategy supported by a coherent coalition of industries will be the key to success, given the need to assemble a coherent package for large investments and long-term off-take agreements.

To deal with end-of-life emission from incinerators. Because certain portion of chemical products is not recycled and reaches an incineration site[81], CCS will be needed to deal with the end-of-life emission at more than 1,000 incinerators[82] located across Japan for the chemical industry to reach scope 3 net zero. This need for CCS is in addition to dealing with the emission from the chemical industry's production processes (e.g., emission from fossil-fed naphtha crackers). Dealing with emission from incinerators will be challenging for individual chemical companies, because of the distance in the supply chain, as well as certain emission that does not originate from chemical products. Therefore, a collaborative approach between the chemical industry and local/national governments will be needed. One approach may be to install post-incinerator CCS through additional contributions through the existing EPR program. Another approach may be to take the CE-NFAX2 pathway (using bio-based feedstock, for example) to avoid the need for CCS. Yet another approach may be to centralise waste processing in chemical complexes and utilise the heat and CO_2 (or syngas) for chemical production.

Opportunities to improve the carbon capture process. Instead of the CCS explained above, emission from production processes and incinerators can be utilised as CCU if hydrogen is available. Such CCU will reduce the need for CCS, since part of *(A)* and *(E)* shown in **Figure 15** will be replaced by *(B)* and *(F)*. The extensive use of CCS and CCU in the future (in Japan and abroad) highlights the growing need to further enhance the carbon capture yield (i.e., reduce uncaptured CO_2) and energy efficiency of the carbon capture process, which will provide opportunities for R&D in advanced absorbents and membranes, and a new business for the chemical industry.

3.7 Significant infrastructure shifts are required to achieve net zero: $61–95 billion in cumulative capital expenditures

To achieve net zero, all existing olefins and aromatics capacity will require retrofit or decommission. Under the BAU-ME pathway, the existing cracker infrastructure will be mostly retrofitted (10.7 Mt output capacity retrofitted with hydrogen/ammonia, recycled pyrolysis oil, and/or CCS), while a portion of the capacity (1.9 Mt) will have to be decommissioned. In contrast, under the CE-ME, CE-NFAX, and CE-NFAX2 pathways, two thirds of the capacity will be retrofitted (7.8 Mt output capacity retrofitted with hydrogen/ammonia, electrification, recycled pyrolysis oil, and/or CCS), while a third of the capacity will have to be decommissioned (4.8 Mt output capacity) by 2050. The production of aromatics from catalytic reforming is assumed to be phased out as fuel production is assumed to decrease and running catalytic reformers to upgrade fuel in refineries becomes unprofitable and/or obsolete.

80 Ministry of Economy, Trade and Industry (METI), https://www.meti.go.jp/press/2023/02/20240213002/20240213002-6.pdf
81 According to the estimate in Japan's National Greenhouse Gas Inventory Report (2023) by the Ministry of the Environment, 14.1 Mt of CO_2 was generated in 2021 from the end-of-life incineration of fossil-based chemical products (e.g., plastics and synthetic textile) with or without energy recovery (excluding emission from RPF, RDF, waste oil, and waste used in blast furnaces and coke ovens). See Tables 7-30 and 7-31 therein. https://www.nies.go.jp/gio/archive/nir/index.html
82 Ministry of the Environment, Nihon No Haikibutsu Shori Reiwa Gannendoban. [Waste Management in Japan for 2019] (2021) https://www.env.go.jp/recycle/waste_tech/ippan/r1/data/disposal.pdf

BAU-ME and CE-ME require smaller capital expenditures than CE-NFAX. The lion's share of the capital expenditures will be for the MTA infrastructure for aromatics production ($27–$32 billion for CE-ME and BAU-ME, or 44% of the entire cumulative CapEx) followed by methanol infrastructure ($17–$20 billion for CE-ME and BAU-ME, or 27%–28%) and cracker retrofits ($13–$15 billion, or 21%). Given Japan's good waste management infrastructure, the investment required in the waste sector will be smaller.

CE-NFAX requires larger capital expenditures, although its carbon negativity could bring in additional revenue. CE-NFAX's cumulative CapEx is of the same order of magnitude as that of BAU-ME and CE-ME. CE-NFAX will additionally provide 18 Mt of negative CO_2 emission, which at a carbon price of 100 $/ton, would provide an annual revenue of $1.8 billion, which could be used to finance a fair share, if not all, of the transition.

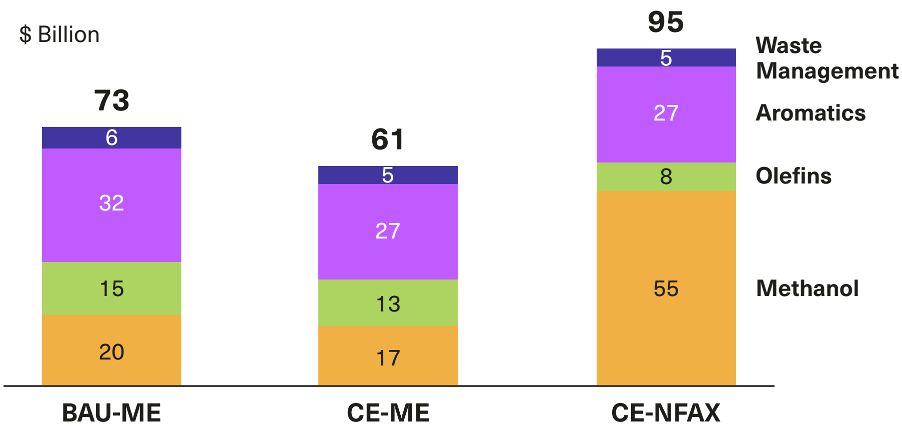


Figure 16: **Cumulative capital expenditures till 2050.**

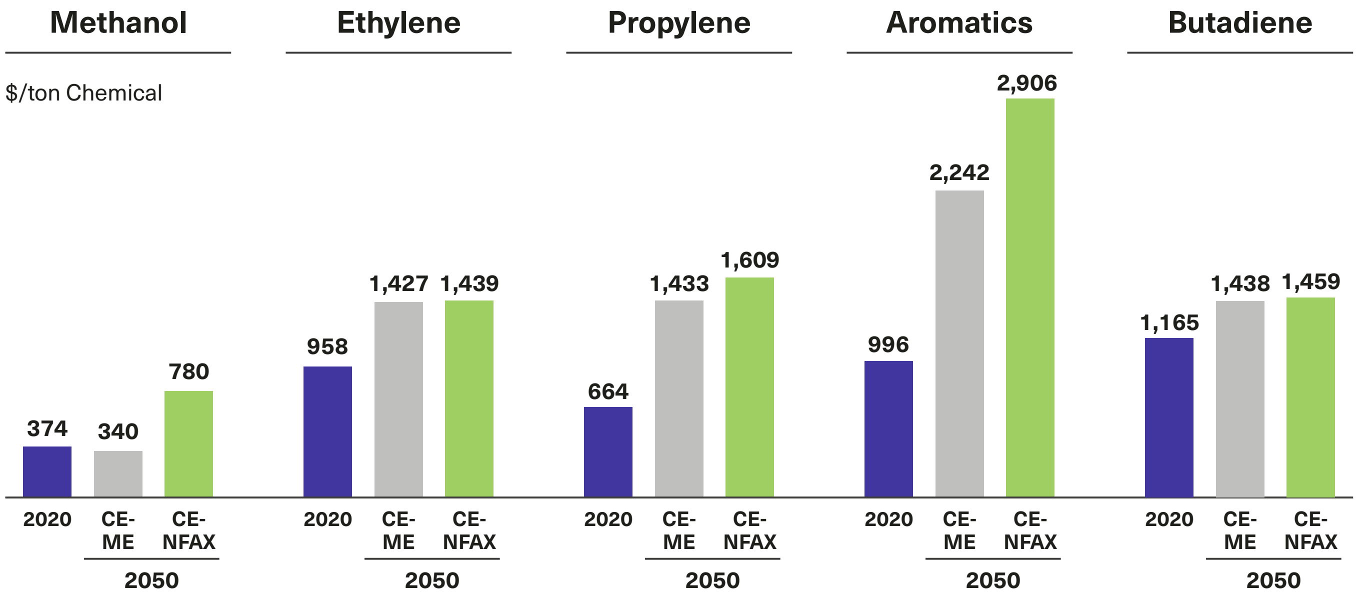


Figure 17: **Unit production cost of chemicals in net zero pathways in 2050.**

3.8 Net zero olefins and aromatics will cost significantly more than today's fossil counterparts, but their impact on the production cost of consumer products is limited

Levelised unit production costs of chemicals will increase under net zero. The unit production cost for chemicals to achieve net zero is expected to rise compared with the current cost of unabated chemicals, except for methanol in the CE-ME pathway based on abated forms of gas reforming. The costs of ethylene and propylene, which are based mostly on abated forms of naphtha and recycled pyrolysis oil steam cracking, are expected to increase between 50% and 140% to $1,400 and $1,600 per ton, respectively, whereas those for aromatics are expected to increase more significantly between 130% and 190% to $2,200 and $2,900 per ton, respectively. Aromatics costs will roughly double in CE-ME and triple in CE-NFAX, because of the higher cost of the MTA process compared to catalytic reforming and the higher methanol cost for CE-NFAX, which uses green methanol made from DAC-CCU and biomass gasification with CCS. Thus, the technology development agenda should include cost reduction for the MTA process and biomass gasification.

Cost impact analysis in the supply chain suggests that impacts on consumers will be limited in 2050. The cost impacts on the supply chain were analysed to estimate the ripple effect caused by the cost increase in olefins and aromatics. That is, if the cost of producing olefins and aromatics doubles, how this will affect the cost of producing everything in the downstream, assuming that all other factors remain the same. This analysis uses government statistics (Japan's input-output table for 2015 and its Leontief inverse matrix[83]) and provides an objective and reproducible estimation of the supply chain impact caused by an upstream cost increase. Our analysis shows that a 100% cost increase (i.e., double cost) of olefins and aromatics in 2050 would result in a 0.7% cost increase in beverage production, a 1.0% cost increase in passenger car production, and a 0.6% cost increase in food products production (**Figure 18**). Note that this increase will occur over the next 30 years (i.e., a 1% increase over 30 years would correspond to an annual increase of 0.03%). Although this cost increase does not include the impacts of cost changes from non-chemical goods and services, it is lower than most people would assume. This is because the inputs (in the form of additional material, labour, and profit margin) by companies in the supply chain between olefins/aromatics and the production of consumer products are much greater than the cost of olefins/aromatics. This uneven impact in the supply chain indicates that immediate customers of the net zero chemicals and those in the middle of the supply chain, facing greater cost increases, would want to reject such cost increases, despite the more limited cost impact and regardless of the need for such chemicals at the downstream end of the supply chain, which faces consumers and NGOs demanding a reduction in the carbon footprint of its products. Therefore, to overcome the uneven impact on the supply chain, collaboration between the both ends of the supply chain (i.e., downstream brand owners and the chemical industry) is needed to communicate the future demand for net zero chemicals to reduce the carbon footprint of consumer-facing products. Note that this analysis assumes that a cost increase is passed along by companies in the supply chain without opportunistic price increases or cost absorption, among other assumptions detailed in the footnote[84].

83 Japan's input-output table for 2015 and its Leontief's inverse matrix can be found in https://www.e-stat.go.jp/stat-search/files?page=1&layout=datalist&toukei=00200603&tstat=000001130583&cycle=0&year=20150&month=0 and https://www.e-stat.go.jp/stat-search/file-download?statInfId=000031839469&fileKind=0

84 Key assumptions in this input-output price model analysis are as follows: (1) The results are based on the industry structure in 2015 in Japan. (2) If an upstream industry (Industry X) increases the price, each of the downstream industries accepts it and reflects it in its price to its downstream industries without changing the production volume and materials. Thus, Industry X's price increase propagates towards end users, while industries in between neither absorb nor inflate the price increase. Industry X's impact will influence downstream industries' costs through raw materials as well as production equipment that uses Industry X's output. (3) The price of the imported products in Industry X also increases by the same rate as the domestic products in Industry X. (4) The price increases shown in this analysis are those in the manufacturing sectors only, and price increases in the distribution and retail sectors are not included. For example, for the passenger automotive supply chain, price increases in basic chemicals could increase the price of showroom furniture and fixtures at car dealers, but these increases are not included. For mathematical handling of the analysis, see pages 27–28 in https://www.pnas.org/doi/suppl/10.1073/pnas.2218294120/suppl_file/pnas.2218294120.sapp.pdf or K. Miyazawa, Sangyo renkan bunseki nyumon, 7th edition, Nikkei Bunko (2022)

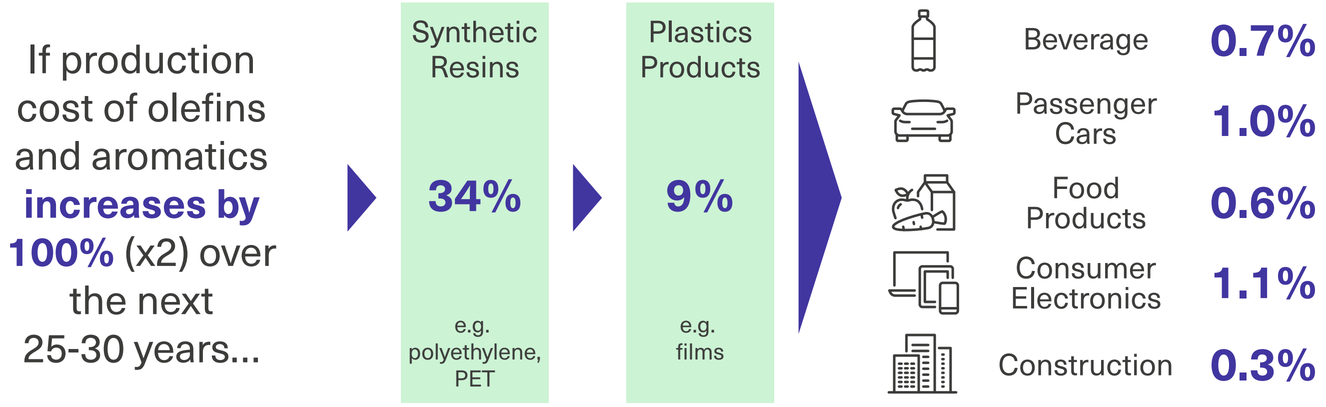


Figure 18: Production cost increase across the supply chain. Upstream cost increases of 100% have a modest impact on the production cost of end user products of approximately 1%.

The greatest challenge is to overcome today's cost gap (not 2050's). Our earlier study on the global chemical industry's pathways to net zero[85] showed that the carbon pricing necessary for net zero chemicals to reach cost parity with conventional unabated fossil-based chemicals would be the highest today and will gradually decrease towards 2050 as the cost of green/blue hydrogen and renewable energy becomes more affordable. In other words, the challenge (i.e., cost gap) is greatest today and will decrease by 2050. Indeed, the limited (<1%) impact on the production cost of consumer products discussed in the previous paragraph concerns about the situation in 2050, when the cost gap will become smaller. Today, in contrast, the cost of net zero chemicals could be greater than that is shown for 2050 in Figure 18, although the diminishing effect of the cost impact along the supply chain still applies (i.e., a 300% cost increase or x4 cost would translate to approximately 3%). Recommendations on the steps to overcome today's cost gap and the risks of taking the wait-and-see approach (i.e., holding the investment in net zero chemicals until the cost gap becomes small enough in the future) will be discussed in detail in Section 4.

85 University of Tokyo and Systemiq, Planet positive chemicals (2022), https://cgc.ifi.u-tokyo.ac.jp/en/research-en/chemistry-industry-en/, https://www.systemiq.earth/systems/circular-materials/planet-positive-chemicals/

Section 4: Recommendation

Section Summary

To reach scope 1, 2, and 3 net zero, the chemical industry in Japan as whole must concurrently pursue alternative feedstocks (e.g., bio-based feedstock) and CCS while maximising recycling. Japan should not rely solely on CCS or alternative feedstocks, because it has not secured sufficient amount for either.

To break out of the infinite "chicken and egg" loop of "high cost" and "low demand". A chemical company must first establish a new process technology to utilise new feedstocks at a smaller pilot scale. As it advances to invest in a full commercial-scale plant, leadership needs to be demonstrated from a long-term perspective because of the huge risk of investment. While such leadership is needed to seize the opportunity to turn the commoditised upstream basic chemical business into differentiated products, it must be founded on the prospect of long-term profitability to enable continued long-term investments. Industry reorganisation in the upstream basic chemical industry to streamline the corporate decision-making process and to provide economies of scope in a broad sense (in addition to economies of scale) could enable and accelerate the pursuit of a net zero transition. Concurrently, collaboration with partners outside the chemical industry is needed, as a chemical company prepares for a commercial-scale plant, to secure (1) key resources (e.g., bio-based feedstock and recyclates) by reaching out to non-traditional partners, (2) future demand by participating in the global First Movers Coalition and additionally establishing similar coalitions in Japan, and (3) supportive regulations.

The future role of the chemical industry could be reshaped by three major trends in sustainability: (1) mitigation of climate change, in which the chemical industry has two roles to play, one to reduce its own and supply chain emission, and the other to support the emission reduction of other industries; (2) adaptation to climate change, in which the chemical industry could support agriculture, access to water, and disaster control, among others; and (3) prevention of plastic pollution, which could call for simpler formulations and more transparency in ingredients to enhance recycling. Furthermore, as the traditional customer base of the chemical industry (e.g., automotive and electronics industries) seeks to add more value through software than hardware, in which chemical products are often used, the chemical industry may need to shift its focus to a lower carbon footprint and better recyclability in most hardware products, and away from pursuing higher chemical performance at the expense of sustainability. As a result, a major shift in the value proposition for both the upstream (basic chemicals) and downstream (functional chemicals) chemical industry towards sustainability is expected.

This section discusses the higher-level recommendations and actions needed to transition to net zero, whereas the second half of Section 3 discusses specific recommendations for each of the key resources (e.g., recyclate and bio-based feedstock). Specifically, this section discusses insights into competitive strategies and necessary actions by combining findings from the quantitative pathways and the existing knowledge of the Japanese chemical industry.

4.1 Net zero vision for the chemical industry in Japan as a whole

Conceptual map of the four net zero pathways. The four pathways discussed in the previous section are plotted on a conceptual map (**Figure 19**) to discuss the direction of the chemical industry in Japan as a whole. The X and Y-axes represent the extent to which the GHG reduction in each pathway relies on CCS and alternative feedstocks (such as bio-based feedstock and recyclates), respectively. Because the BAU-ME and CE-ME pathways mainly use fossil feedstock and CCS, they are plotted on the X-axis, whereas the CE-NFAX2 pathway is plotted on the Y-axis because it relies entirely on alternative feedstocks.

The chemical industry in Japan as a whole must pursue both alternative feedstocks and CCS concurrently, while maximising recycling. Because the chemical industry in Japan has secured neither alternative feedstocks nor CCS, relying on only one of them, as suggested by the BAU-ME, CE-ME, and CE-NFAX2 pathways, would be a risky strategy. Instead, it must pursue both CCS and alternative feedstocks concurrently. As a result of pursuing both, the chemical industry in Japan as a whole will land somewhere in the green net zero triangle as shown in **Figure 19**, in which the use of alternative feedstocks, fossil feedstock, and CCS are combined. The exact combination the chemical industry in Japan should target remains uncertain, because the cost and availability of alternative feedstocks and CCS are too uncertain for such a precise analysis. However, because the main goal of this study was to identify key actions for the Japanese chemical industry, we consider this conclusion sufficient. While pursuing both alternative feedstocks and CCS concurrently, the chemical industry in Japan must specifically maximise recycling, which will reduce the burden of securing a large amount of bio-based feedstock, DAC-CCU, and CCS (under the constraint of scope 3 net zero; see **Figure 15** and the accompanying text for details), as well as contribute to minimising plastic pollution.

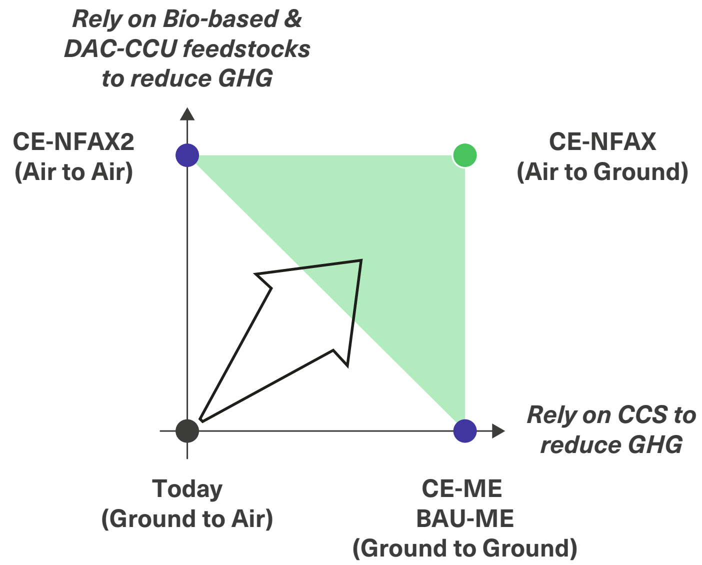


Figure 19: Conceptual map of the direction of GHG reduction. Repeated from **Figure 4**. The chemical industry in Japan as a whole should concurrently pursue both alternative feedstocks in the Y-axis (such as bio-based feedstock) and CCS in the X-axis, so that it lands in the green triangle, which indicates net zero or beyond net zero.

4.2 Net zero vision for individual chemical companies and the supply chain (to break out of the chicken and egg loop)

Chemical industry has not reached a tipping point. As discussed in Section 1, the chemical industry has not reached a tipping point (see **Figure 5**), either in Japan or globally, at which low GHG solutions are accepted in the mass market to overtake conventional solutions. This means that any country or company still has the opportunity to become a dominant player in the chemical industry's transition to net zero. This is unlike the solar panel, windmill, electric vehicle, and lithium-ion battery markets, where dominant players have emerged or are beginning to emerge.

"Chicken and egg" infinite loop of high cost and low demand. The high production cost of net zero chemicals is creating a "chicken and egg" situation, which is a major bottleneck that is slowing down the transition to net zero in the chemical industry and possibly in other industries as well. As shown in Section 3, the production cost of net zero chemicals could nearly double in 2050, and it may be even higher today compared to today's unabated fossil-based products. As a result, this high cost drives low demand, which keeps the production volume low, which, in turn, keeps the production cost high because of the lack of economies of scale (see **Figure 20**). In fact, Japanese and overseas chemical companies have not been able to exit this infinite loop, which may be one reason why the chemical industry lies at the bottom of the rankings in transition, as shown in **Figure 5**.

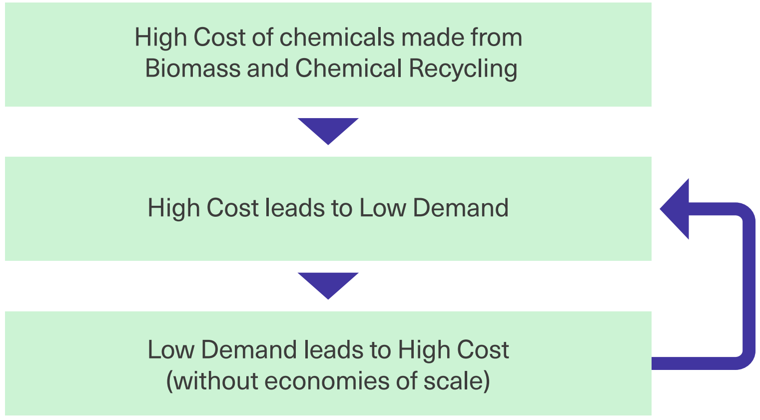


Figure 20: Chicken and egg loop of high cost and low demand is slowing down the transition to net zero in the chemical industry, and possibly in other industries as well.

Steps to break out of the "chicken and egg" loop. In order to get out of the bottleneck of the "chicken and egg" infinite loop, the following steps need to be taken. Step 1 is to be followed by Step 2A and the three elements in Step 2B. Steps 2A and 2B are to be taken concurrently (**Figure 21**).

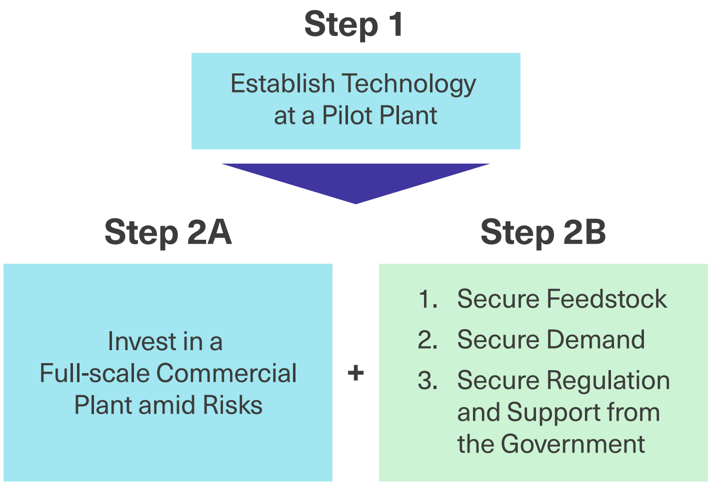


Figure 21: Steps that need to be taken to get out of the bottleneck of the chicken and egg loop. Actions in the blue boxes are to be taken by chemical companies, and those in the green box are to be taken by chemical companies in collaboration with external partners.

Step 1:

Step 1 involves establishing a new process technology to utilise alternative feedstocks on a smaller pilot scale, as in any new production processes. This is the responsibility of the chemical industry. Many Japanese and global chemical companies are still at this stage of the production of net zero chemicals.

Step 2A:

Step 2A, for which the chemical industry is also responsible, involves investing in a full-scale commercial plant to seek economies of scale after the technology is established on a smaller scale. Because of the huge investment and accompanying risks, this is the stage at which leadership needs to be demonstrated from a long-term perspective by contenders to lead the future Japanese chemical industry.

Why leadership matters in the transition to net zero. Leading companies will enjoy the opportunity ahead of the competition to establish scale (i.e., low cost), learning-curve, and brand, as well as pre-empt access to key downstream markets that are more forgiving of the higher costs of net zero chemicals and access to the limited key feedstocks such as recyclates and bio-based feedstock. They will also have the opportunity to face issues first, solve them, and possibly patent the solutions first. Specifically, the use of alternative feedstocks to produce basic chemicals presents a golden opportunity for the upstream basic chemical business to transition from commodities to differentiated products. Because Japanese chemical companies and the government will sooner or later be forced to transition to net zero through pressure from overseas, leaders should strive to establish their position in their transition to net zero ahead of the pack. Furthermore, given the unpredictable nature of global warming and the increasing frequency of extreme weather events, the urgency for global GHG reduction may unexpectedly accelerate. Should this happen, it will be the leading companies with established capacities that will be relied upon for their products and expertise. Only those companies that are willing to undertake continued long-term investments (in establishing the market, supply chain, technology, and production facilities to make sustainability a core business) are entitled to become leaders in the next stage. However, it is also important to note that continued investments over the long term would be unsustainable unless they were accompanied by and founded on the prospect of long-term profitability from the current business.

Risks for followers. In contrast, "a second-mover" strategy is risky, as it allows the leader to run unchallenged and dominate the market. In addition, waiting for the introduction of carbon pricing is ill-advised because carbon pricing acts as a tailwind for all chemical companies. In other words, it does not lead to differentiation, nor does it provide a competitive advantage to any chemical company. COP28 in December 2023 ended with a historic agreement to "transition away from fossil fuels." However, it only represents the least possible agreement among parties, similar to the greatest common denominator, in the consensus-based agreements of UN conferences. Similarly, the government, being attentive to a broad electorate, generally finds it difficult to implement regulations that are too progressive. As such, companies that wait for COP agreements or government support will not lead but instead lag.

Industry reorganisation could accelerate the pursuit of the net zero transition. Investment in a large-scale commercial plant, as required in Step 2A, is never a simple decision; however, there is a factor in Japan that makes the decision more challenging. Currently, most major Japanese chemical companies adopt the corporate structure of a vertically integrated conglomerate, in which upstream basic chemicals divisions and downstream functional chemicals divisions coexist. Moreover, most of these companies have a corporate strategy to focus their resources for growth (e.g., capital expenditures) in the latter divisions. Because Japanese chemical companies are still in Step 1 today, they are not pressured to make the decision for a commercial plant required in Step 2A yet. However, once they are ready to proceed to Step 2A, Japanese chemical companies could find themselves in an impasse, as experienced by conglomerates in other industries. For reference, in other industries in Japan in the past, there were numerous cases in which Japanese conglomerates, despite their technological advantage, fell behind competitors in other countries because of slow or non-decision-making under the conglomerate corporate structure, among other reasons (see **BOX 1**). This impasse could be avoided by industry reorganisation which breaks apart vertically integrated companies and generates horizontally consolidated companies that focus on upstream basic chemicals. This will enable management to make huge but necessary investment decisions in a timely manner. In addition, waiting for the withdrawal of other companies to reap survivor benefits—a situation that could be referred to as a dangerous "chicken game" in game theory—will disappear with such a reorganisation, resulting in accelerated actions by the industry as a whole. Consolidation in the upstream could trigger reorganisation in the downstream (derivatives and functional chemicals) as well.

BOX 1: Supply-side challenges in Japan in the past during business expansion

There are numerous examples in which Japanese companies once dominated certain global markets in business and technology but later lagged behind and lost against competitors in South Korea, Taiwan, and mainland China, when large-scale investments for production expansion (and cost reduction) were called for and when technology generation changed. Examples include semiconductor memory chips in the 1990s and liquid crystal display (LCD) panels in the 2000s.

Many Japanese memory chip and LCD panel manufacturers were slower to make large-scale investment decisions. Among other reasons, this was because these businesses were often just one of many business divisions under a vertically integrated or conglomerate-style corporate structure and they were faced with decisions on the priorities between business divisions. In other words, they were unable to justify huge investments in just one of the divisions in a timely manner[86]. They had to make strategic and political decisions at the corporate level, in addition to the judgement on the feasibility of the investment itself, to enable such an investment.

One lesson is that companies in Japan need a corporate structure that enables the management to make large and strategic decisions in a timely manner.

Reorganisation could provide economies of scope in a broad sense (in addition to economies of scale) that are needed to deal with an uncertain future. The chemical industry in Japan needs to prepare for an uncertain future, in which there are multiple approaches to net zero with opposite directions (e.g., use of bio-based feedstock vs. fossil feedstock with CCS, and cracker retrofits vs. non-cracker processes using methanol or bioethanol). A reasonable approach to preparing for an uncertain future is to diversify the investment portfolio from a broader perspective. Consolidated upstream-specialised companies would not only have scale, but also an expanded scope that would enable diversification that spans across several cracker units—an approach that an owner of one or two units could not take. A diversified portfolio in the basic chemical industry would mean, for example, introducing a non-cracker process, such as MTO or bioethanol, in a few of the complexes, whereas for the remaining complexes, decisions could be made among the options of replacing or retrofitting existing crackers (e.g., replacing with a larger cracker with CCS, retrofitting an existing cracker with CCS, replacing with a non-naphtha process, or decommissioning). The exact decision for the remaining crackers could be postponed until after observing future technological progress in abated crackers and non-naphtha processes, as well as future demand trends for net zero chemicals. In contrast, an owner of one or two cracker units will be compelled to take an all-or-nothing approach for its sole unit, which is a risky approach prone to indecision.

86 K. Toyama, After all, what did management get wrong? *Toyo Keizai*, May 27, 2017.
M. Taguchi, Learning from past failures, earlier spin-off and consolidation of power semiconductors are needed, *Nikkei XTech*, Nov 29, 2021.
Y. Nakata, Japanese Competitiveness in Liquid Crystal Display Industry, Research Institute of Economy, Trade and Industry, Discussion paper (Apr 2007)

Step 2B:

Step 2B is for chemical companies, in collaboration with external partners, to secure (1) feedstock, (2) demand, and (3) supporting policies, while a commercial-scale investment is contemplated in Step 2A.

Step 2B-1: Securing Key Resources

Need for securing recyclates, bio-based/DAC-CCU feedstocks, and CCS. Chemical companies need to secure alternative feedstocks and access to CSS by working with or investing in partners in the upstream and downstream of the supply chain (**Figure 22**). As discussed in Section 3, scope 3 net zero brings about a theoretical upper limit on the amount of chemical products that a chemical company can supply (see **Figure 15**). That is, access to alternative feedstocks (e.g., recyclates and bio-based/DAC-CCU feedstocks) and CSS determines the supply limit of a chemical company. This implies that those who control access to recyclates, bio-based/DAC-CCU feedstocks, and CCS will gain a strategically advantageous position to control the supply of chemical products, and subsequently end-user products in which chemical products are used, under scope 3 net zero. This situation is similar to that of lithium and cobalt in the supply chain of electric vehicles. That is, the supply of raw materials (e.g., lithium and cobalt) far up in the supply chain could determine the supply of finished goods (electric vehicles) all the way down in the supply chain, and as a result, exerts strategic influence across the entire supply chain.

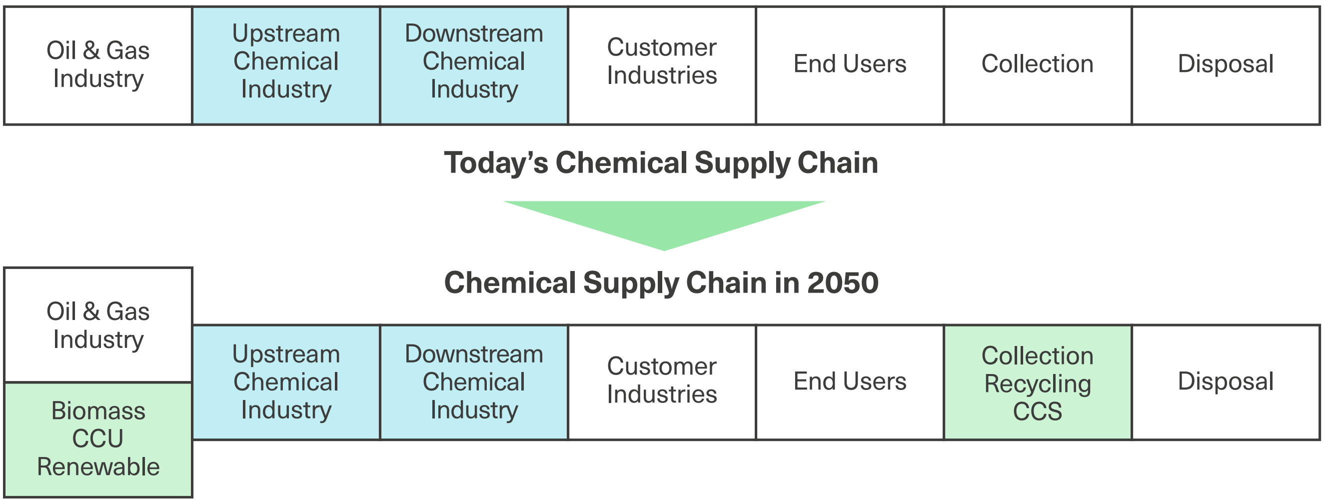


Figure 22: Today and future chemical supply chain. New partners in the supply chain are shown in green, who could place an upper limit in the supply of chemical products under scope 3 net zero.

Chemical companies need to reach out for new resources, or someone else will. Chemical companies in Japan have traditionally relied on other parties to secure commodity fossil feedstock and have focused on processing feedstock. To overcome the potential supply limit of scope 3 net zero, chemical companies need to depart from this traditional practice and start securing key feedstocks on their own. Because bio-based feedstock and recyclates will not be commodities, at least in the initial stage, they need to find new sources for feedstock that are not in today's chemical supply chain. This is a time-consuming and painstaking process that they are not used to. Today, certain global players and Japanese trading companies with foresight are aggressive in expanding their access to new feedstocks. In addition, in the power generation sector in Japan, trading companies are investing heavily in renewable energy, to the extent that they overshadow existing regional electric power companies, indicating that defining the scope of the existing business too narrowly at the time of transformative changes in industry could result in missing growth opportunities[87]. The competition for access to used cooking oil has already become fierce. If chemical companies continue to rely on someone else for feedstock, they will remain dependent on, and their supply volume will ultimately be controlled by those who secure the key feedstocks first. Consequently, they could miss the rare opportunity to add value and differentiate themselves in the basic chemicals business. Musical chair games have quietly begun, targeting key feedstocks for the chemical industry.

Seize the opportunity for basic chemicals to become differentiated products. As discussed thus far, there are two approaches by which the chemical industry can reach net zero. One is to continue using fossil feedstock and rely on CCS to deal with CO_2 at the end of life, and the other is to use alternative feedstocks. Exporting chemical products made using the former approach (fossil feedstock and CCS) requires destination countries to conduct CCS to deal with end-of-life CO_2. In contrast, exporting chemicals made with the latter feedstock (bio-based or DAC-CCU) will enable exporters to claim added value by reducing the need for CCS in destination countries. As more downstream customers become conscious of the carbon footprint of their sourced products, and as more countries become conscious of meeting their national emission targets (i.e., NDC, or nationally determined contribution under the UNFCCC), chemical products made with the latter could thrive as chemicals that enable low carbon footprint products. These chemicals could also compensate for the shrinking domestic market in Japan. Conversely, relying on fossil feedstock with CCS will not make Japanese chemical products more competitive in the export market (particularly against countries with lower-cost access to fossil feedstock and CCS[88] and/or with greater production capacity). In addition, the production cost of fossil-based chemicals could increase in the near future due to carbon pricing and/or boarder adjustment mechanisms upon exportation. Overall, continuing to rely on fossil feedstock with CCS could result in missed opportunities for basic chemicals to become differentiated products.

Step 2B-2: Securing Demand

Participate in the First Movers Coalition (FMC). The FMC will be a critical step in securing future demand at the global level, and Japanese chemical companies should participate once the chemical FMC is established. The FMC was initiated by the World Economic Forum and the US government for industries such as steel and cement in 2021 at the time of COP26 in Glasgow[89]. In the FMC, progressive downstream customers commit to purchasing a certain amount of low-GHG products at a specified future time. It is a scheme for downstream companies to secure access to low-GHG products, which will reduce their scope 3 emission, and for upstream companies to enable risky investments that would otherwise be difficult without such demand signals. Exchanging future demand and supply signals

87 Levitt T., Marketing Myopia, *Harvard Business Review* (July-August 2004), https://hbr.org/2004/07/marketing-myopia
88 Compare, for example, with ethane (gas) steam crackers fuelled by blue hydrogen, in which CCS to capture CO_2 from steam methane reforming is considered less expensive than from combustion, due to higher CO_2 concentration.
89 World Economic Forum, First Movers Coalition, https://initiatives.weforum.org/first-movers-coalition/home

between the upstream and downstream ends of the supply chain will help overcome the chicken and egg loop, by taking advantage of the uneven impact of the cost increase in the supply chain, as discussed in Section 3.

Additionally, establish a first movers coalition in Japan. To supplement the global FMC, it is equally important to establish a first movers coalition in Japan within the domestic supply chain. One reason is that not all Japanese chemical and downstream companies have enough overseas businesses to participate in the global FMC, but they also need a coalition to exchange future demand and supply signals. Another reason is that the global "one-size-fits-all" approach may not always be effective because of particularities in the supply chains. For example, the relationship between buyers and suppliers, exact expectations from the "commitment" by the downstream, and product specifications that the parties are comfortable with may vary in different countries and different supply chains. Yet another reason is that Japan, or any other country for that matter, should not rely on other countries for market creation of net zero chemical products, because market development would be less effective, and a country could lose competitive advantage. There are a number of examples in which Japanese companies once took an initial technological lead in developing "green" products, but they lagged later and lost in business expansion (see **BOX 2**). Conversely, despite an initial delay, China successfully nurtured its solar panel industry, which almost the entire world now depends on. A key lesson is that the process of market creation of "green" products, which tend to be more expensive than conventional products in the initial stage, can nurture or kill a fledgling industry, and this must be carefully driven between manufacturers and brand owners under adequate support from the government. Specifically, reaching economies of scale to produce "green" products at a low cost cannot be achieved in one step. Demand and supply can only grow stepwise, similar to the two wheels on either side of a car, as one cannot grow too far ahead of the other. Such interactions would be faster and more effective under domestic coalitions. The chemical industry in Japan should leverage the strength of domestic close-knit supply chains in a large country economy, in addition to participating in the global FMC to drive the global transition.

Build partnership to experience growth together. As a practical step, chemical companies in the upstream and brand owners in the downstream should identify specific end-user products and markets together. For example, end-user products, in which chemical products represent a large portion of brand owners' scope 3 emission but a small portion of the cost, will be more capable of bearing the initial high cost of net zero chemicals. They must collaborate closely to cycle through the loops of market expansion, production expansion, and cost reduction. At the same time, the government needs to adequately support the leaders who have taken on huge risks through such measures as government purchases, regulations, and subsidies, while promoting competition to nurture a "green" industry. At this stage, close coordination and competition within the supply chain, in sync with government actions will be tested. Neither insufficient support, insufficient competition, nor subsidies bubble would nurture the "green" industry. Standardising the definition (as well as the measurement, reporting, and verification) of such "green" products will also be essential infrastructure, but this alone will be insufficient, given the past lessons in **BOX 2**. Ultimately, the chemical industry will enter into competition to determine which companies or countries will first achieve economies of scale for net zero chemicals. The initial winners will enjoy lower production costs to expand demand and production to further lower the cost, leaving behind late entrants, while benefiting society as a whole by reducing the societal cost of the transition to net zero.

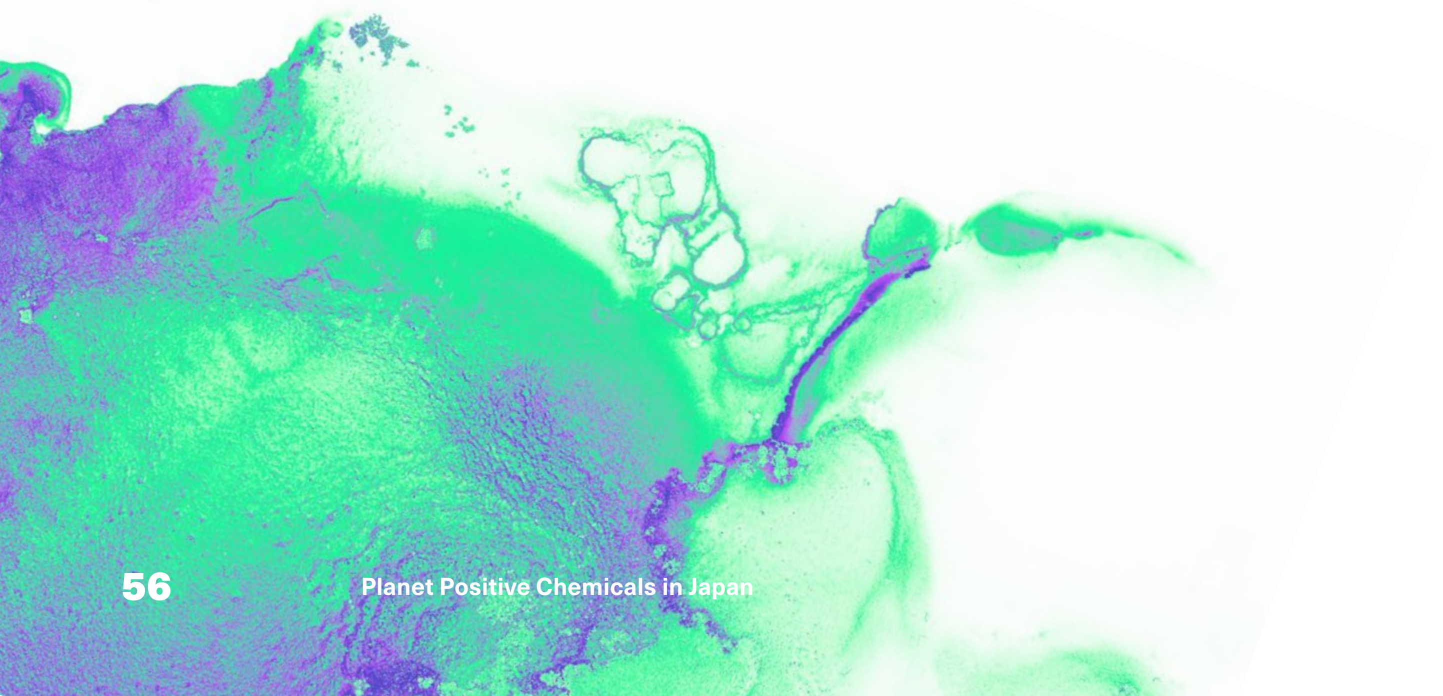
BOX 2: Demand-side and Supply-side challenges in the past during the market expansion of "green" products

There are numerous examples in which companies in Japan were initially leading the market in business and technology for "green" products but lagged in commercialisation. Whereas **BOX 1** discusses large scale investments on the supply side, this box discusses the demand side and supply side synchronisation of fledgling "green" products. Examples include solar panels, light-emitting diode (LED) lighting, and lithium-ion batteries, which were more expensive than conventional products at first and/or require the demand side to make an initial investment, which conventional products do not need to reap the benefit later.

Japanese companies lost market share in these products despite the initial leadership in technology (for which some Japanese scientists won the Nobel Prize) and commercialisation. Among other reasons, there was insufficient demand-supply coordination and policy support to jump-start demand, to break out of the chicken-and-egg cycle of high cost and low demand, and to drive market growth. For example, China supported domestic demand and production, and encouraged competition among suppliers, all of which fuelled market growth, expansion of production capacity, and cost reduction of solar panels[90], and possibly LED lighting and lithium-ion batteries as well. In contrast, Japanese manufacturers' global solar panel market share was 55% in 2002[91], but by the time the installation of solar panels in Japan skyrocketed after the introduction of feed-in tariff (FIT) in 2012, they had already lost competitiveness and market share, and later withdrew from the market. The installation of offshore windmills has accelerated since the government designated several "promotion zones" with favourable wind conditions in 2019, by which time Japanese windmill manufacturers have lost competitiveness and exited the market.

These examples demonstrate why a country should not rely on other countries for market creation, which is indeed the industry creation of fledgling green products. Close coordination and competition in the supply chain, in sync with government actions, are required to nurture demand and supply.

90 Gregory F. Nemet, How Solar Energy Became Cheap, Routledge (2019)
91 Ibid.



Step 2B-3: Securing supportive regulations

Regulations and subsidies will be needed to support first movers and to create new and sustainable industries. Once a company has started preparing to invest in a commercial scale plant, it will start demanding greater support from the government in terms of regulations, subsidies, and government purchases. Regulations could include higher minimum bio-based content and recyclate content, as well as reducing target carbon footprint in chemical products. Standardising the definition for these (including the methods for measurement, reporting, and verification) will also be important. Regulations and subsidies must be foreseeable in order to provide legal certainty and enable leaders to make long-term commitments. Subsidies for operating expenses, in addition to capital expenditures, will be needed. A clear intention to nurture new industries is imperative under these policies, taking into account the lessons in **BOX 2**. Clearly, the government could not enforce a technology on the public before it becomes commercially available. Meanwhile, as discussed in Section 3, carbon pricing will be essential to bridge the cost gap between conventional products and low GHG products, but it will not be a panacea because the cost gap could vary widely across different chemical products.

4.3 New role of the chemical industry with planet positive chemicals: Business of the future

Three major trends in sustainability could reshape the future role of the chemical industry. Each will urge the chemical industry to change its current practices but will also present new opportunities for added value, which first movers are more likely to capture. These are (1) mitigation of climate change (i.e., GHG reduction), (2) adaptation to climate change (i.e., dealing with increased temperature, etc.), and (3) prevention of plastic pollution. The following paragraphs discuss how they will affect the chemical industry and its value propositions.

(1) Mitigation of climate change: Two roles for the chemical industry to play - reduce its own and supply chain emission, and support the emission reduction of other industries. The mitigation of climate change means reducing GHG emission. Broadly, the chemical industry will be required to play two types of roles. The first type utilises alternative resources and processes (recyclates, bio-based, CCU, CCS, and zero emission energy) to produce the same chemical products the industry is making today and reduces its own emission to net zero, including those from its supply chain. The second type involves chemical products or processes that help reduce GHG emission from other sectors, such as chemical products used for lightweighting and heat insulation, as well as materials for functional products such as lithium-ion batteries and perovskite solar cells. This report focuses on the approaches and impacts of the first type, whereas the second type is beyond the scope of this study. However, one example that spans both types and is expected to grow rapidly is carbon capture technologies with improved yield and energy efficiency, given the growing demand for CCUS, as indicated by the International Energy Agency (IEA)[92] to reach 6 Gt/year in 2050.

(2) Adaptation to climate change: Support agriculture, access to water, and disaster control, among others. Adaptation to climate change refers to adjusting to and living with the effects of climate change by avoiding or alleviating harm. Although the speed at which global GHG emission reduction will actually take place in the future is uncertain, the rise in temperature from the pre-industrial period caused by human activities is considered "unequivocal"[93], which makes the need for the chemical industry to

92 IEA, Net Zero Roadmap: A Global Pathway to Keep the 1.5C Goal in Reach (2023 Update) page 102, https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach
93 IPCC 6th Assessment Report (Working Group 1), Summary for Policymakers (2021), https://www.ipcc.ch/report/ar6/wg1/chapter/summary-for-policymakers/

play a role in adaptation more certain. Examples of how chemical products can play a greater role in adaptation include improved access to water using desalination or purification membranes and wildfire control using improved and non-toxic fire retardants.

(3) Prevention of plastic pollution: Need for more transparency in ingredients and simpler formulations for enhanced recycling. Although negotiations at the UN towards an international legally binding instrument have not been concluded, discussions thus far indicate that additives to plastics will likely be more tightly regulated and required to disclose for better transparency. This trend could reduce the value of new and proprietary ingredients and formulations. In the past, the downstream functional chemicals industry generally pursued higher performance of chemical products by developing proprietary ingredients and by making formulations and compositions more complex, generally at the expense of making recycling more difficult. This practice is likely to face headwinds.

New role of the chemical industry. Once a UN agreement to prevent plastic pollution is reached, a simpler formulation or composition that is easier to recycle will likely be preferred, and a new recycling technology that can recycle previously unrecyclable products will be in higher demand. In contrast, the value of proprietary additives will decline, and unrecyclable products will become more difficult to sell. This trend, when combined with that driven by climate change mitigation, could develop into a fundamental shift in the value proposition and sources of competitive advantage of the upstream and downstream chemical industries as shown in **Table 1**. In addition, another important transformation is taking place in the chemical industry's traditional customer industries, such as automotive and electronics. Chemical products have been used both as ingredients for, and in the production process of these industries' hardware products, thereby adding functionality and value to these hardware products. However, more of the key functionalities of these products are defined by software today, where the main added value is pursued through software. This could mean that there will be less added value from hardware products, and chemical products used in such hardware products. Given this trend, the chemical industry may need to shift its focus towards a lower carbon footprint and better recyclability in most hardware products, and away from pursuing higher performance at the expense of sustainability, except where the highest performance is sought. A major shift in the value proposition for both upstream (basic chemicals) and downstream (functional chemicals) chemical industries towards sustainability may be looming ahead.

		Upstream Chemical Industry (Basic Chemicals)	Downstream Chemical Industry (Functional Chemicals)
Value Proposition	**Conventional**	• Low cost • Stable supply	• High performance
	Newly Added	• Low carbon footprint	• Low carbon footprint (using bio-based or recycled materials) • Transparency of ingredients used in products • Recyclability of products
Sources of Competitive Advantage	**Conventional**	• Large production scale • Access to low-cost feedstock • Stable operations	• High performance, using complex mixture of many ingredients • Development of new proprietary functional additives
	Newly Added	• Access to new feedstocks (Bio-based, Recyclate, DAC-CCU, etc.). • Establish new process technology to use new feedstocks • Speed in achieving economies of scale (i.e., low cost)	• Products that are easy to recycle • Possession of proprietary recycling technology • Exhibiting high functionality and performance with a simpler formulation • Transparency in the composition of products • Creating a closed loop with customers and their customers through recycling • Securing access to raw material with a low carbon footprint

Table 1: Shift in the value proposition and sources of competitive advantage under the new role of the chemical industry.

Conclusion

The chemical industry in Japan stands at a crossroads, facing a shrinking domestic population, shifting needs from customer industries, and sustainability challenges, including GHG emission reduction. This report presented pathways to net zero, insights and strategies for the transition that leverage Japan's strengths, and a future role for the industry. Individual chemical companies must develop their own pathways by taking advantage of globally available solutions (e.g., technologies for renewable energy and the First Movers Coalition), Japan's strengths, and their own strengths to differentiate themselves from others. Learning from lessons from past transitions in other industries is also essential to prepare for a major transformation to net zero. The time has come for individual companies to act on their visions of the industry's future role, value proposition, and industrial structure. We hope that this report will catalyse such transformative actions.

Appendix A: Conceptual overview of the demand-supply model

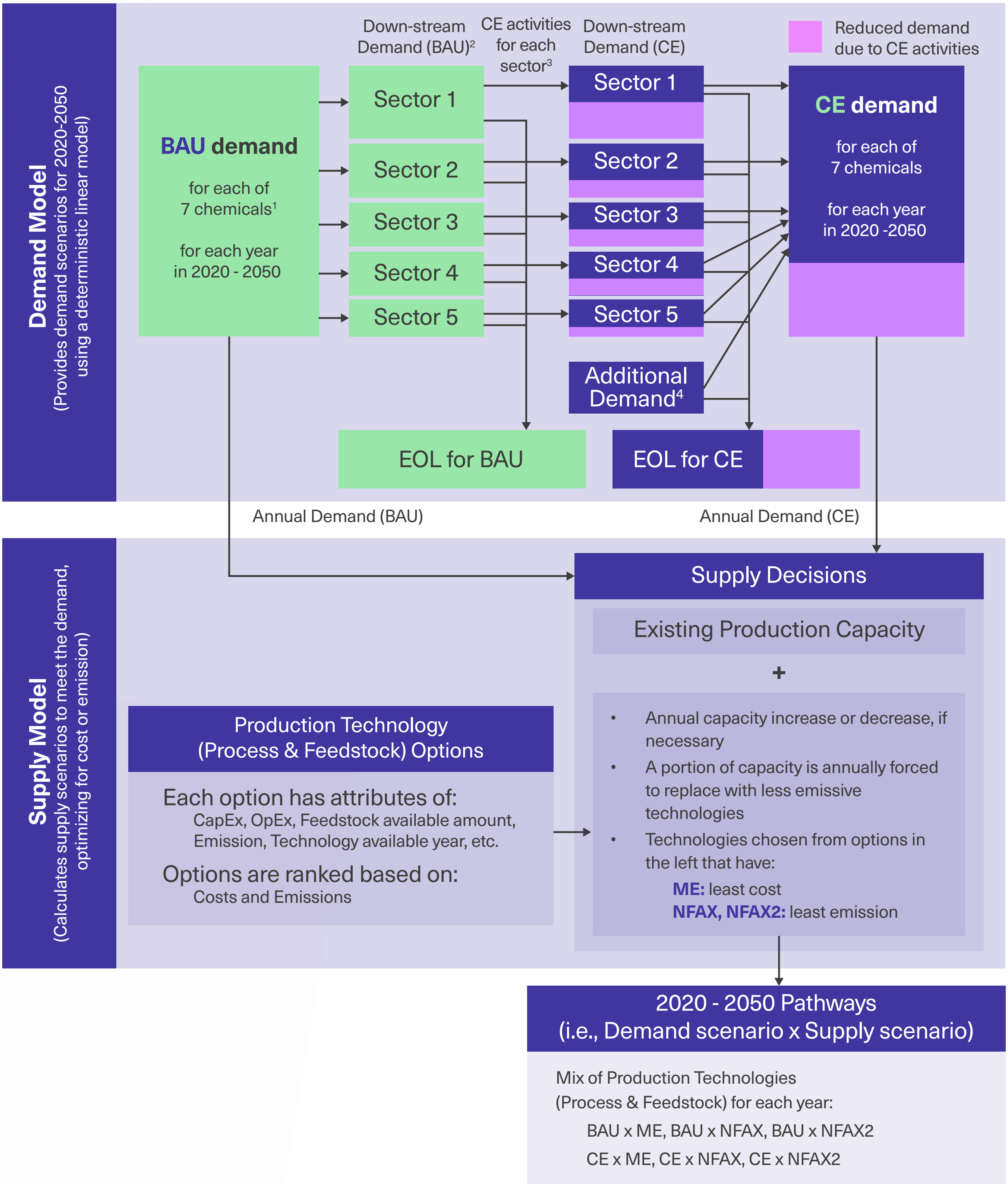


Figure 23: Conceptual overview of the demand-supply model. Arrows represent flow of information for model calculation; EOL stands for end of life; and CE stands for circular economy. (1) The 7 chemicals are ethylene, propylene, butadiene, benzene, toluene, xylenes, and methanol. (2) Downstream sectors are packaging and household goods, transportation, building and construction, apparel, and other sectors. (3) CE activities include (i) elimination, (ii) reuse, (iii) substitution, and (iv) recycling. (4) Additional demand includes demand from products used in energy transition, including wind, solar, and batteries.

Appendix B: Key process technologies and feedstocks considered in the supply model

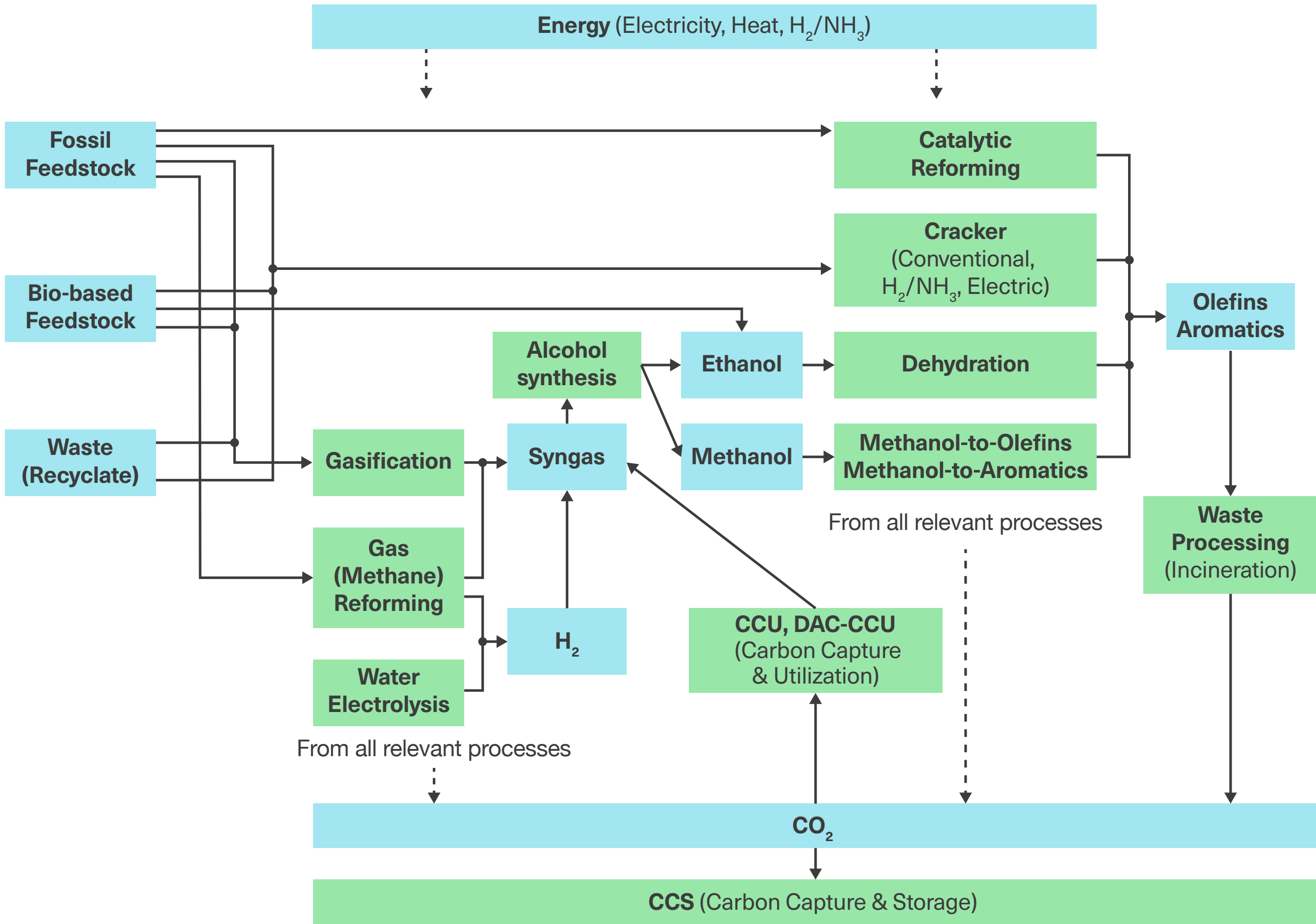
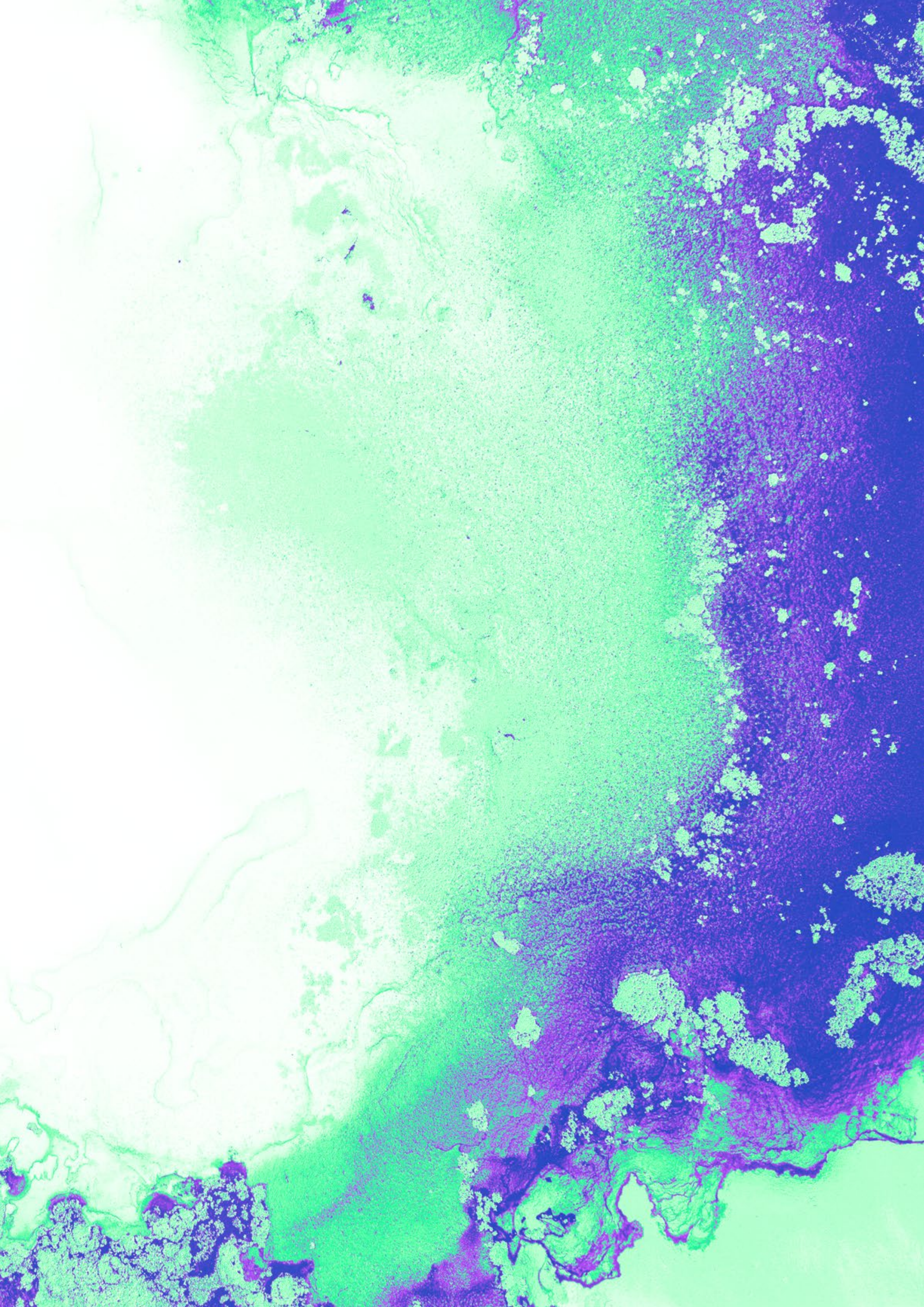


Figure 24: Key process technologies and feedstocks considered in the supply model. The green boxes represent process technologies, and the blue boxes represent key input and output from process technologies.



October 2024

Planet Positive Chemicals in Japan

Unlocking new roles of the Japanese chemical industry in achieving scope 1–3 net zero and safeguarding the Global Commons

This research was funded by Mitsubishi Chemical Corporation.

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