Scope 1, 2, and 3 net zero pathways for the chemical industry in Japan

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Scope 1, 2, and 3 net zero pathways for the chemical industry in Japan

Scope 1, 2, and 3 net zero is a major technological challenge for the chemical industry in Japan, but a failure or even a delay in achieving this goal could result in exclusion from international financing and supply chains. This study presents, for the first time to the best of our knowledge, multiple quantitative pathways from today until 2050 for the chemical industry operating in Japan to reach scope 1, 2, and 3 net zero. These pathways indicate that the demand for basic chemicals in Japan could decrease by 43% by 2050 owing to a combination of population decline and advances in circularity. Furthermore, these pathways demonstrate that securing access to bio-based feedstock and carbon capture and storage (CCS) is essential to avoid a supply limit that could be imposed under scope 3 net zero. Given the uncertainty of Japan's access to both, the chemical industry should pursue both concurrently, while maximizing recycling. Specifically, it should secure long-term and stable sources of sustainable bio-based feedstock and aid in implementing carbon dioxide capture from incinerators in the waste management. This approach could also apply to chemical industries in other countries and regions with similar constraints.

Keywords: greenhouse gas; circular economy; recycling; bio-based feedstock; decarbonization

Introduction

Today, the global chemical industry supplies products essential to most sectors of the economy, accounting for more than 8% of the gross domestic product of the manufacturing sector in 2017 (Oxford Economics 2019). However, this has environmental impacts on many of the processes in the planetary boundaries, including climate change (Steffen et al. 2015), and novel entities such as microplastics pollution (Persson et al. 2022). In the context of climate change, for instance, the Intergovernmental Panel on Climate Change is calling for increasingly urgent actions to reduce greenhouse gas (GHG) emissions. This urgency has compelled the international financial community (GFANZ 2022), and brand owners in the downstream of the supply chain (WBCSD 2021), to demand GHG emission reductions in all three scopes (i.e., scope 1, 2, and 3) of the GHG Protocol (WBCSD and WRI 2004, 2011), from upstream suppliers such as the chemical industry.

However, as a part of the hard-to-abate industries, GHG reductions in the chemical industry are notoriously challenging (Systemiq 2021). This is especially true in Japan, where renewable energy is not as abundant or accessible as it is in other countries (Carbon Tracker Initiative 2021). Furthermore, the fact that most chemical products contain carbon makes the management of end-of-life emissions after incineration particularly challenging in Japan, where incineration has been one of the primary waste treatment methods to minimize landfill (Ministry of the Environment 2014). Given the ubiquity of chemical products, the importance of these challenges is highlighted by the fact that unless the chemical industry achieves scope 1, 2, and 3 net zero, other industries will not be able to do so either. Thus, a failure, or even a delay, on the part of the chemical industry in Japan to achieve scope 1, 2, and 3 net zero could result in exclusion from international financing and supply chains.

Several studies have reported pathways for the chemical industry to achieve net zero GHG emissions. Some are qualitative roadmaps developed by the Japanese government (Ministry of Economy, Trade, and Industry 2021, 2023a), whereas others are quantitative European or global studies (Saygin and Gielen 2021; Meys et al. 2021; CEFIC 2021; Stegmann et al. 2022; Bachmann et al. 2023). However, these studies failed to present a holistic perspective on the transition to net zero, omitting elements such as financial impacts, end-of-life emissions, demand-side measures, and environmental impacts other than GHG emissions. Our group has recently reported quantitative pathways for the global chemical industry to achieve scope 1, 2, and 3 net zero, while taking these previously omitted perspectives into consideration (Meng et al.

2023). By applying this methodology to Japan, this study presents, for the first time to the best of our knowledge, quantitative pathways to scope 1, 2, and 3 net zero from today until 2050 for the chemical industry operating in Japan. In addition, it provides strategic insights into the necessary actions based on the quantitative analysis. The scope 3 emissions in this study are limited to categories 1 and 12 only (see the Method section below for more detail).

Method

General description of the demand-supply model

A demand-supply model was developed to analyze pathways for the chemical industry in Japan to achieve net zero emissions between 2020 and 2050. The model considered seven basic chemicals (ethylene, propylene, butadiene, benzene, toluene, xylenes, and methanol) at the start of the petrochemical supply chain.

Our model was a combination of a demand model and a supply model. The demand model specified the yearly demand for each of the seven chemicals, whereas the supply model was an agent-based model in which the agents were the manufacturing plants that produced the seven chemicals to meet the annual demand specified separately by the demand model. The supply model included an external forcing mechanism to replace existing conventional plants on an annual basis in order to drive the scope 1, 2, and 3 emissions toward net zero. This replacement could take the form of retrofitting existing plants into less emissive plants or a combination of decommissioning old plants and constructing new plants with new GHG reduction technologies.

The demand and supply models each generated scenarios, and the combination of a demand scenario and a supply scenario constituted a pathway. We considered two demand scenarios and three supply scenarios, resulting in six pathways, as shown in **Figure 1**. Four of these pathways (BAU-ME, LC-ME, LC-NFAX, and LC-NFAX2) that were deemed the most insightful are discussed in depth. The results presented by the demand and supply model were not precise projections or forecasts but rather simulations that identified the key elements necessary to implement a transition to net zero.

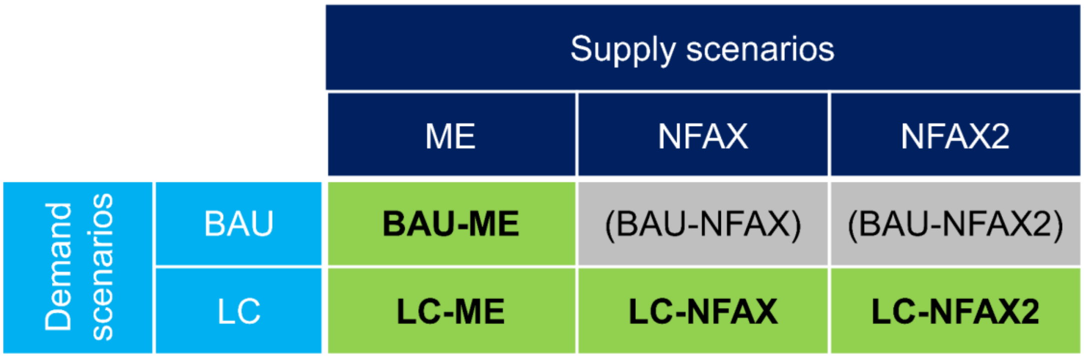


Figure 1. Demand scenarios, supply scenarios, and combined pathways.

General description of the demand model

The demand model we developed was a deterministic linear model which did not include optimization. For each of the seven chemicals, it calculated the annual volume demand from key downstream industry sectors, the demand reduction through circular economy, the volume of generated waste, and end-of-life emissions.

The demand model utilized the 2020 demand in Japan as its starting point. The BAU demand scenario assumed a decline in domestic demand proportional to a 20% decline in the population of Japan by 2050 (United Nations 2022), while net exports were assumed to remain flat until 2050. The LC demand scenario assumed a further reduction in demand compared to the BAU scenario as a result of the four circularity activities in the downstream industry sectors, as described in the following section. In the LC scenario, circularity was implemented at 50% of its maximum potential while still providing the same utility as the BAU scenario did.

Circular economy, waste, and recycling in the demand model

The four circularity activities assumed in the LC scenario were elimination (e.g., using less or no plastics through avoiding overpackaging), reuse (e.g., using new business models for packaging and delivery, as well as sharing), substitution (e.g., replacing plastics with paper and wood), and recycling (e.g., mechanical, depolymerization, and solvent-based recycling). The demand model estimated demand reductions through these circularity activities in the following industry sectors: packaging and household goods, transportation, building and construction, apparel, and other sectors.

Next, the demand model estimated the annual waste generation from each sector, assuming a delay from production to waste generation of 1, 12, 30, 5, and 5 years for the above five sectors, respectively (Geyer et al. 2017).

The model calculated the amount of mechanical recycling from the amount of waste based on the assumed mechanical recycling rates for each industry sector. Waste that was not mechanically recycled was cascaded to upstream chemical recycling (e.g., depolymerization and solvent-based recycling) and subsequently to downstream chemical recycling (e.g., pyrolysis and gasification). Upstream chemical recycling was addressed in the demand model because it reduced the demand for the seven basic chemicals. In contrast, downstream chemical recycling was accounted for in the supply model because it did not affect the demand for the seven basic chemicals but rather generated feedstocks for these seven chemicals. An annual recycling rate was assumed for each recycling method between 2020 and 2050, while the amount of recycling was capped by waste availability.

General description of the supply model

The supply model we developed was based on bottom-up plant-level decisions made year by year, where the type of new plants (i.e., which production technologies to use) and the fate of existing plants (i.e., retrofitting or decommissioning) were decided based on the ranking of the technologies. Each production technology has corresponding attributes for emissions and levelized unit production costs. The ME supply scenario prioritized production technology with the lowest cost, whereas the NFAX supply scenario prioritized production technology with the lowest emissions.

From 2020 toward 2050, the external forcing mechanism in the supply model replaced 5% of the existing capacity every year with production technologies that had lower emissions. After the forced replacement, plants were further built or decommissioned based on the gap between the production capacity and the demand for each year. Note that certain new technologies were not expected to become available until 2030 (**Table 1**). Note further that scope 3 category 12 emissions (explained later) were included in the calculation of the total amount of emissions for each pathway but were excluded when production technologies were selected in the NFAX scenario; therefore, they were not part of the optimization.

This approach of applying the external forcing mechanism starting in 2020 did not guarantee that emissions would reach precisely net zero by 2050, but it did ensure continuity from 2020 to 2050 in terms of total production capacity and the mix of production technologies. As such, this approach was a combination of backcasting and forecasting, in which transition pathways start with the current status and approach the desired target status by 2050. In addition, this model assumed domestic production with a plant size of 3,000 tons/day to meet domestic demand and net exports. The impact of imports from explicit production abroad was qualitatively evaluated outside of the model and discussed in the Discussion section.

Production technologies, emissions, and constraints in the supply model

The production technologies for the seven basic chemicals with a technology readiness level (TRL) above six were considered in the model (see **Table 1** for the technologies considered). They were categorized into three types: an initial technology, which was today's unabated production technology; an end-state technology, which was a fully abated production technology; and a transition technology, which only partially reduced emissions and required an upgrade to an end-state technology in a later year but was needed when end-state technologies were unavailable yet.

Carbon capture and storage (CCS) was assumed to be installed to capture emissions from incinerators in the waste management, and the installation base was assumed to increase along an S-curve until all incinerators were fitted with CCS by 2050. CCS was also applied as an abatement solution for several production technologies in the supply model.

In accordance with the GHG Protocol's definitions, the types of emissions considered in the model were as follows: scope 1 (direct GHG emissions), scope 2 (indirect GHG emissions from purchased energy, such as electricity and steam), and scope 3 (other indirect GHG emissions) category 1 (purchased goods and services) and category 12 (end-of-life treatment of sold products). The GHGs considered in the model were carbon dioxide (CO_2) and methane (CH_4).

Several key constraints were considered in the model to remain within the planetary boundaries. With respect to the impacts on biodiversity and land use, we ensured that biomass use did not exceed 0.5 EJ per year. This amount of biomass was considered to be sustainably available from abandoned farmland and surplus woods in Japan. We conservatively estimated this amount by scaling down the potential availability in Japan as reported in the literature (Wu et al. 2020), to account for sustainable sourcing (Wu et al. 2019). Regarding the impact on novel entities, because of the reduced future demand and improved waste management in the model, the environmental leakage and microplastic pollution in 2050 should be less than those experienced today; thus, no constraints were set regarding the novel entities. Similarly, no constraints were imposed based on other processes in the planetary boundaries because they were less relevant to the chemicals within the scope of this study, which were ethylene, propylene, butadiene, benzene, toluene, xylenes, and methanol.

Other key constraints considered in the model were as follows: the upper limit on the ramp up rate for new production technologies, which was set at four plants or a 30% increase in capacity per year to prevent unrealistic explosive growth of a new production technology; the prohibition of new plants with initial technologies after 2025 in order to drive GHG reduction while respecting any existing commitments; and the prohibition of new fossil-based plants in NFAX after 2030 in order to accelerate GHG reduction in this supply scenario. No upper limit was placed on the CCS in the ME or NFAX supply scenarios, assuming the potential export of CO_2.

Detailed assumptions for the demand and supply model and the Python program for the model can be found on our GitHub site (See data availability statement below). Further descriptions of the model and assumptions can be found in the supporting information (pages 3–26, 30–53, 55, 126, and 127–141) of our earlier study (Meng et al. 2023), which used the same model and assumptions but studied the global chemical industry, whereas this study focused on Japan to gain country-specific insights.

Results

Future demand scenarios

Two demand scenarios were investigated: BAU and LC. As shown in **Figure 2**, the combination of a 20% population decline between 2020 and 2050 and a flat net export reduced the joint demand for olefins and aromatics from 25.1 million tons per year (Mt/y) in 2020 to 22.7 Mt/y in 2050 in the BAU demand scenario. This scenario included an increased demand for olefins and aromatics of 1.1 Mt/y in 2050 from products such as solar panels and windmills to advance GHG reduction. In this context, olefins represent ethylene, propylene, and butadiene, whereas aromatics refer to benzene, toluene, and xylenes. The BAU demand was further reduced to 14.4 Mt/y in the LC demand scenario, in which the four circular economy activities reduced the demand for olefins and aromatics from BAU by 8.3 Mt/y (or by 8.9 Mt/y if the decrease in methanol demand was included).

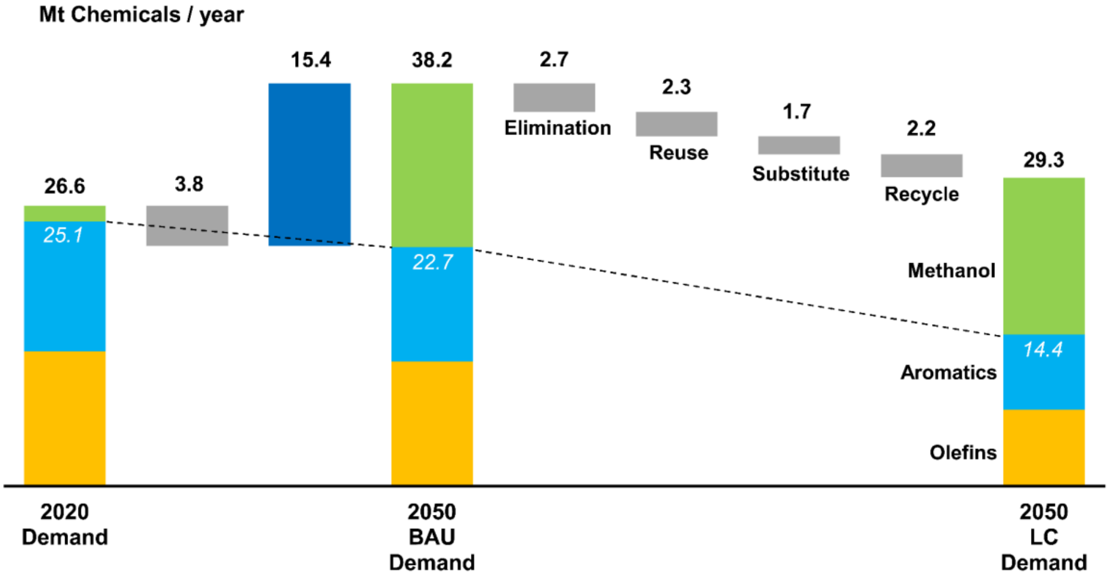


Figure 2. Changes in the demand for olefins, aromatics, and methanol between 2020 and 2050 in Japan. White type indicates the total demand for olefins and aromatics only.

The BAU demand scenario consisted of olefin, aromatics, and methanol demands of 11.8, 10.9, and 15.5 Mt/y in 2050, respectively. The LC demand scenario consisted of olefin, aromatics, and methanol demands of 7.2, 7.1, and 14.9 Mt/y in 2050, respectively. This was in contrast to the demands of 12.8, 12.3, and 1.5 Mt/y in 2020 for the same chemicals. Methanol demand increased significantly by 2050 to serve as an intermediate in the production of olefins and aromatics via the methanol-to-olefin (MTO) and methanol-to-aromatics (MTA) processes.

The four circular economy activities that reduce the demand for chemicals

Elimination rendered chemical products unnecessary for delivering the same benefit to society, thereby reducing the demand by 2.7 Mt/y by 2050. This reduction included the elimination of unnecessary plastic packaging (0.7 Mt/y), improved office and building utilization (0.6 Mt/y), decreased demand for gasoline additives for antiknock (0.4 Mt/y), and the extension of vehicle life (0.4 Mt/y). Reuse required less chemicals to deliver the same benefit and reduced the demand by 2.3 Mt/y by 2050. This reduction consisted of new business models for the packaging and delivery of food and consumer products (1.5 Mt/y) and mobility-as-a-service (0.7 Mt/y). Substitution, in which chemical products were replaced by products not produced by the chemical industry, reduced the demand by 1.7 Mt/y by 2050. This reduction included the substitution by paper products in packaging (1.3 Mt/y) and by wood-based products in housing (0.2 Mt/y). Recycling reduced the demand by 2.2 Mt/y by 2050. This reduction consisted of mechanical recycling (1.8 Mt/y) and chemical or solvent-based recycling (0.4 Mt/y).

Net zero supply scenarios that meet the demand

Three supply scenarios were investigated: ME, NFAX, and NFAX2. In these scenarios, three basic supply strategies for GHG reduction (alternative feedstock, renewable energy, and CCS) were deployed at different levels.

Alternative feedstocks were derived from non-fossil sources of carbon, where carbon atoms came from the atmosphere (bio-based and direct air capture – carbon capture and utilization (DAC-CCU)) or from recyclates (chemical recycling, such as pyrolysis and gasification, as well as point-source CCU). The energy used in the production processes for the seven chemicals within the scope of this study was assumed to be net zero by 2050, coming from renewable sources such as solar and wind, and non-fossil sources such as nuclear energy. CCS was deployed to capture scope 1 CO_2 emissions from production processes, such as steam methane reformers used to produce hydrogen and off-gas used as fuel in naphtha crackers. CCS was also used to capture CO_2 emissions from incinerators in waste treatment in the downstream of the value chain, with all incinerators assumed to be fitted with CCS by 2050.

As shown in **Figure 3(a)**, the two ME supply scenarios that sought the most economical solution relied on fossil-based feedstock for more than 95% of their carbon source. In these scenarios, the carbon in waste that was not recycled was incinerated and sequestered by CCS or disposed of in landfills. In addition, off-gas (mostly methane) from crackers was used as fuel and sequestered via CCS. The ME supply scenarios selected solutions based on fossil feedstock and CCS for the most part because they were less expensive than processes utilizing alternative feedstocks.

Figure 3(a) also shows that the NFAX supply scenario, which sought the fastest abatement, used diversified feedstocks, including bio-based, DAC-CCU, recyclates, as well as fossil-based feedstocks, while combined with CCS. The combination of bio-based or DAC-CCU feedstocks with CCS removed carbon from the atmosphere and stored it in the ground over the course of the lifecycle, thereby providing an opportunity to reduce atmospheric CO_2. The NFAX scenario continued using fossil feedstock, mainly because the model placed an upper limit on the annual rate at which conventional fossil-based plants were replaced by plants that used alternative feedstocks.

The NFAX2 supply scenario did not use CCS but was otherwise identical to the NFAX scenario. This scenario provided insight into cases in which CCS was found prohibitively expensive or impractical in Japan.

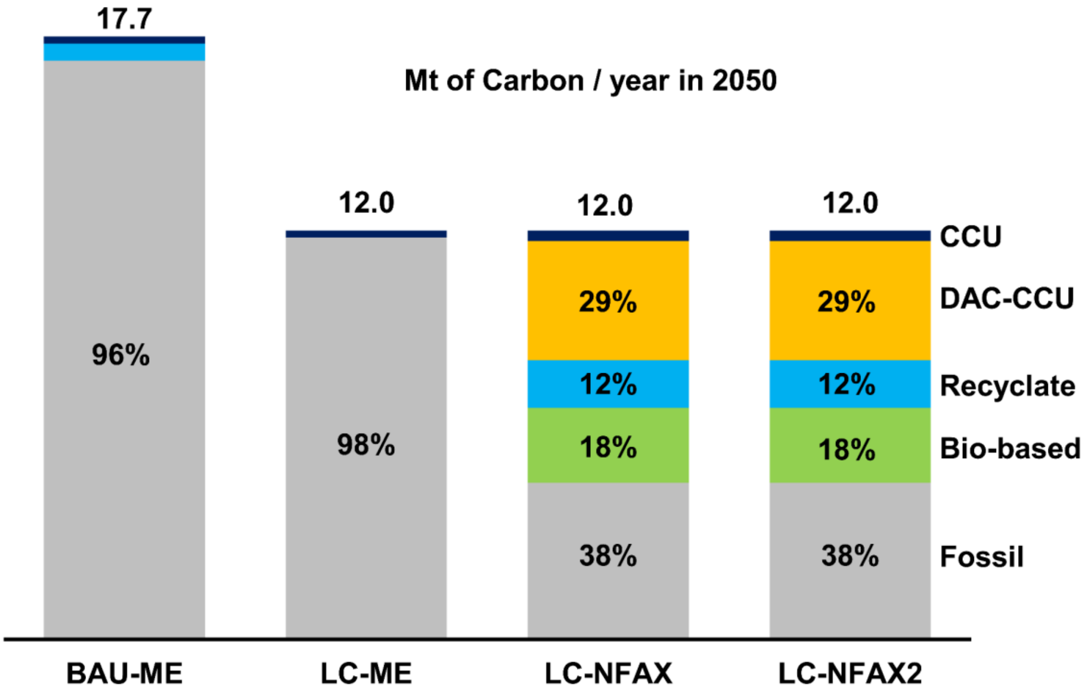
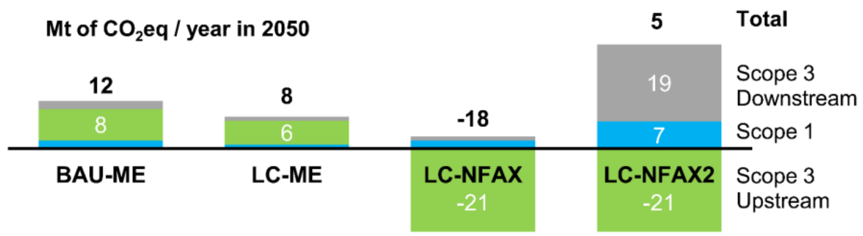


Figure 3(a). Sources of carbon in the feedstocks for different pathways, for the seven chemicals in the scope of this study.



Mt of CO_2 stored / year in 2050

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

Figure 3(b). Emissions in 2050 for different pathways, and the amount of CCS assumed in each pathway.

Pathways (demand scenarios + supply scenarios) and GHG emission

In the value chain of plastics, scope 3 downstream emissions (2.7 ton CO_2 per ton of plastics), which are generated primarily from end-of-life incineration, are known to be particularly high (compared to scope 3 upstream emissions of 0.3 ton and scope 1 and 2 emissions of 2.0 ton, for a total of 5.0 ton CO_2 per ton of plastics) (Material Economics 2019). Furthermore, there is a concern that scope 3 upstream emissions (mainly methane leakage) may be underestimated (Hmiel et al. 2020). Therefore, it is essential to manage scope 3 emissions using alternative feedstocks, CCS, or CCU.

In the BAU-ME pathway (the combination of the BAU demand scenario and the ME supply scenario), 96% of the feedstock came from fossil sources and required 47 Mt/y of CCS by 2050 to achieve near net zero emissions of 12 Mt CO_2eq, as shown in **Figures 3(a) and 3(b)**. In the LC-ME pathway (the combination of the LC demand scenario and the ME supply scenario), 98% of the feedstock came from fossil sources and required 26 Mt/y of CCS by 2050 to achieve near net zero emissions of 8 Mt. The requirement for CCS in the LC-ME pathway was less than that in the BAU-ME pathway because the unimpeded demand in the BAU demand scenario generated more emissions from production and end-of-life incineration than in the LC demand scenario. The BAU-ME and LC-ME pathways did not achieve strict net zero, partly because of leakage from the CCS system, whose capture rate was assumed to be 95% in 2050.

In the LC-NFAX and LC-NFAX2 pathways (the combinations of the LC demand scenario and the NFAX or NFAX2 supply scenarios), 62% of the feedstock came from alternative sources. The LC-NFAX pathway required 23 Mt/y of CCS in 2050 and achieved negative emissions (-18 Mt/y), whereas the LC-NFAX2 pathway required no CCS and achieved near net zero emissions (5 Mt/y). The LC-NFAX pathway produced negative emissions, with the entire chemical supply chain functioning as a carbon sink. In addition to CCS, the chemical products that remained in the economy (i.e., those produced using bio-based or DAC-CCU feedstock but have not yet reached the end-of-life stage) also served as temporary carbon sinks.

Figure 4 shows a breakdown of the production technologies for olefins, aromatics, and methanol. Olefins are currently produced with naphtha crackers using fossil feedstocks in Japan. However, in the BAU-ME and LC-ME pathways, they were mainly produced by crackers retrofitted with CCS or those fueled by hydrogen or ammonia. In the LC-NFAX pathway, in addition to hydrogen/ammonia-fueled crackers, electric crackers and crackers using pyrolysis oil with CCS were used in order to achieve greater abatement. Currently, aromatics are mainly produced via catalytic reforming and naphtha cracking. However, in the BAU-ME and LC-ME pathways, they were mainly produced by a methanol-to-aromatics (MTA) process using methanol produced via natural gas reforming, which requires CCS to abate the end-of-life emissions. This shift from catalytic reforming to MTA was based on the assumption that catalytic reformers in refineries would be decommissioned by 2050, following a decline in fuel production for vehicles with internal combustion engines. In the LC-NFAX pathway, CCU, DAC-CCU, or biomass gasification was used instead of natural gas to produce methanol and aromatics via an MTA process. Regardless of the net zero pathways and feedstock for methanol, it was anticipated that the production volume using an MTA process would increase, necessitating an improvement to the MTA process.

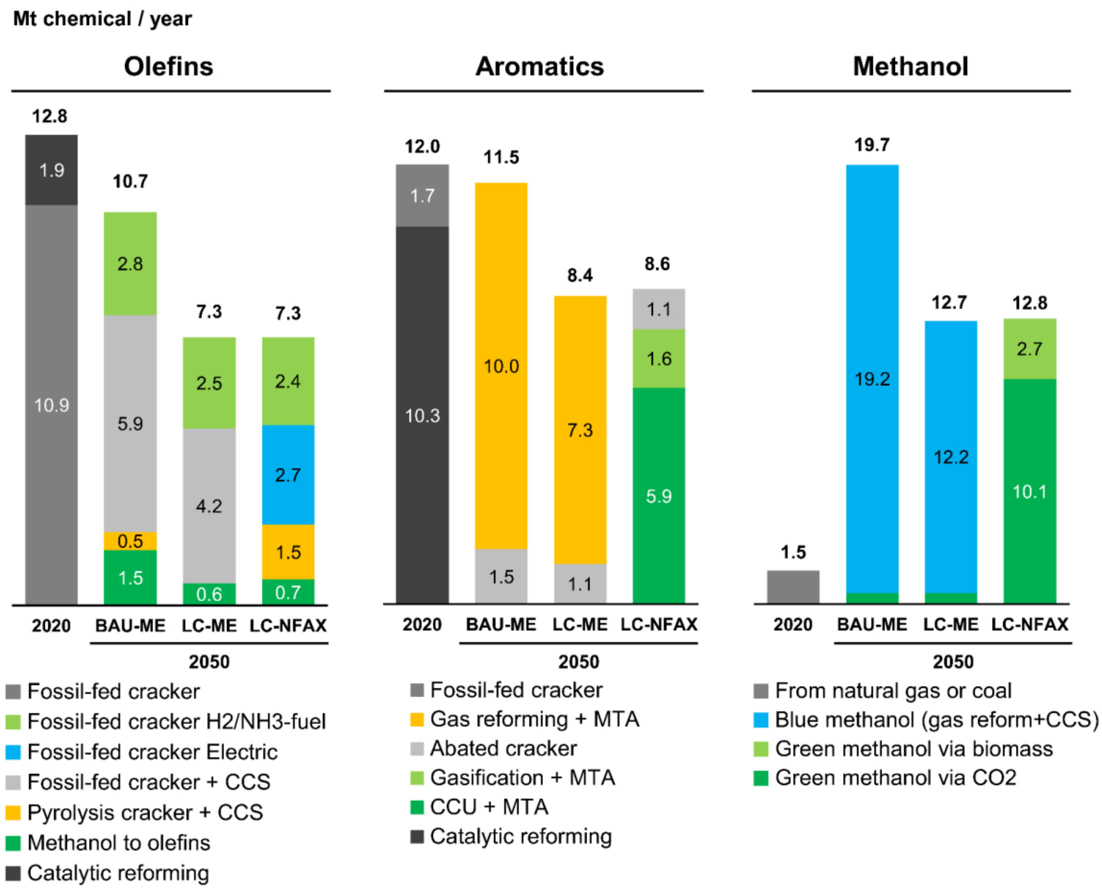


Figure 4. Breakdown of production technologies to produce olefins, aromatics, and methanol for different pathways.

Capital expenditures and unit production costs

The cumulative capital expenditures until 2050 are shown in **Figure 5(a)**. The LC-ME pathway had lower capital expenditures than those of the BAU-ME pathway because the demand in the LC-ME pathway was smaller; thus, fewer new plants and retrofits were needed. The LC-ME pathway also incurred lower capital expenditures than those of the LC-NFAX pathway. This was because the LC-NFAX pathway required more expensive processes to utilize bio-based or CO_2 as feedstocks, and more expensive cracker retrofits were required to use recyclates and renewable energy to achieve greater emission reductions.

As shown in **Figure 5(b)**, the unit production cost for olefins and aromatics in 2050 was approximately 20–130% higher than in 2020 in the LC-ME pathway and 30–

190% higher in the LC-NFAX pathway. The increase in the cost of aromatics was greater than that of olefins because of the required transition from catalytic reformers to newly built methanol-to-aromatics (MTA) processes.

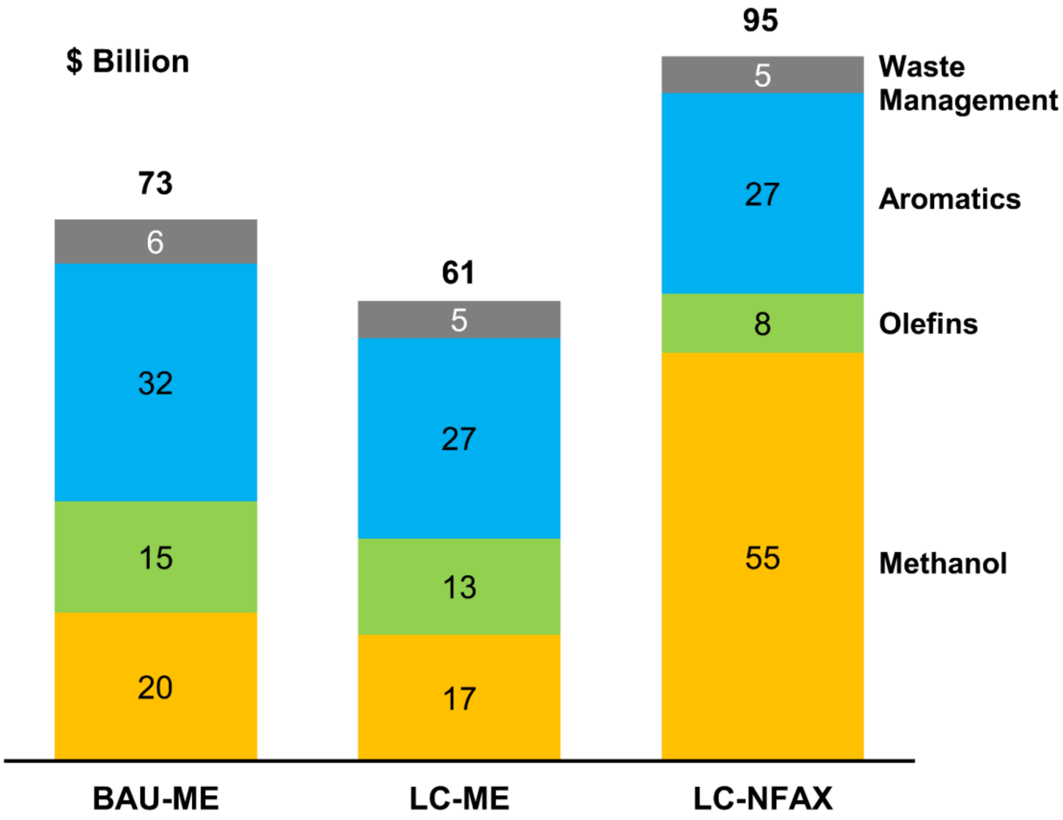


Figure 5(a). Cumulative capital expenditures until 2050, broken down by target products.

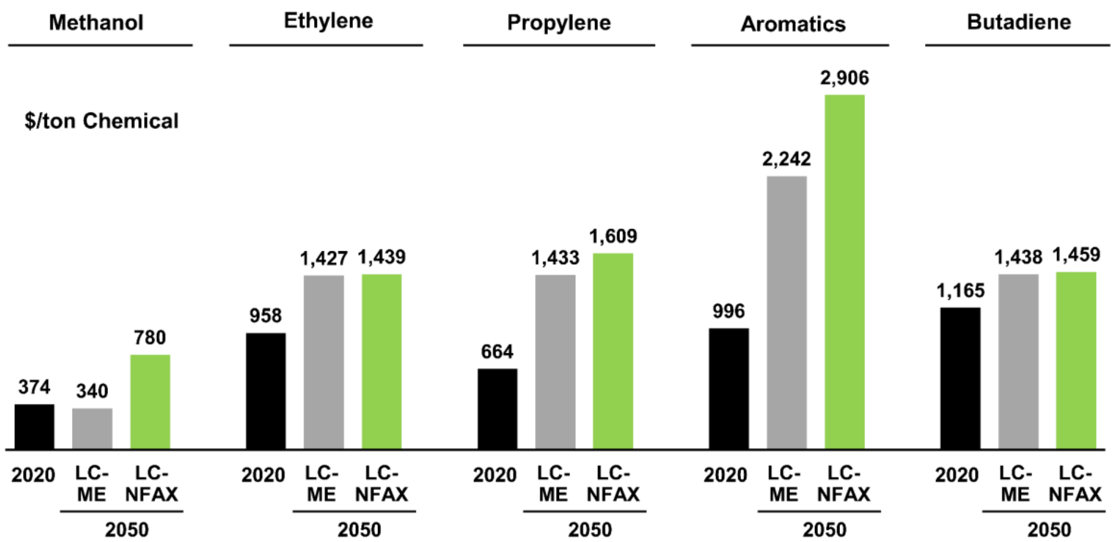


Figure 5(b). Unit production cost of chemicals in net zero pathways in 2050.

Discussion

Scope 1, 2, and 3 net zero pathways

Today, most of the feedstock for chemical products is fossil-based, and they are mostly incinerated without CCS or CCU at their end-of-life stage (with or without energy recovery) in Japan. In other words, the carbon vector is from the ground (fossil) to the air (incineration without carbon capture), as shown in **Figure 6**.

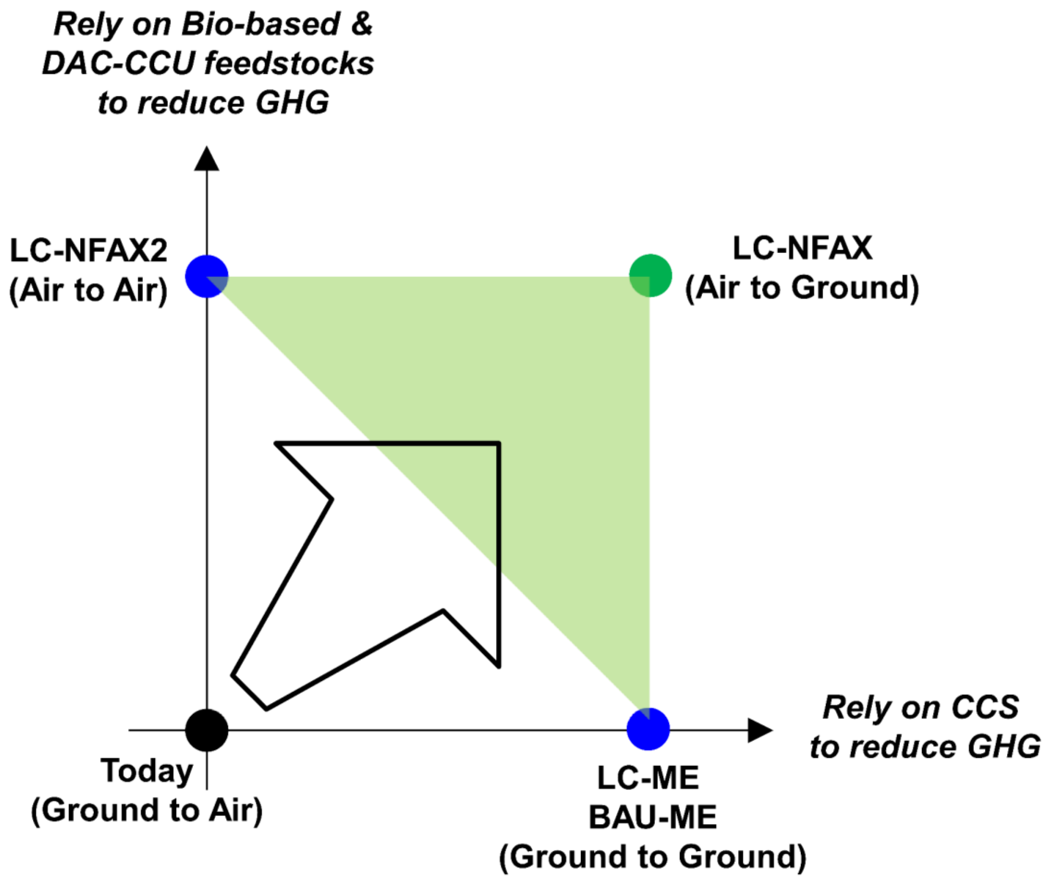


Figure 6. Conceptual positioning and carbon vector of where we are today, the four net zero pathways, and the target zone of net zero, with respect to two GHG reduction measures.

As presented thus far, there are multiple pathways that could bring the chemical industry in Japan near or beyond scope 1, 2, and 3 net zero. The first set of net zero pathways is LC-ME and BAU-ME, which mainly combine the use of fossil feedstock with CCS, where the carbon vector is from the ground (fossil) to the ground (CCS).

These are the most economical pathways and appear to be financially more viable than the other pathways. However, they rely almost entirely on CCS for GHG reductions, despite the fact that Japan is yet to prove large-scale CCS destinations within its territory and exporting CO_2 for overseas sequestration is only planned (Ministry of Economy, Trade, and Industry 2023b). For these reasons, the LC-ME and BAU-ME pathways are considered highly risky for Japan.

Another net zero pathway is LC-NFAX2, which relies on alternative feedstocks; thus, even if chemical products are incinerated without carbon capture as they are today, a near net zero can be achieved owing to the CO_2 absorbed from the atmosphere by the feedstocks. In this context, the carbon vector is from the air to the air. While this pathway does not rely on untested CCS, it relies intensively on bio-based feedstock and DAC-CCU, despite the fact that very little bio-based feedstock and even less DAC-CCU are used in practice today. Furthermore, sustainably sourcing a large amount of bio-based feedstock is considered a major challenge (Energy Transitions Commission 2021). Given the rising demand for securing food for the growing global population and the accelerating movement to safeguard biodiversity, relying on imported bio-based feedstock is a simple but risky option in terms of supply chain management, not to mention trade security and currency fluctuations. Conversely, long-term investment in the under-explored domestic supply of large-scale bio-based feedstocks for chemicals represents an opportunity.

The last net zero pathway is LC-NFAX, which is a combination of the LC-ME and LC-NFAX2 pathways, in that it combines the use of alternative feedstocks with CCS. The carbon vector for this pathway is from the air to the ground, which resulted in negative emissions.

Because the future availability and economic viability of CCS and alternative feedstocks (bio-based and DAC-CCU) in Japan are both uncertain, relying solely on one of them to achieve net zero, as in LC-ME or LC-NFAX2, would be a risky strategy. In conclusion, the chemical industry in Japan should instead diversify its risks by concurrently pursuing both CCS and alternative feedstocks, aiming for the shaded area in **Figure 6**, where net zero is achieved through a combination of CCS and alternative feedstocks.

Managing the sources and destinations of carbon and their strategic implications

Scope 3 net zero is a requirement from the financial community as well as the direct and indirect customers of the chemical industry in the downstream of the supply chain. Under scope 3 net zero, our group has previously demonstrated that the total supply of carbon in chemical products is limited to the sum of sequestered carbon (CCS), recycled carbon (recyclates and CCU), and carbon in bio-based and DAC-CCU feedstock (Meng et al. 2023). In other words, this indicates *(D) = (C) + (E) + (F)* in **Figure 7**. This is because *(A) = (E), (B) = (F),* and *(C) = (G)* can be derived under the constraints of scope 3 (category 12) net zero, assuming a steady amount of stock of embedded carbon in chemical products within the economy over time, and that scope 1 and 2 emissions are net zero, among other assumptions detailed in the supporting information of our previous study. The equation *(D) = (C) + (E) + (F)* indicates that the capability of the chemical industry to meet the demand *(D)* will be capped by the sum of the three components, *(C)*, *(E)*, and *(F)*, each of which could be limited in supply. For example, for *(C)*, the supply of sustainably sourced bio-based feedstock is considered limited, whereas that of DAC-CCU could be limited owing to its high cost. For *(E)*, the availability of CCS could be limited, especially considering the site development time until 2050. Finally, for *(F)*, the recycling rate (measured with respect to carbon atoms in the production volume) is unlikely to reach 100% and could be limited. Overall, this means that securing stable access to *(C)*, *(E)*, and *(F)* will be of vital strategic importance for companies in the chemical industry under scope 3 net zero.

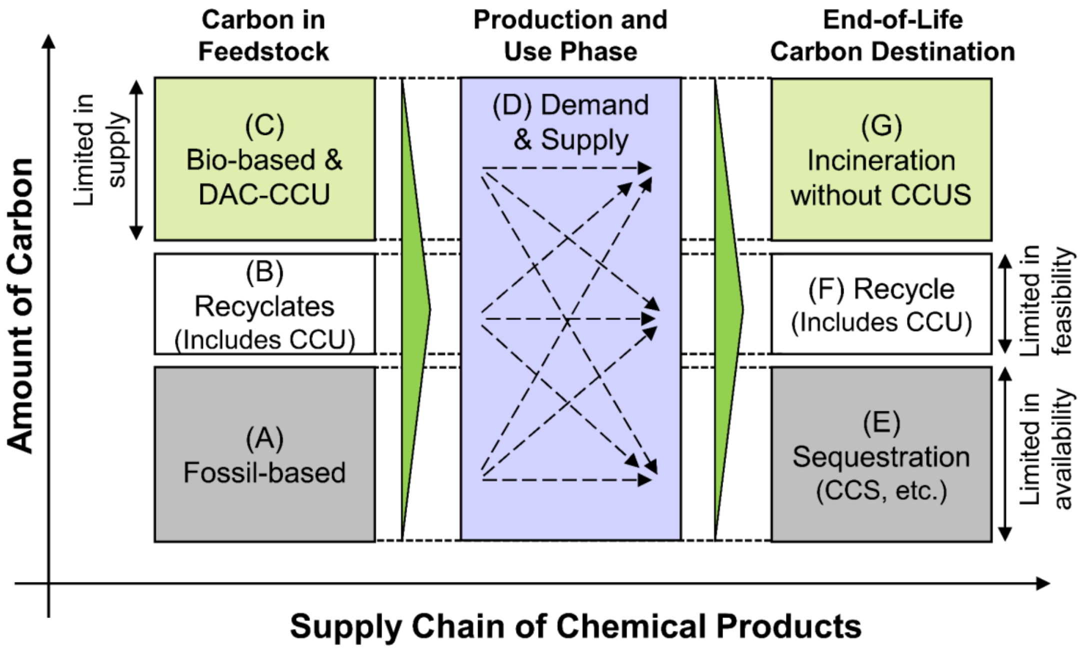


Figure 7. Carbon balance in the chemical supply chain. Carbon balance and scope 3 (category 12) net zero together require *(A)=(E)*, *(B)=(F)*, and *(C)=(G)*. These equations must hold true to be scope 3 (category 12) net zero, although fossil feedstock, for example, can reach any of the three destinations as indicated by the dotted arrows in the Production and Use Phase. The proportion of *(A):(B):(C)* or *(E):(F):(G)* is for illustrative purposes only.

As for the sources of carbon, given Japan's uncertain access to bio-based feedstock and CCS, the chemical industry in Japan should maximize the recycling rate of chemical products. Doing so will expand *(B)* and *(F)* and decrease the requirements for the uncertain *(C)* and *(E)* to accommodate the same level of demand *(D)*. In fact, the recycling rate of plastics in Japan in 2021 was only 25% (Plastic Waste Management Institute 2022), if energy recovery is not considered to recycle carbon.

Furthermore, regarding the sources of carbon, as the LC-NFAX2 pathway indicates, securing bio-based and DAC-CCU feedstocks *(C)* is key. The fastest way to establish a supply chain that uses these feedstocks in Japan is likely to use imported methanol or ethanol to produce olefins and aromatics, rather than waiting for the development of domestic sources. For methanol, it could be produced through DAC-CCU, where CO_2 is converted overseas into methanol using less expensive green hydrogen, or it could be produced from bio-based feedstocks. Ethanol will likely be bioethanol. However, given the rising demand for sustainable aviation fuel (SAF), the supply for the chemical industry could compete with aviation fuel, and may no longer be joint products from petroleum. This constraint adds to the aforementioned supply chain risks. Therefore, securing domestic and dedicated sources for the chemical industry is essential, such as long-term investments by the chemical industry in domestic woody biomass and abandoned farmland. Conversely, the relatively smaller and geographically distributed petrochemical complexes in Japan would be a comparative advantage when compared to the larger and more concentrated complexes abroad. This is because alternative feedstocks, such as bio-based feedstocks and recyclates, are typically generated in a more distributed manner than petroleum and naphtha, which are imported in bulk.

As for the destinations of carbon, in order to achieve scope 3 net zero, **Figure 7** shows that as long as fossil feedstock remains part of the feedstock, CCS is required to sequester the same amount of carbon as that in the fossil feedstock. CCS is required to sequester CO_2 from production processes and end-of-life incineration. Because the latter is located outside of chemical plants and far down the value chain, it may be unrealistic for chemical companies to operate CCS after incineration. However, because post-incineration CCS is vital for achieving scope 3 net zero for the chemical industry and its value chain, the chemical industry should not detach itself from this issue. As Japan has over one thousand incineration facilities (Ministry of the Environment 2021), one way to deploy post-incineration CCS could be through an additional contribution to an existing extended producer responsibility program, such as the existing Containers and Packaging Recycling Law. In addition, the CCS demand for post-incineration CCS needs to be considered, when Japan estimates the total demand for CCS and pursues CCS capacity both domestically and internationally. Instead of CCS, post-incinerator CO_2 could be utilized for CCU if hydrogen is accessible. The post-incinerator CCU reduces the need for CCS as parts of *(A)* and *(E)* in **Figure 7** are replaced by *(B)* and *(F)*. In conclusion, the chemical industry in Japan should pursue the implementation of post-incineration carbon capture, either in the form of CCS or CCU.

Dealing with the cost increase

The unit cost increase of the basic chemicals that achieve scope 1, 2, and 3 net zero (net zero chemicals) is extremely high (20–190%), particularly for immediate customers of the chemical industry. However, suppose this unit cost increase is 100% (double cost). In that case, the ultimate impact on the production cost of end-user products is limited to approximately 1%, assuming there is no opportunistic price increase in the supply chain, among other assumptions. This is because the impact of cost increases in the chemical industry is diluted by the additional material input and value added by companies in the middle of the supply chain. Given the seemingly prohibitive cost increase, it is natural for companies in the middle of the supply chain to delay the introduction of net zero chemicals despite the limited cost impact and regardless of the need for such chemicals at the downstream end of the supply chain. Therefore, it is essential that downstream brand owners who need to reduce scope 3 emissions collaborate with the chemical industry at both ends of the supply chain. For example, they could share signals for the future demand and supply of net zero chemicals via an open coalition.

Conclusion

We quantitatively demonstrated that the chemical industry located in Japan could transition from where it is today to scope 1, 2, and 3 net zero. Even though there are multiple pathways to net zero, they should not be regarded as forecasts, but rather simulations to identify key elements necessary to implement a transition to net zero, which are as follows.

The chemical industry in Japan must expand access to both bio-based / DAC-CCU feedstocks and CCS, while maximizing recycling including CCU, in order to remain in the international financing and supply chain. Given the uncertainty in the access to these feedstocks and CCS in Japan, the chemical industry should explore both concurrently.

Concerning the access to bio-based and DAC-CCU feedstocks, the chemical industry in Japan can start with the import of blue or green methanol or green ethanol to establish a supply chain, but it should also make a long-term investment in establishing a secure and stable supply. In addition, implementing post-incineration CCS or CCU throughout Japan is essential for achieving scope 3 net zero for the chemical industry and its value chain. This can be achieved through an extended producer responsibility program.

The increase in the production cost of the seven basic chemicals was substantial; however, its impact on the production costs of end-user products was limited. This uneven impact on the supply chain should be addressed by a coalition between the chemical industry and downstream brand owners to communicate future demand and supply of net zero chemicals.

Japan's combined approach to bio-based feedstock and CCS could also apply to chemical industries in other countries and regions with limited access to these resources.

Table 1. Production technologies considered in the model, categorized by the year when they become available. (I), (T), and (E) stand for an initial, transition, and end-state technology, respectively.

	Now	2025	2030
Olefins	(I) Naphtha steam cracking (I) Ethane steam cracking (I) Propane dehydrogenation (I) Catalytic Reforming Propylene (T) Pyrolysis oil/bio-oil-fed steam cracking (T) Naphtha steam cracking + byproduct upgrade (E) Methanol-to-olefins (E) Methanol-to-propylene (E) Bioethanol dehydration (E) Ethanol-to-butadiene (E) Bio-oils-fed steam cracking + byproduct upgrade	(T) Naphtha steam cracking + CCS (E) Naphtha steam cracking + CCS + byproduct upgrade (E) Ethane steam cracking + CCS (E) Pyrolysis-oil-fed steam cracking + CCS +byproduct upgrade (E) H_2-fueled naphtha steam cracking + byproduct upgrade (E) H_2-fueled ethane steam cracking (E) H_2-fueled pyrolysis oil/bio-oil-fed steam cracking + byproduct upgrade (E) Propane dehydrogenation + CCS	(E) Electrified naphtha steam cracking + byproduct upgrade (E) Electrified ethane steam cracking (E) Electrified pyrolysis oil/bio-oil-fed steam cracking + byproduct upgrade
Aromatics	(I) Naphtha steam cracking (I) Catalytic reforming (T) Pyrolysis oil/bio-oil-fed steam cracking (T) Naphtha steam cracking + byproduct upgrade (E) Bio-oil-fed steam cracking + byproduct upgrade	(T) Naphtha steam cracking + CCS (E) Naphtha steam cracking + CCS + byproduct upgrade (E) Ethane steam cracking + CCS (E) Pyrolysis oil / bio-oil-fed steam cracking + CCS + byproduct upgrade (E) H_2-fueled naphtha steam cracking + byproduct upgrade (E) H_2-fueled pyrolysis oil / bio-oil-fed steam cracking + byproduct upgrade (E) Methanol-to-aromatics (E) Methanol-to aromatics (+Toluene Disproportionation)	(E) Electrified naphtha steam cracking + byproduct upgrade (E) Electrified pyrolysis oil / bio-oil-fed steam cracking + byproduct upgrade
Methanol	(I) Coal gasification (I) Natural gas reforming	(E) Coal gasification + green H_2 (E) Coal gasification + CCS (E) Natural gas reforming + CCS	(E) Green H_2 + DAC (E) Natural gas e-SMR

	(E) Natural gas reforming + gas heated reformer (E) Green H_2 + point-source CO_2 (CCU) (E) Biomass gasification + CCS (E) Biomass gasification + green H_2 (E) MSW-RdF gasification + CCS (E) MSW-RdF gasification + green H_2	

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Data availability statement

Detailed assumptions for the demand and supply model and the Python program for the model can be found on our GitHub site (https://github.com/systemiqofficial/Pathways-Chemical-Industry-Japan).

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