Transforming China's Chemicals Industry: Pathways and Outlook under the Carbon Neutrality Goal

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RMI is an independent nonprofit founded in 1982 that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and NGOs to identify and scale energy system interventions that will cut greenhouse gas emissions at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; and in Beijing, People's Republic of China.

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Executive Summary

China is the world's largest producer and consumer of chemical products. China's chemicals industry accounts for 20% of the total national industrial emissions and 13% of the country's total CO_2 emissions. **The zero-carbon transformation of the chemicals industry is of great significance to the national goal of carbon neutrality and the low-carbon transformation of the global chemicals value chain.**

Challenges and opportunities coexist in the process of transformation. The zero-carbon transformation of China's chemicals industry faces three main challenges:

- The overall demand for major chemical products in China will continue to increase.
- Chemical production in China is highly dependent on coal, which has a carbon intensity much higher than that of other fuels and feedstocks.
- Existing production assets are relatively young, and the risk of stranded assets may be higher due to rapid transformation.

Also, there are three major opportunities:

- China has a strong capability in technology integration and a large market scale, which enables rapid scale-up of new technology deployment.
- Key players in China's chemicals industry are mainly state-owned, so they have the ability and resources to lead the overall industry.
- The large-scale and integrated pattern of China's chemicals industry allows the optimal utilization of resources and energy and achieves economies of scale.

This report focuses on three representative chemical products, namely, ammonia, methanol, and ethylene. On the one hand, these three products will be the main source of carbon emissions within China's chemical industry in the future. The total carbon emissions of ammonia, refinery, and methanol are currently the highest in the chemicals sector. However, given the limited growth potential of refined oil demand, the size of the refinery industry will tend to shrink. For ethylene, although its self-sufficiency rate in China is about 60%, it has great potential for capacity growth, so the carbon emissions of the ethylene industry are on track to increase in the future. On the other hand, from the perspective of their positions in the value chain, ammonia, methanol, and ethylene are key primary chemicals in the sector with numerous downstream products and high added value.

As China gradually enters the later stage of industrialization and urbanization, its demand for steel and cement is expected to decrease in the long run. In contrast, China's demand for chemical products will take longer to peak. The first step to analyze the zero-carbon transformation of China's chemicals industry is to project the demand of major products, analyzing the influencing factors as well as the effect of the carbon neutrality target.

In this report, zero-carbon production means achieving net-zero CO_2 emissions in the production process (back-end treatment like carbon capture and storage [CCS] can be used), and the final products are called zero-carbon chemical products. Also, the chemicals industry should optimize feedstock sources, promote carbon reduction during production processes, and cooperate with upstream and downstream companies to achieve life-cycle zero-carbon emissions. Low-carbon production is a transitional solution to zero-carbon production (i.e., a significant reduction in carbon emissions from the production process). The chemicals industry needs to utilize diverse carbon abatement technologies to reduce or even eliminate carbon emissions from both energy and feedstock perspectives, striving for carbon peaking and carbon neutrality in the chemicals industry.

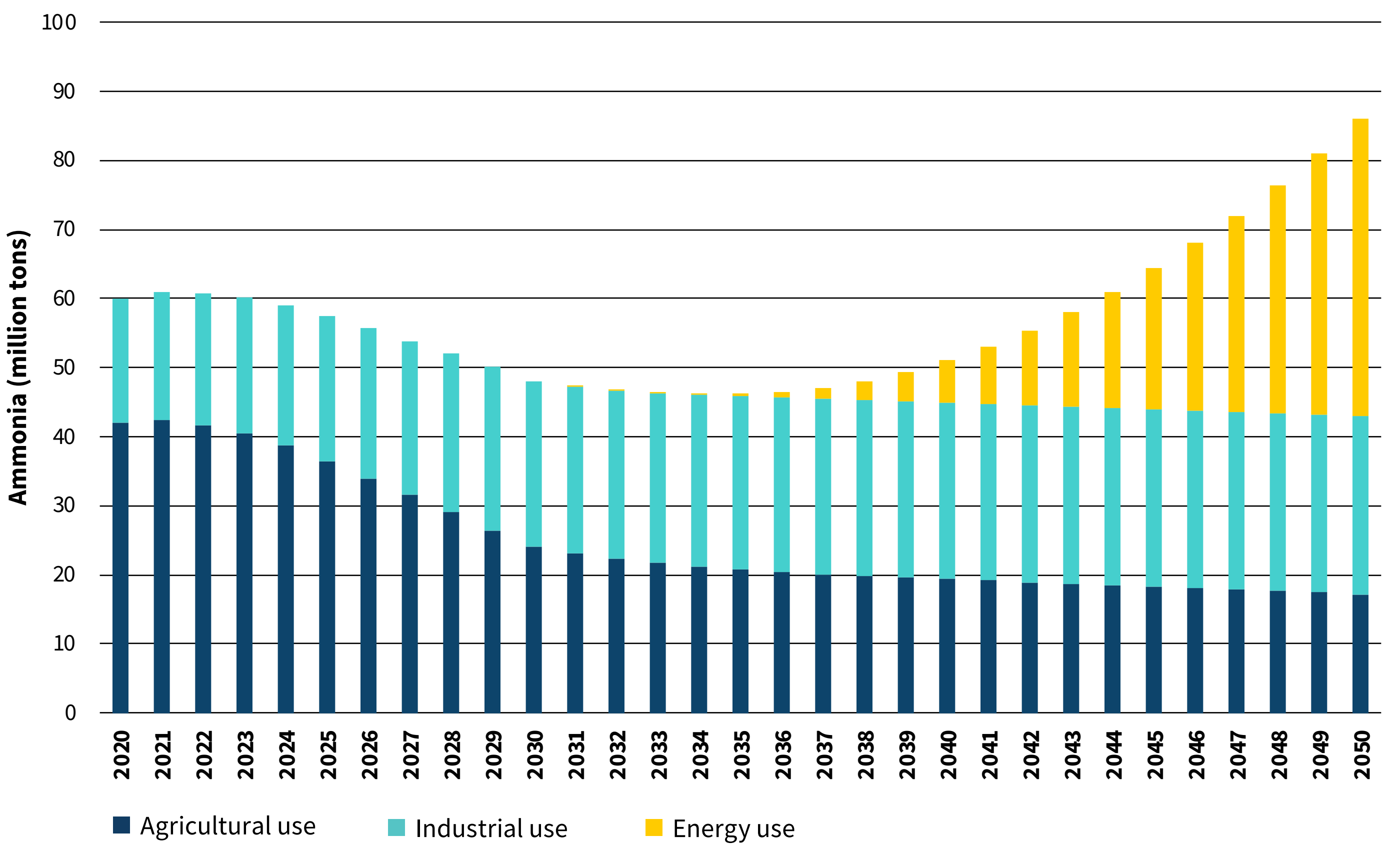
Demand Outlook in the Zero-Carbon Scenario

In RMI's zero-carbon scenario, structural change, efficiency improvement, and full release of recycling potential could contribute to as much as a 49% reduction of primary chemicals in their conventional end use by 2050. Concurrently, their emerging end use as new energy and materials is expected to expand significantly, with an increase of more than 165%.

In the next three decades, ammonia demand in China will decrease first and then increase. The main demand comes from agriculture, which will decrease in the future due to more efficient fertilizer use. Industrial use of ammonia will be unlikely to increase on a large scale due to the limited room for construction as China's industrialization and urbanization is gradually entering a later stage.

After 2035, the use of ammonia as an energy source is likely to grow rapidly, with applications ranging from shipping to power generation. The total demand for ammonia will be around 60 million tons by 2025, with a continuous but slight decline, and will fall to about 46 million tons by 2035 mainly due to shrinking agricultural use as fertilizer efficiency improves. By then, the growth rate of industrial use for ammonia will slow and ammonia used as energy will be piloted around 2030 but only in smaller-scale applications. From 2035 to 2050, the total demand for ammonia will increase due to the expansion of energy use where large-scale commercial applications are available. By 2050, energy use will account for 50% of total demand for ammonia, with agricultural and industrial use leveling off.

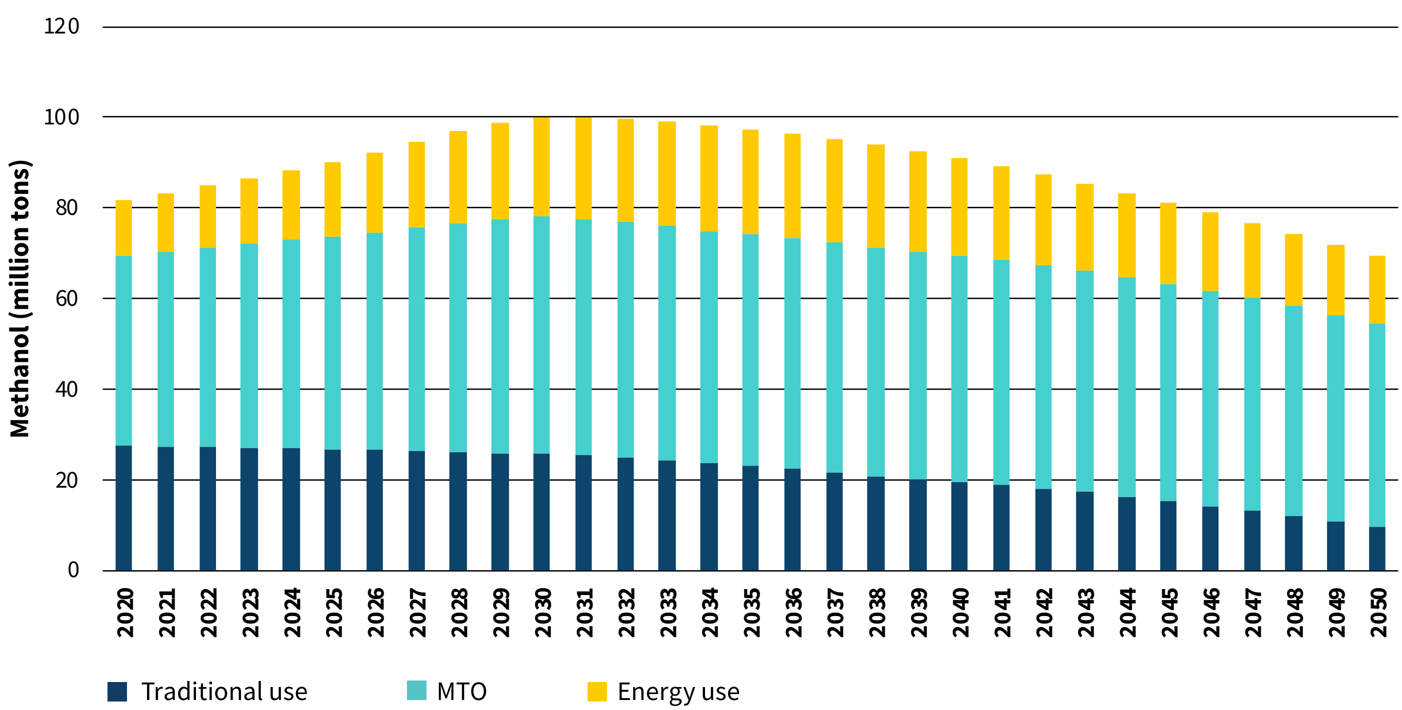
Exhibit ES1 Ammonia demand projection in China



Methanol demand will increase first and then decrease through 2050. At present, traditional use such as acetic acid, methyl tert-butyl ether (MTBE), and formaldehyde, which are mainly used in building materials, decoration, and gasoline blendstock, remain among the major demands for methanol. However, under the pressure of environmental protection, safety, and carbon control, traditional use for methanol will be restrained with gradually accelerating decline. The methanol-to-olefin (MTO) process can efficiently utilize coal resources and relieve dependence on crude oil import; hence, the increasing demand for ethylene in the future will drive a certain growth of MTO. However, in the long run methanol should be gradually shifted to low-carbon and zero-carbon sources. Energy use of methanol will maintain steady growth, but the long-term potential is limited, mainly because the transition to cleaner fuels is subject to competition with other energy sources. China's total methanol demand will increase to about 100 million tons by 2030, with MTO and energy use as the main growth drivers, while traditional use will slowly decline. From 2030 to 2050, total methanol demand in China will continue to decrease to 70 million tons.

Ethylene demand in China will continue to increase through 2050, gradually stabilizing after 2040. Ethylene is one of the critical building blocks in the petrochemicals industry, with plastic as a large proportion of its downstream end products. The growth of total demand for plastics and the release of recycling potential will be the main factors affecting the trend of ethylene demand in the future. Plastics recycling includes mechanical and chemical recycling. Mechanical recycling relies more on the improvement of the recycling system, (e.g., the improvement of the collecting and sorting system), whereas chemical recycling needs technological breakthroughs and development. Ethylene demand will continue to grow at about 1% per year until 2040. After 2040, the demand of ethylene will flatten at about 87 million tons.

Exhibit ES2 **Methanol demand projection in China**



Source: 2020 data from *Early Warning Report of China Petrochemical Market,* China Petroleum and Chemical Industry Federation and Shandong Longzhong Information Technology Co., 2021

Exhibit ES3 Plastics demand projection in China

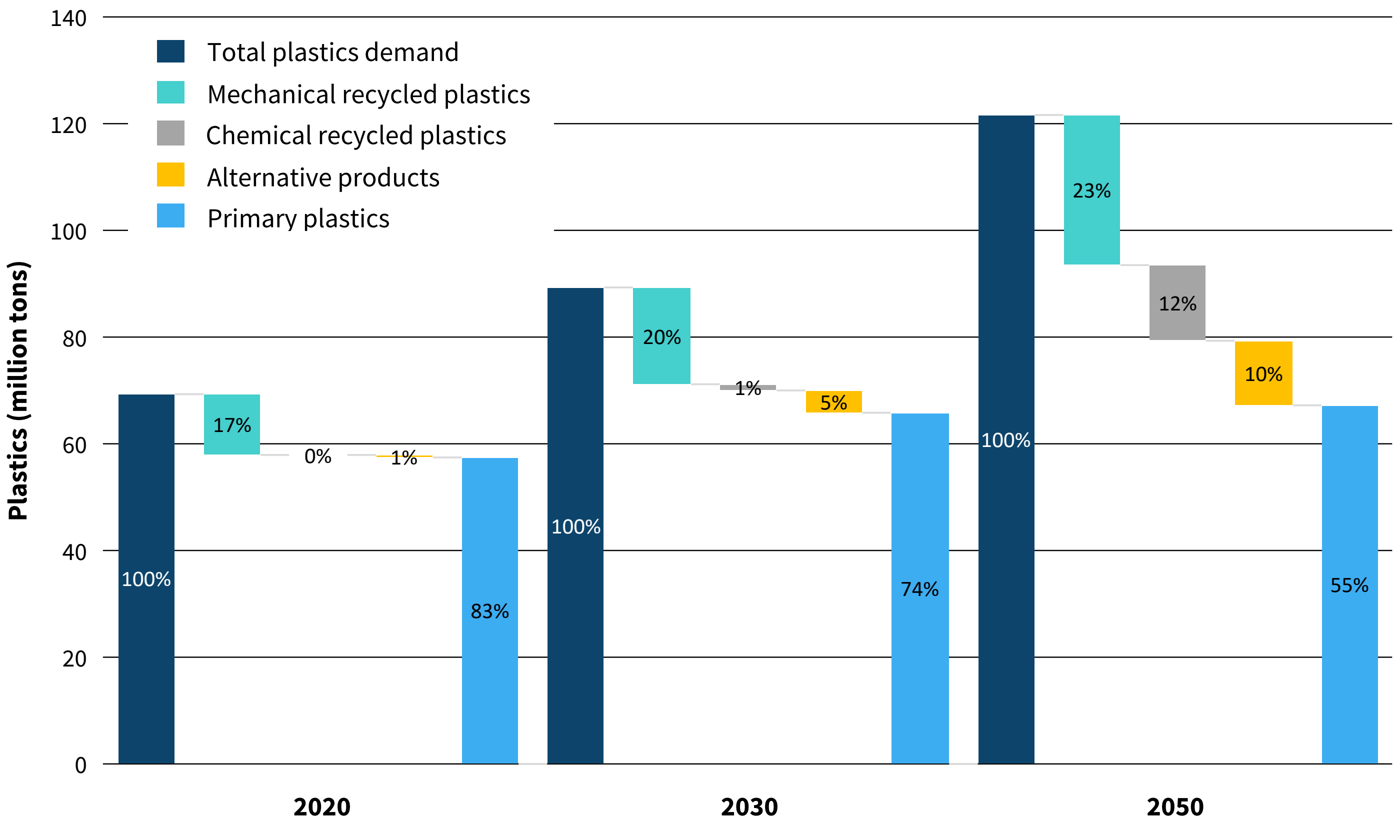
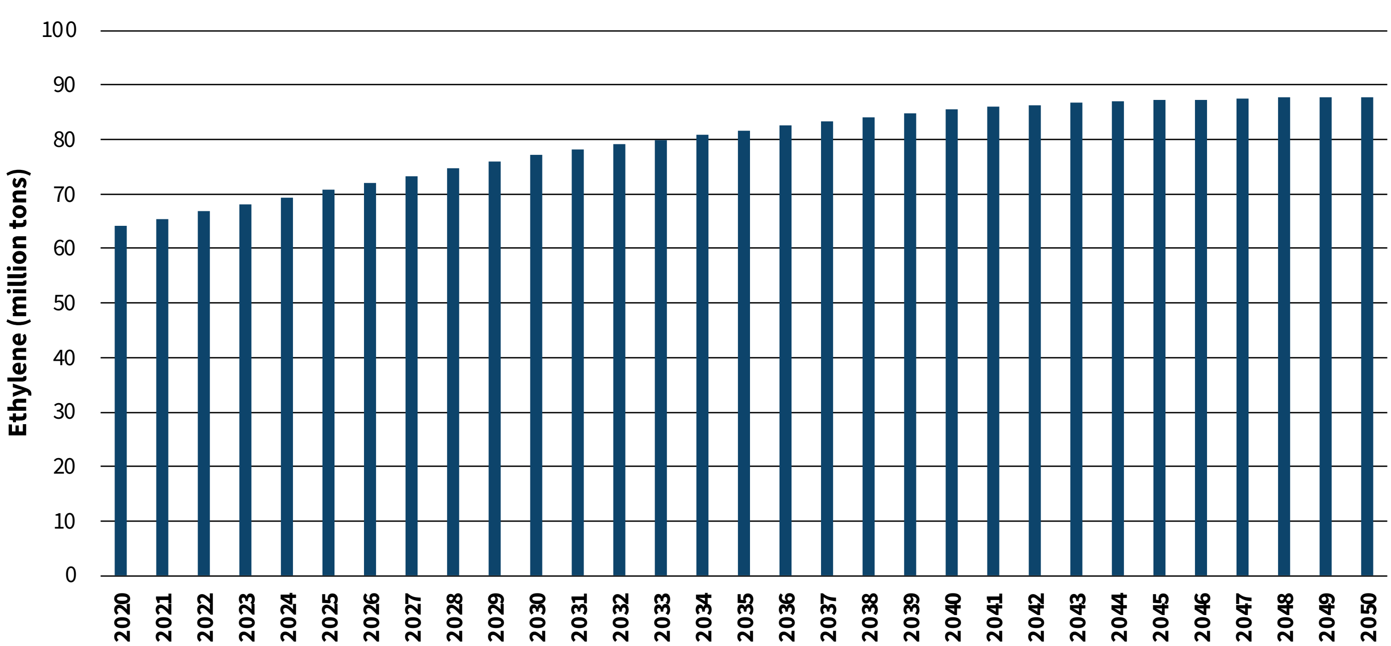


Exhibit ES4 Ethylene demand projection in China



Source: 2020 data from *Early Warning Report of China Petrochemical Market*, China Petroleum and Chemical Industry Federation and Shandong Longzhong Information Technology Co., 2021

Chemicals Industry Decarbonization Pathways: Develop Disruptive Technologies Based on Resource Endowment

Decarbonization of the chemicals industry can proceed from both the demand side and the supply side, and the paths include consumption reduction, high-end production, end-product substitution, efficiency improvement, fuel substitution, feedstock substitution, and back-end treatment. The focus of demand-side decarbonization is to reduce dependence on carbon-intensive products. This includes reducing demand while maintaining the same service level by means of improving efficiency and recycling. It is also important to pivot to greener high-end products or alternative products. Supply-side decarbonization routes mainly deal with process emissions and fuel combustion emissions, supplemented by negative emissions technologies, to fully realize decarbonization.

Exhibit ES5 **Decarbonization pathways of petrochemicals and chemicals industries**

DEMAND SIDE		SUPPLY SIDE	
Consumption reduction	• Increase fertilizer efficiency, reduce fertilizer consumption • Plastic ban/restriction, increase recycling of waste plastics, rubber, and synthetic fiber	**Efficiency improvement**	• Reduce energy consumption through integrated method of production • Reduce energy consumption through coal-based cross-industry production and one-step production of hydrocarbon
High-end production	• Develop high-end products, increase share of advanced materials, special chemicals, and high-end fertilizer • Adjust product structure of oil refining industry, increase share of downstream chemical products, and reduce share of refined oil use	**Fuel substitution**	• Electrify low- to medium-temperature reactions • Substitute fossil fuels with biomass, hydrogen, etc.
End-product substitution	• Develop bio-based material, substitute or partly substitute synthetic materials produced from fossil fuel	**Feedstock substitution**	• Develop low- and zero-carbon feedstocks such as renewable hydrogen and biomass to replace fossil fuel feedstocks
		Back-end treatment	• Develop CCUS to reduce or eliminate carbon emissions from fossil fuel–based processes

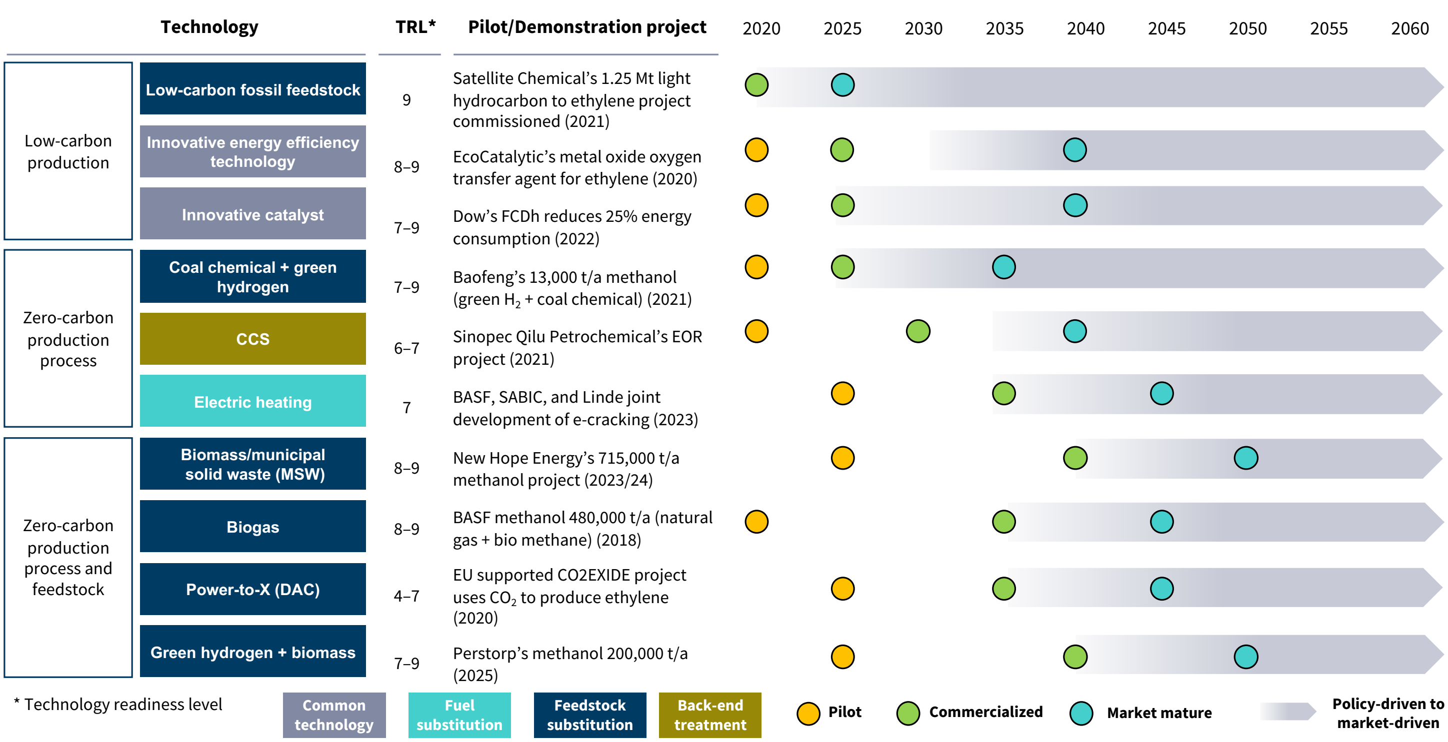
Carbon emissions reduction methods related to chemical product production modes can be considered from three aspects: feedstocks substitutions, fuel decarbonization, and systematic energy conservation. The carbon element in the feedstock should gradually shift from fossil fuels to biomass, biogas, and CO_2, while the hydrogen element should gradually shift from coal and natural gas to biomass, biogas, and green hydrogen.

Even if fossil fuels continue to be used, less carbon-intensive feedstocks should be selected. For example, in ethylene production, the feedstock can be gradually shifted from coal and naphtha to light hydrocarbons where possible. In terms of fuel selection, chemical processes should be electrified as much as possible, and the energy source should be gradually shifted from fossil fuels to renewables. In terms of systematic energy conservation, optimization of energy management and catalyst technologies should be used to reduce the energy demand of the reaction to reduce the carbon emissions.

Technologies that can promote decarbonized transformation of chemical production will generally reach the level of large-scale deployment by 2050, and the timing of developments can be estimated according to their readiness levels. In terms of technology readiness, demand reduction methods like recycling and energy efficiency improvement are highly feasible in the short and medium term. Such technologies have unlocked significant carbon reduction potential so far but could be further advanced. However, neither demand reduction nor energy efficiency improvement could achieve complete decarbonization.

Although disruptive technologies such as fuel electrification, green hydrogen utilization, biomass utilization, and carbon capture, utilization, and storage (CCUS) have greater potential to reduce carbon emissions, their technology maturity is relatively low. In general, available decarbonization technologies in the chemicals industry will achieve commercial application around 2035, which will greatly boost zero-carbon transformation in the medium and long term. Exhibit ES6 shows the technology readiness outlook for related technologies.

Exhibit ES6 **Chemicals industry decarbonization technology outlook**



Because the cost of disruptive technologies such as green hydrogen and CCS is expected to drop significantly in the future, the cost competitiveness of low-carbon and zero-carbon chemical production will be greatly enhanced. The cost of low-carbon and zero-carbon production routes is largely determined by fuel and feedstock costs, while the cost of capital and equipment plays a smaller role unless extensive retrofitting is required. In addition, the cost competitiveness of various production routes varies from region to region due to different resource endowments and market conditions.

Green hydrogen is an important feedstock for zero-carbon chemical production, and its cost reduction mainly comes from the sharp drop in the cost of renewable power, the reduction of the cost of electrolyzers, and the improvement of conversion efficiency. Electricity cost is a major part of green hydrogen cost at as much as 60%–70%. At present, the cost of hydrogen production in areas with abundant green power resources in China is about US$2.6/kg, and it could drop to US$1.7/kg or even lower in areas with rich renewable resources by 2050. In terms of equipment, the current cost of electrolyzer is around US$300/kW, and the price is expected to drop to US$100/kW by 2050.

In terms of conversion efficiency, electricity consumption in hydrogen production could drop to 45 kWh/kg hydrogen by 2050, about 20% lower than current levels. Green hydrogen cost will depend on whether on-site renewables or grid electricity are utilized. Because electricity market reform might bring uncertainties to the trend of electricity prices in different regions in the future, the electricity and hydrogen prices in this cost model are at the national average level.

The high concentration of CO_2 emitted from chemical production creates excellent conditions for CCS applications at a relatively lower cost. In the future, the cost of CCS will continue to fall as the technology evolves and is used at economies of scale. The cost of first-generation capture technology will drop by 15%–25% by 2035, and as second-generation capture technology becomes commercially available its cost will be 5%–10% lower than that of first-generation technology. By 2040, with the formation of CCS clusters, the cost of second-generation capture technologies will be 40%–50% lower than current levels. By 2050, the cost will drop even further.

Biomass resources are relatively limited in China. Although the future trend of biomass large-scale utilization is expected to reduce the cost of biomass-based chemical production, compared with other technologies, biomass will play a limited role and is only likely to be applied on a large scale in areas where biomass resources are particularly advantageous.

As is shown below, this study analyzes the cost of different zero-carbon production routes for ammonia, methanol, and ethylene.

In the short term, conventional coal to ammonia with CCS is a more economical routes of producing decarbonized ammonia, while with the rapid decline of green hydrogen cost, green hydrogen-based ammonia could achieve lower cost in the long term. At present, the production cost of ammonia with CCS is about US$570/t, with a cost premium of about 60% compared with the conventional route. However, this cost will drop to US$490/t by 2030 and US$430/t by 2050. Due to the overall low cost of CCS application in ammonia production, existing coal-to-ammonia plants could be equipped with CCS in the short term.

In the long run, however, if carbon price is not taken into account, the cost of green hydrogen-based ammonia will reach parity with the cost of coal-based ammonia at a hydrogen end-use price of about US$1.5/kg by 2050. With the higher future expected carbon price, green hydrogen-based ammonia synthesis will be more cost competitive. In addition, in regions with good renewable energy conditions and low zero-carbon electricity price, the cost competitiveness of green hydrogen-based ammonia will be more prominent.

When hydrogen is cheaper than US$1.8/kg, green hydrogen-based ammonia will be more cost competitive than coal-based ammonia with CCS. If on-site renewable power is utilized for hydrogen production when the electricity price is less than US$27/MWh, the cost of green hydrogen-based ammonia is even lower. By comparing these cost conditions, early opportunities for ammonia production pilots with CCS or green hydrogen can be identified and the most cost-competitive zero-carbon production route can be selected for ammonia production in different regions.

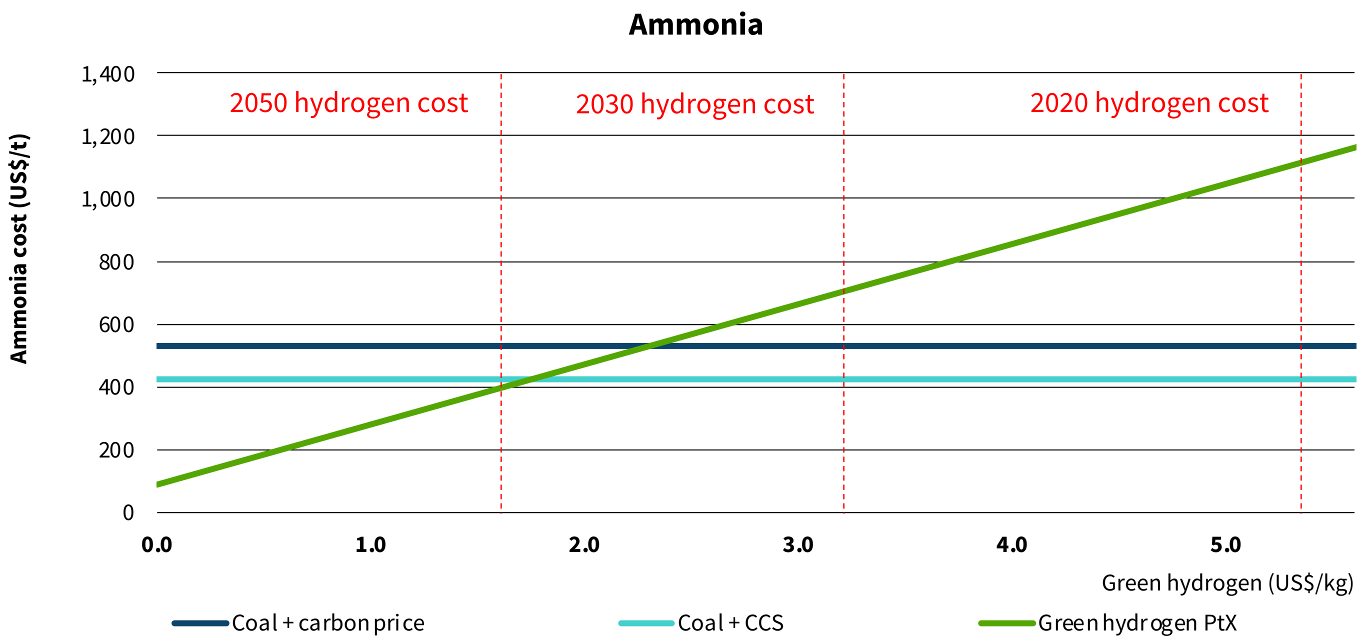
Similarly, the conventional coal-to-methanol process with CCS is the most cost-efficient zero-carbon production route for methanol. Even with a green premium of more than 70%, the cost of this process with CCS was still significantly lower than other zero-carbon production routes in 2020. By 2030, the green premium for coal-based methanol with CCS would be less than 15% even at a lower carbon price. By 2050, coal-based methanol with CCS will be more cost competitive than coal-based methanol with a carbon price. The competitiveness of the CCS route comes from two aspects. First, the CO_2 concentration in coal chemical production is very high at close to 100%, so the cost of carbon capture can be significantly reduced. Second, China's methanol production is highly dependent on coal, and the application of CCS enables the best use of existing production capacity and assets, avoiding uncertainties caused by large-scale transformation.

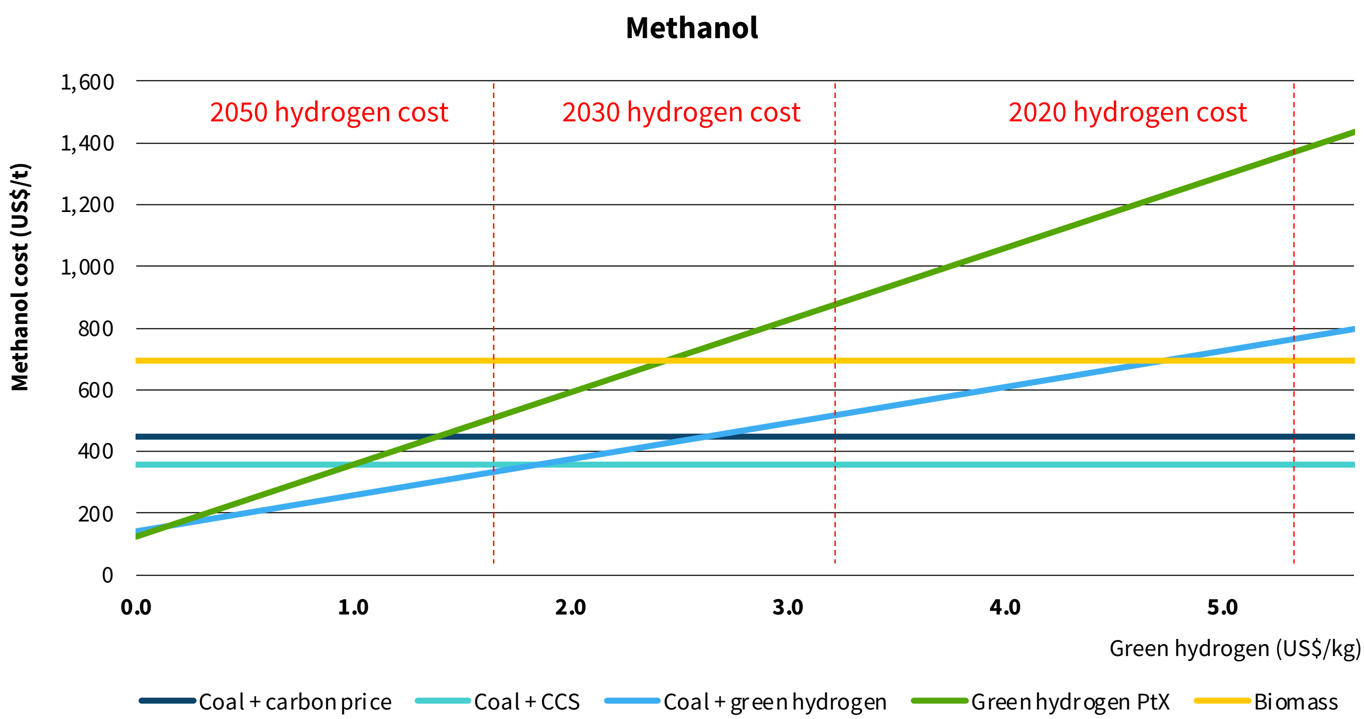
However, with the rapid cost reduction of green hydrogen, methanol production routes using hydrogen — through either the conventional coal chemical process coupled with hydrogen or direct hydrogen-based power-to-X (PtX) — could achieve ideal cost-effectiveness in the long term. Compared with the cost of CO_2 feedstock, the cost of green hydrogen is still the bottleneck factor determining the cost competitiveness of PtX methanol production, while industry by-product hydrogen could be utilized as a transitional solution. By 2050, even if the cost of CO_2 feedstock is as high as US$100/t, which is equivalent to the current cost of direct air capture, the cost of green hydrogen will still account for about 60% of the total at a hydrogen price as low as US$1.6/kg. When the end-use hydrogen price is lower than about US$0.8/kg, the production cost of green hydrogen-based zero-carbon methanol will be lower than that of coal-to-methanol with CCS.

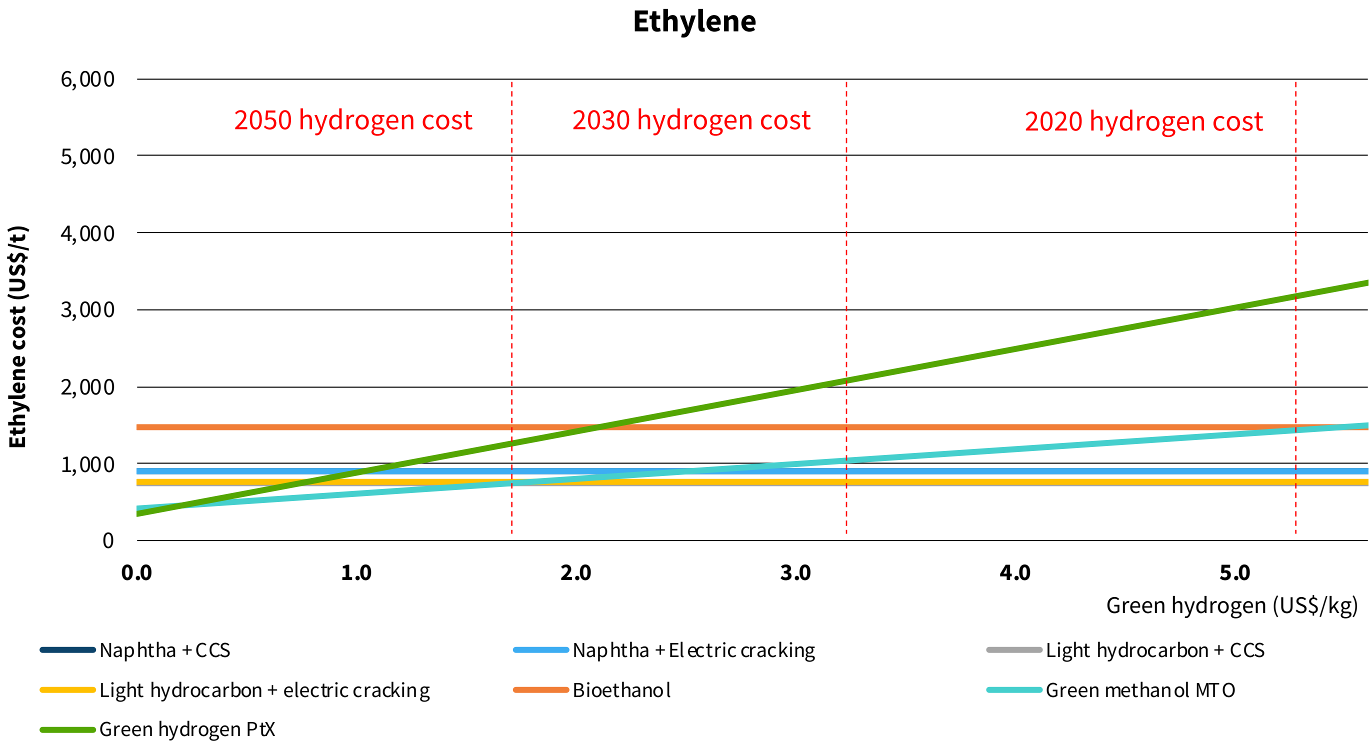
The cost of green methanol-based ethylene production has great potential to decline, mainly due to the decreasing cost of green hydrogen. The cost of naphtha- and light hydrocarbon-based ethylene production can be reduced slightly due to the maturity of energy management technology, the reduction of electricity price, and the declining naphtha feedstock cost. The cost of the fossil fuel feedstock route with CCS or electric cracking will reach about US$800/t, but the cost competitiveness of naphtha- and light hydrocarbon-based routes will be weakened if Scope 3 emissions are considered.

The cost of the biomass route could be reduced with the development of biomass technology, but the constraints on feedstocks and the demand for electricity could become obstacles to further cost reduction. It is estimated that the cost of biomass-based ethylene will still be close to US$1,600/t in 2050. The declining cost of green methanol-based ethylene has great potential, which is mainly due to the decreasing cost of green hydrogen. The maturing of PtX breakthroughs will also lead to cost reduction. The cost of green hydrogen-based PtX and green methanol-based MTO routes is expected to decrease to about US$1,100/t in 2050, which will be competitive with fossil energy routes.

Exhibit ES7 **Zero-carbon production cost of ammonia, methanol, and ethylene under different green hydrogen prices (2050)**



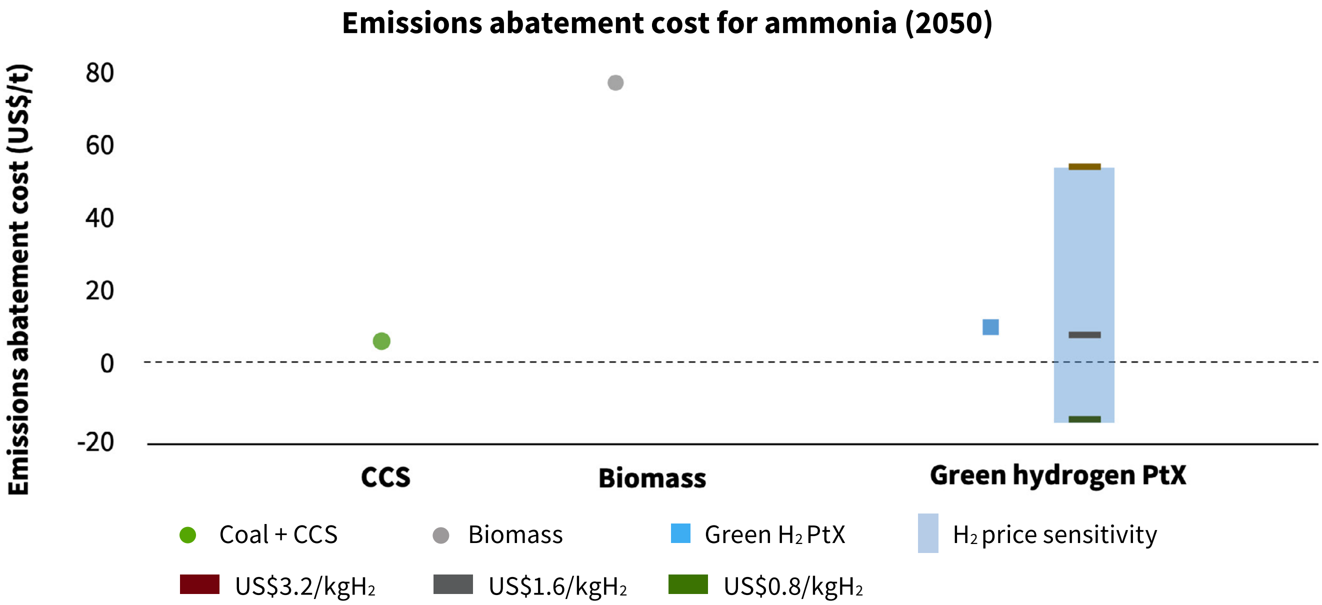


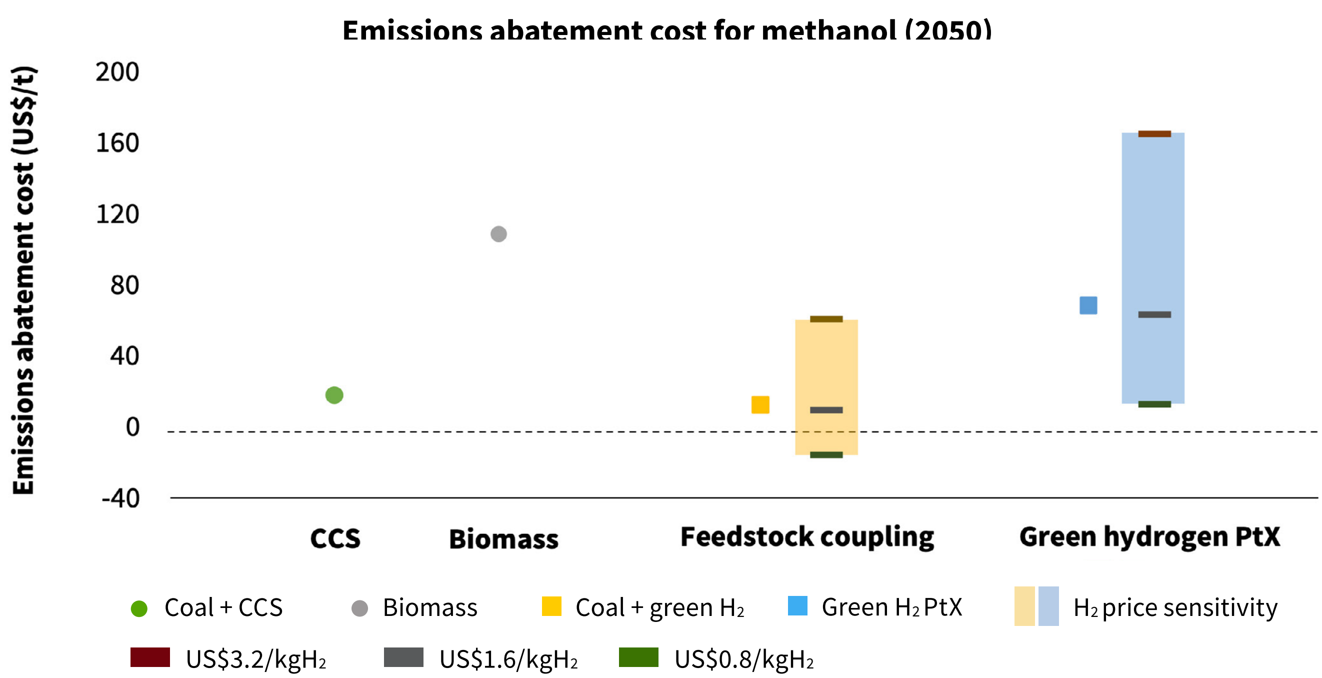


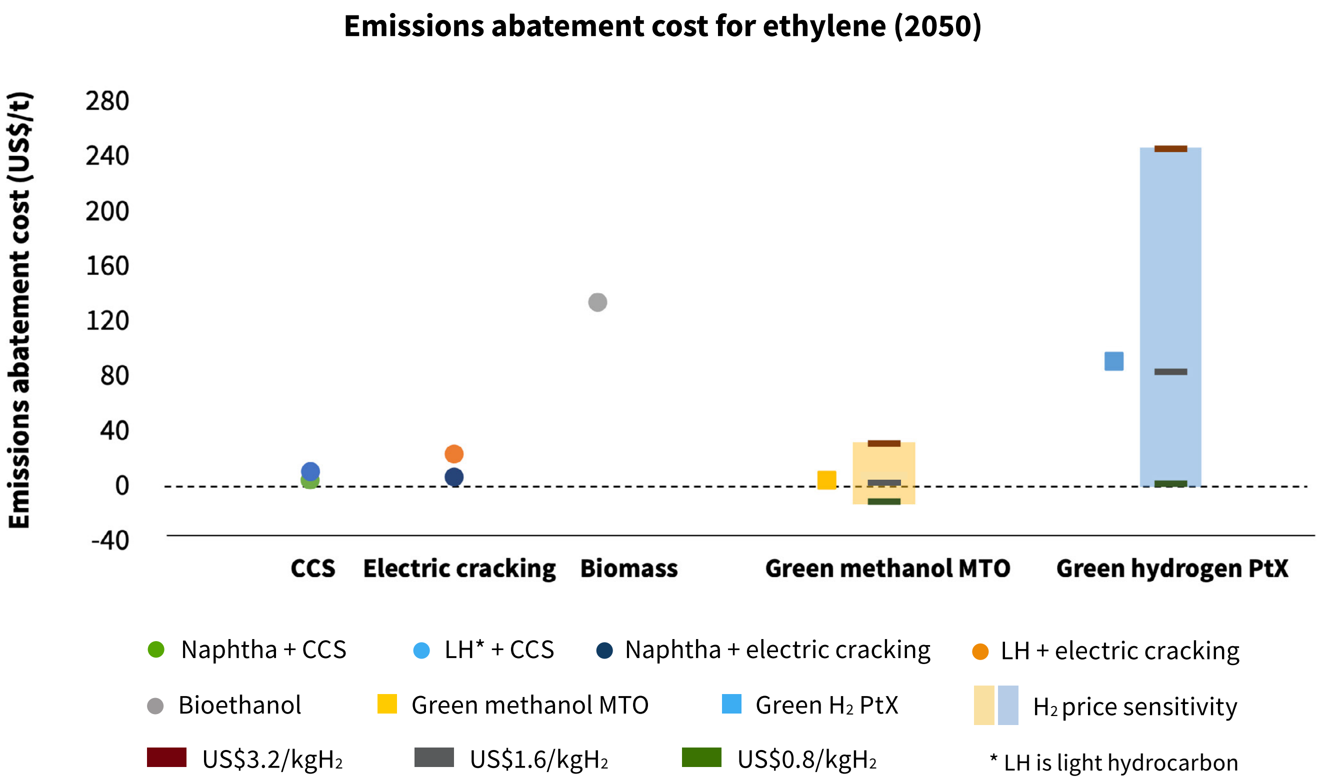
Assumptions: Carbon price US$0/t in 2020, US$21/t in 2030 and US$43/t in 2050; CCS costs US$56/t in 2020, US$36/t in 2030 and US$18/t in 2050 for high concentrated CO_2 capture.

Exhibit ES8 shows the carbon abatement cost for each zero-carbon production routes for ammonia, methanol, and ethylene in 2050. The carbon abatement cost of CCS and electric heating will be about US$32/t. The carbon abatement cost of the biomass route will remain high. For the green hydrogen-based route, the cost varies greatly with the delivery price of green hydrogen. In this study, the carbon abatement cost is calculated at three green hydrogen delivery costs of US$3.2/kg, US$1.6/kg, and US$0.8/kg, respectively. When the green hydrogen cost is low enough, the abatement cost could even be negative. In the future, when the carbon price is higher than the carbon abatement cost, zero-carbon production routes will be more economical than conventional routes.

Exhibit ES8 **Carbon abatement costs for different chemicals (2050)**






Emissions abatement cost for ethylene (2050)
Emissions abatement cost (US$/t)
280
240
200
160
120
80
40
0
-40
CCS
Electric cracking
Biomass
Green methanol MTO
Green hydrogen PtX
Naphtha + CCS
LH* + CCS
Naphtha + electric cracking
LH + electric cracking
Bioethanol
Green methanol MTO
Green H2 PtX
H2 price sensitivity
US$3.2/kgH2
US$1.6/kgH2
US$0.8/kgH2
* LH is light hydrocarbon

The Road to Zero Carbon: Timeline, Regional Implication, and Transition Model

Methods for zero-carbon transformation of China's chemicals industry include industrial structure optimization, energy structure change (including feedstock and fuel switch), energy conservation, resource recycling, and CCUS. Due to the different technology readiness, cost competitiveness, and development stages of different methods, it is critical to establish an integrated action plan that combines the optimal options.

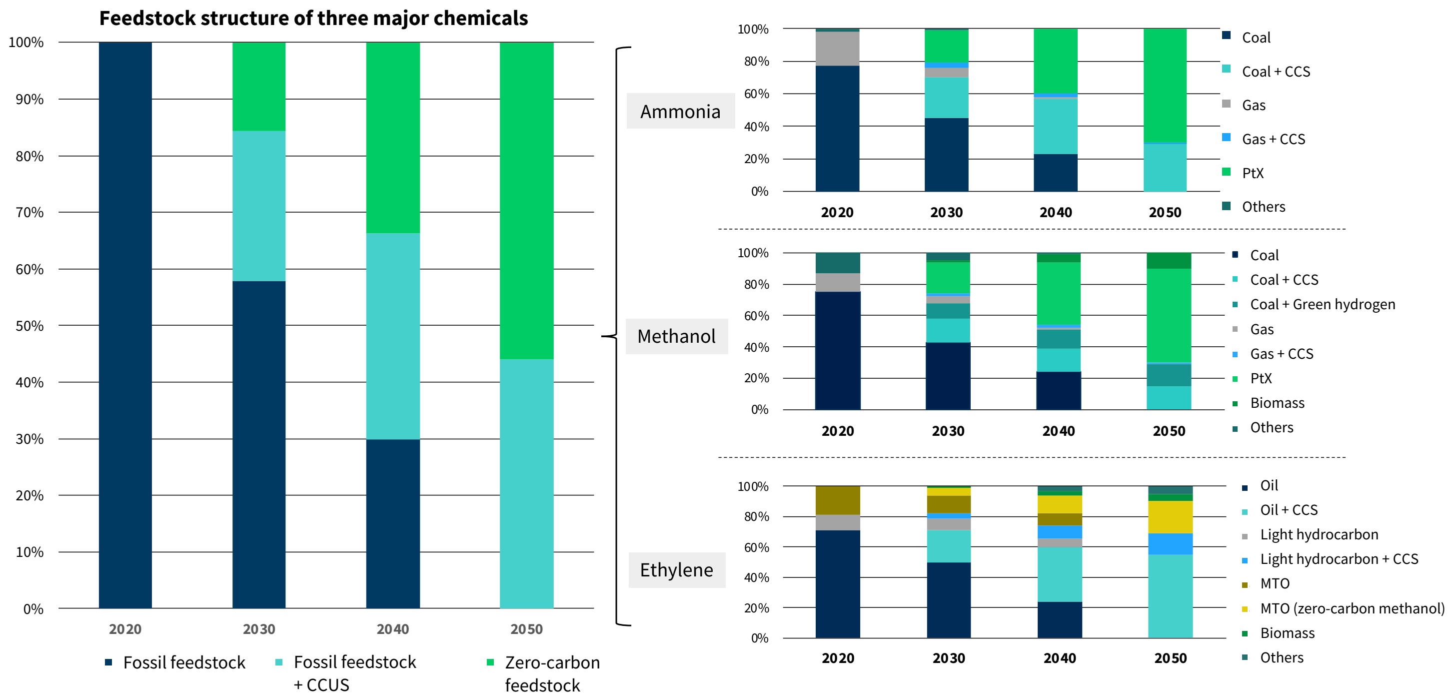
In the zero-carbon scenario, the transformation of China's chemicals industry will present the following main features. First, the current production mode with coal as the dominating feedstock and fuel will gradually shift to one with more diversified feedstocks and fuels, and green hydrogen will replace coal as the most important feedstock due to the gradual expansion of the PtX route. Second, because the existing assets based on fossil fuel are relatively young, CCUS could be installed on the existing facilities at a large scale in the short to medium term, while green hydrogen-based production routes will be deployed at scale in the medium and long term. Third, even if fossil fuel–based production routes could be equipped with CCUS, there will still be large-scale withdrawal of assets based on coal and gas, given the constraints of backward capacity phaseout and emissions control.

Exhibits ES9 and ES10 respectively show the transformation roadmap of China's chemicals industry in the zero-carbon scenario, and the changes of penetration of different routes in the transformation process of ammonia, methanol, and ethylene production.

Exhibit ES9 **Transformation roadmap for China's chemicals industry in the zero-carbon scenario**

		2020 / 2030	2040	2050 / 2060
Industrial structure optimization		Phase out backward capacity, increase share of high-end products, increase chemicals while reducing oil consumption, and strictly control added capacity		
Energy structure change	Fuel	30% electrified	Nearly 50% electrified	Almost 100% electrified where possible
	Feedstock	Share of fossil fuel (mainly coal) to primary chemicals reduced to 80%	<60% coal-to-primary chemicals	<40% coal-to-primary chemicals, while zero-carbon feedstock accounts for 60%
Energy conservation		Reuse of waste heat and pressure, advanced coal gasification technology, increased level of automation and intelligent production		
Resource recycling		Optimized plastic collection and sorting system, enhanced mechanical recycling, with a recycling rate of nearly 40%	Breakthrough in chemical recycling and optimized value chain, with a recycling rate of nearly 50%	Scaled plastic recycling industry with a recycling rate of over 60%, 1/3 of which comes from chemical recycling
CCUS		Key pilots and demonstration, with over 30% fossil-based capacity equipped with CCUS	Scaled development with over 60% fossil-based capacity equipped with CCUS	Largely deployed with 100% fossil-based capacity equipped with CCUS

Exhibit ES10 Feedstock structure of three major chemicals in the zero-carbon scenario

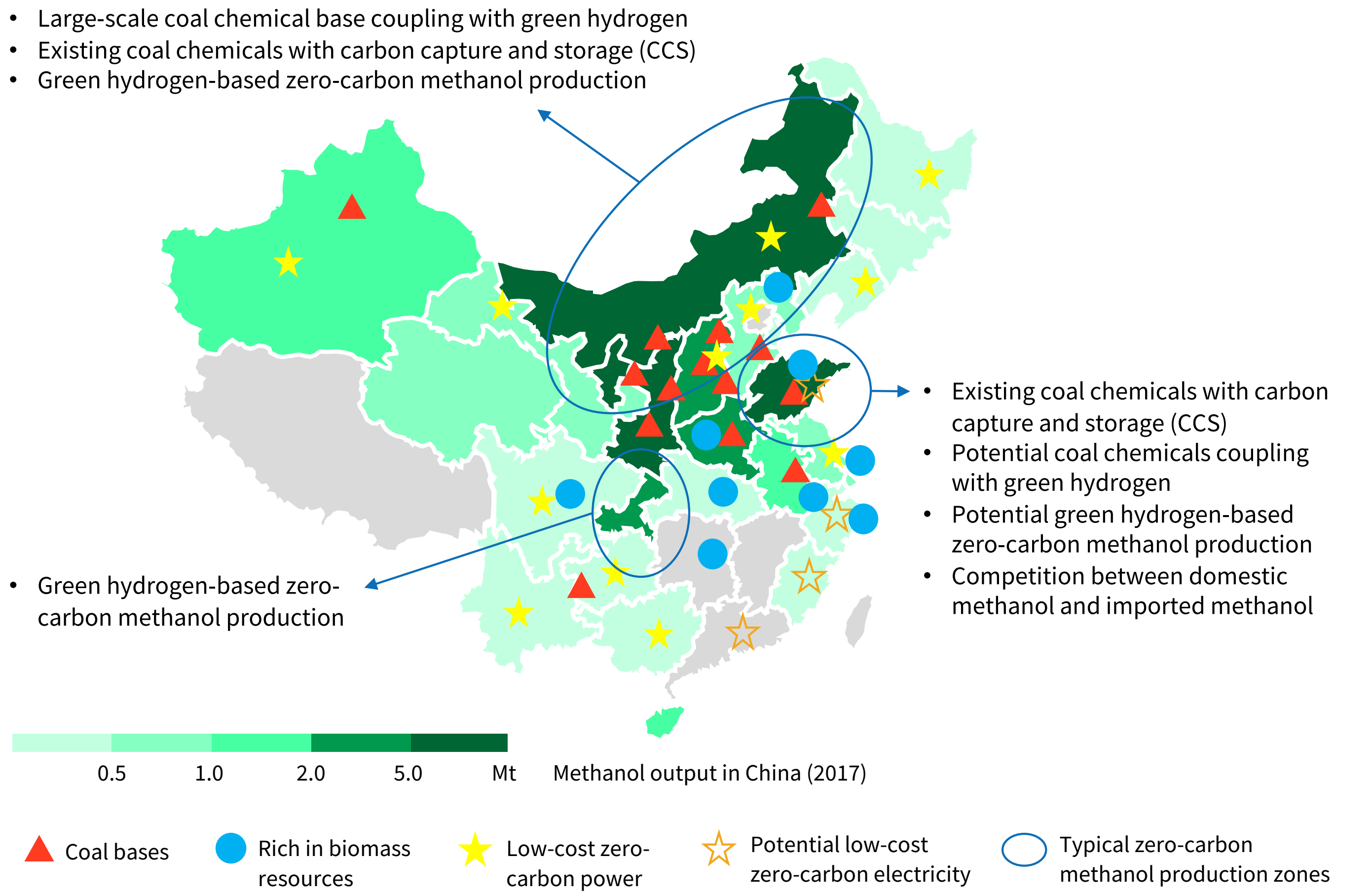


The pathway of zero-carbon chemical production depends on decarbonization technologies and resources, including zero-carbon electricity, suitable CCS storage locations, and biomass resources. Through comprehensive analysis of technical feasibility, cost competitiveness, and resource availability, zero-carbon chemical production capacity is more likely to be close to regions with better zero-carbon resource conditions. Accordingly, the distribution of chemical production will likely relocate from places close to fossil energy to places close to zero-carbon resources.

Based on the comprehensive analysis of current capacity distribution, existing chemical base planning, and distribution of zero-carbon resources, the potential geographical distribution of China's zero-carbon chemical capacity in the future could be identified. Taking the distribution of zero-carbon methanol as an example, the following characteristics could be identified:

- In the coal chemicals industry in the "Golden Triangle" region in northwest China, coal chemical plus green hydrogen, coal chemical with CCS, and green hydrogen-based PtX methanol production can be simultaneously developed due to the excellent renewable resources and available carbon storage locations.
- Southwest China including Yunnan, Sichuan, and Chongqing could become a typical region for green hydrogen-based PtX methanol production due to its advantages in hydro resources and the relatively high cost of methanol production from fossil fuels.
- Regions located in coastal areas with superior coal resources, such as Shandong, have a lot of uncertainty in their potential zero-carbon production mode.
- Only relatively small methanol capacity is possible in provinces with abundant biomass resources.

Exhibit ES11 **Typical zero-carbon methanol capacity regions in China and possible capacity types**



The central government's plan for electricity and hydrogen transportation between eastern and western areas will impact the capacity layout of chemicals in the future. If long-distance infrastructure could ensure large-volume cheap electricity or hydrogen transported from the west to eastern coasts, the existing production capacity in the east could leverage abundant renewable resources in the west and minimize risks of stranded equipment.

In addition, there may be three transition models of decarbonized chemical production in China in the future: (1) large-scale and centralized production model in the chemicals industry; (2) smaller-scale distributed production model; and (3) competition with imported chemical products.

- In Model 1, the transformation requires a combination of multiple routes to form an integrated solution due to land limitations on large-scale green hydrogen applications, the intermittency of on-site renewable-based hydrogen production, and the limitations in distribution and scale of suitable CCS sites.

- In Model 2, the transformation needs to consider how to obtain hydrogen and carbon elements in feedstocks because the location and scale of distributed zero-carbon chemical production are more flexible and areas with better renewable energy conditions will be preferred choices.

- In Model 3, China may also turn to imported chemical products instead of domestic production because there is still a certain green premium for zero-carbon chemical products.

Furthermore, in addition to purchasing end products, China may also choose products from later stages in the value chain as feedstocks to produce end products domestically, avoiding carbon-intensive processes.

Policy Recommendations

Support innovation by leading players including state-owned enterprises (SOEs), with special focus on research, development, and demonstration (RD&D) of key technologies and equipment. After years of development, China's chemicals industry has formed featured development patterns led by SOEs and based on large-scale production bases, with large-scale technology, equipment, and production capacity leading the world. The government should effectively guide SOEs and leading private participants, providing targeted support for key technologies and equipment, strengthening cross-sector synergies, and eliminating concerns about the risks of developing cutting-edge technologies by means of policy support and financial subsidies.

Promote circulation and efficient utilization of products and force elimination of backward production capacity on the supply side through demand reduction. At present, some end products still have problems with extensive and inefficient utilization, but the improvement of utilization efficiency can reduce the demand for primary chemical products, achieving emissions reductions. In terms of policy, standardized management should be improved to guide rational control of chemical consumption and alleviate supply risks and pressure of emissions control. At the same time, recycling of chemical products should be promoted.

Leverage the international market to dynamically adjust the import and export policies of feedstocks while ensuring supply chain security. On the premise of supply chain security, the structure of import and export products should be adjusted dynamically based on the characteristics of China's chemicals industry value chain and global resources. In the short term, attention should be paid to carbon reduction with the use and import of light hydrocarbon feedstocks. In the medium term, green hydrogen could be imported from countries with abundant renewables. In the long term, capacity and structure of primary chemical products could be further optimized. In addition, global technological exchanges should be actively promoted.

Advance support for carbon reduction technologies to reduce their costs and internalize carbon costs of conventional routes by policy methods such as carbon markets. Encouraging routes with low emissions and suppressing routes with high emissions simultaneously could gradually reduce the green premium of low-carbon and zero-carbon chemical production. Policy methods such as subsidies and tax credits could encourage adoption of disruptive technologies such as green hydrogen while accelerating the integration of petrochemicals and chemical industries into the national carbon market and integrating emissions costs of conventional routes into production costs.

Guide the coal chemicals industry to proper utilization of coal, that is, using coal as a feedstock to provide carbon elements, not as fuel or a reaction agent to produce hydrogen. Policy should rationally control the transformation of the coal chemicals industry to avoid excessive radical control, using coal as a feedstock for chemical products, not as fuel. Efforts should be made to promote upgrading heating systems for chemical plants, especially high-temperature reaction equipment, and encourage the development of new energy sources. In addition, priority should be given to clean hydrogen production to avoid using coal as a hydrogen production reaction agent while replacing gray hydrogen with green hydrogen. In the long run, Scope 3 emissions from chemical products could also be included in the assessment, and zero-carbon production routes should be promoted scientifically and under the premise of supply security.

Establish industry standards, improve the certification system for zero-carbon products, and cultivate the demand market for zero-carbon chemical products by means such as tax credits. Industry standards and carbon accounting and certification systems for low-carbon and zero-carbon chemical products should be established, encouraging procurement by governments at all levels and SOEs, and gradually expanding adoption. In addition, the consumption habits of low-carbon or zero-carbon chemical products should be gradually adopted by individual consumers through promotions by large-scale chemical consumer companies as a starting point. Demand for low-carbon and zero-carbon chemical products as well as related consumption habits should be established throughout society.

Promote the formation of a green hydrogen whole-value chain and integrate the application of green hydrogen in the chemicals industry into the green hydrogen policy system. The industrial application side and the production, storage, and transportation of green hydrogen will promote the continued maturation of each other. Green hydrogen is a necessary step for chemicals industry decarbonization, and the chemicals industry is also the largest downstream industry in hydrogen utilization at present. The huge demand for hydrogen from the chemicals industry should be leveraged to alleviate market maturation concerns for major players in other segments such as hydrogen production, storage, and transportation. The structure of the demand side should be optimized to synergize all segments of the hydrogen energy value chain.

Introduction

The chemicals industry — accounting for 20% of the industrial sector's total emissions and 13% of the country's total CO_2 emissions — is a key sector to decarbonize for China to reach carbon neutrality.[i] The challenges to decarbonize this heavy industry include electrifying its processes and using less carbon-intensive feedstocks. The relatively new capacity of China's primary chemicals also brings challenges to its rapid transformation. China has made great efforts to build a 1+N policy system to achieve the goals of carbon peaking and carbon neutrality.[ii] China strengthens top-level deployment while promptly identifying action plans in focused areas, key industries, and local regions.

According to The Opinions of the CPC Central Committee and the State Council on the Complete and Accurate Implementation of the New Development Concept of Carbon Peaking and Carbon Neutrality,[1] equal or reduced capacity substitution must be strictly implemented for energy-intensive and high-emissions projects. Capacity is highly controlled for the coal electricity, petrochemicals, and coal chemicals industries, and all new-built and retrofitted oil refining projects and new-built ethylene projects are prohibited unless being included in the national development plan. At present, Chinese chemical players are actively promoting the advancements of carbon neutrality. For example, Sinopec strives to achieve carbon neutrality 10 years ahead of the national target. Baofeng Group is building the world's largest single-plant solar-powered electrolysis hydrogen production project to reduce the carbon emissions of its coal chemicals business.

RMI is one of the first institutions in China to research China's zero-carbon roadmap. In 2019, RMI and the Energy Transitions Commission (ETC) jointly released *China 2050: A Fully Developed Rich Zero-Carbon Economy,*[2] which analyzed the vision of China's entire economy achieving zero-carbon emissions and provided technical reference for the country's long-term strategic developments. In September 2021, RMI released *Pursuing Zero-Carbon Steel in China,*[3] which forecast a specific roadmap for the steel industry to reach zero carbon. This report is also part of RMI's research series on heavy industry decarbonization and focuses on the chemicals industry.

Compared with the slowing demand growth for steel and cement, the overall demand for China's chemicals industry will reach peak demand later, as the economy develops. The transformation of production technology routes is more important than demand control for chemicals industry decarbonization. The research in this report focuses on zero-carbon production routes in the chemicals industry. Zero-carbon production means achieving net-zero CO_2 emissions during production process. Back-end treatments like carbon capture and storage (CCS) can be used. Chemical products of zero-carbon production are zero-carbon chemical products. The chemicals industry should cooperate with upstream and downstream companies to eliminate Scope 3 emissions to achieve life-cycle zero-carbon emissions. Low-carbon production is a transitional solution to zero-carbon production (i.e., a significant reduction in carbon emissions from the production process). The chemicals industry needs to utilize diverse carbon abatement technologies to reduce

i For the purpose of this research, the chemicals industry refers to the petrochemicals and chemicals industries, which use petroleum, coal, and other upstream feedstocks to carry out chemical processing activities. The chemicals industry includes both the petroleum and nonpetroleum feedstock industry chains.

ii "1+N" is the policy system for China to accelerate carbon peaking and carbon neutrality. The Opinions of the CPC Central Committee and the State Council on the Complete and Accurate Implementation of the New Development Concept of Carbon Peaking and Carbon Neutrality is "1," which is at the central level to promote systematic planning and overall deployment on carbon peaking and carbon neutrality. The Notice of the State Council on the Issuance of Carbon Peaking Action Plan by 2030 is the overall deployment of the carbon peaking stage. "N" includes the implementation plan for carbon peaking in energy, industry, transportation, urban and rural construction, and other sub-fields and industries, as well as the guarantee plans for scientific and technological support, energy security, carbon sink capacity, financial and price policies, standard measurement system, inspection, and assessment.

or even eliminate carbon emissions from both the energy and feedstock perspectives, and to promote carbon peaking and carbon neutrality.

Our analysis shows that the carbon neutrality goal will drive new demand for ammonia, methanol, and ethylene in China as well as increase demand for conventional applications. The product portfolio, feedstock structure, fuel mix, and production technology will also undergo significant changes. Due to the uncertainties in demand and supply balance, technology development pace, and cost structure, this report is more focused on China's chemicals industry zero-carbon transformation and the short-, medium-, and long-term forecast, along with technology and economic development, under the assumed time frame, than on in-depth identification of the decarbonization timetable. The report provides recommendations for policymaking and market developments.

Initiating a Zero-Carbon Pathway for China's Chemicals Industry: Challenges and Opportunities

CO_2 emissions from the chemicals industry account for about 20% of emissions of the industrial sector and about 13% of China's total carbon emissions.[4] China is the world's largest producer and consumer of chemical products. The zero-carbon transformation of China's chemicals industry is of great significance to the national carbon neutrality goal and the zero-carbon transformation of the global chemical value chain. Both challenges and opportunities exist on the zero-carbon pathway for China's chemicals industry. Key challenges include increasing demand, coal dependence, and relatively young assets. However, the zero-carbon transformation of China's chemicals industry also has unique opportunities, including the scaling of new technology, the willingness and ability of state-owned enterprises to lead the decarbonization movement, and integrated industry development.

The World's Largest Producer and Consumer of Chemical Products

The chemicals industry consists of the petrochemicals and chemicals industries, namely, the petroleum feedstock industry chain and the nonpetroleum feedstock industry chain. The chemicals industry is a process industry in the industrial production sector,[iii] using natural resources as feedstocks to produce bulk products for nonretail purposes that are used as feedstocks for the product industry through physical and chemical reactions. The upstream feedstocks of chemical products mainly include coal, oil, natural gas, raw salt, quartz, and other natural resources. Because China is rich in coal and short of oil and gas, its coal chemicals industry accounts for a larger proportion of its chemicals industry than other countries. The chemicals industry has multiple product categories, including bulk chemicals and fine chemicals. Bulk chemicals, such as olefins, aromatics, etc., are in the upstream of the chemicals industry chain and have larger production scale but lower profits. Fine chemicals, which are used for pesticides, coatings, etc., are deep processed from bulk chemicals as feedstock and have smaller production scale but higher added value.

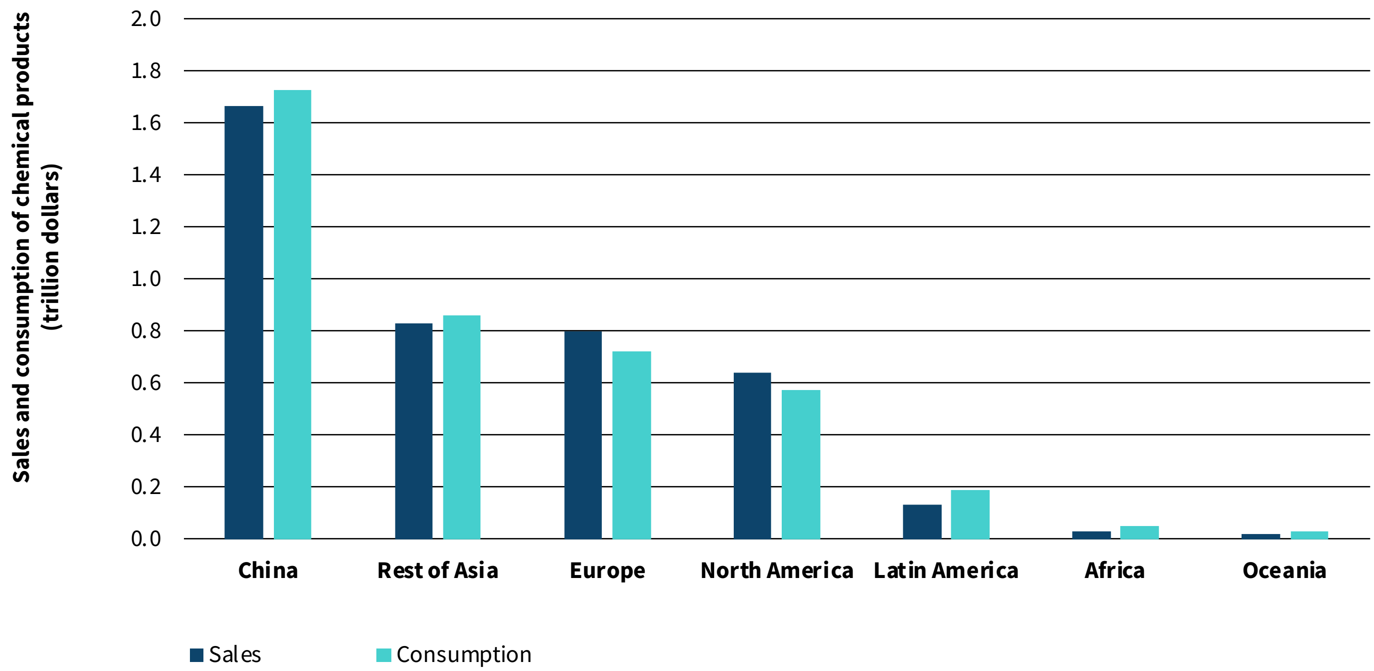
China is the world's largest producer of chemical products, with increasingly international influence. As shown in Exhibit 1, according to the European Chemical Industry Council (CEFIC), the sales volume of China's chemical products in 2019 was US$1.6 trillion, accounting for 40.6% of the global total, and is expected to reach 48.6% of the global total in 2030.[5] China's chemicals industry has maintained rapid growth in recent years, with an average annual growth rate of 5.2% in industrial added value from 2015 to 2020.[iv,6]

China is also the world's largest consumer of chemical products, maintaining rapid growth. According to the German Chemical Industry Association (VCI), China's consumption of chemical products in 2019 amounted to US$1.7 trillion, accounting for 41.6% of the global total, 3 percentage points higher than 2018's 39.1%.[7] China's bulk chemicals also have large global market share, with ammonia, methanol, and ethylene accounting for about 30%, 60%, and 20% of total global consumption, respectively, according to IHS Markit.[8] Ethylene consumption refers to the ethylene apparent consumption. If the downstream products of the ethylene industry chain are included, the proportion can be further increased. For example, China's consumption of low-density polyethylene accounts for 34% of the world's total.

iii The industrial production sector is divided into the process industry and product industry. The process industry involves physical and chemical reactions using natural resources as feedstock, including the chemicals industry, building materials industry, and metallurgy industry. The product industry mainly involves physical reactions using products of the process industry as feedstock, producing products that are directly used by human beings, such as automobiles and refrigerators.

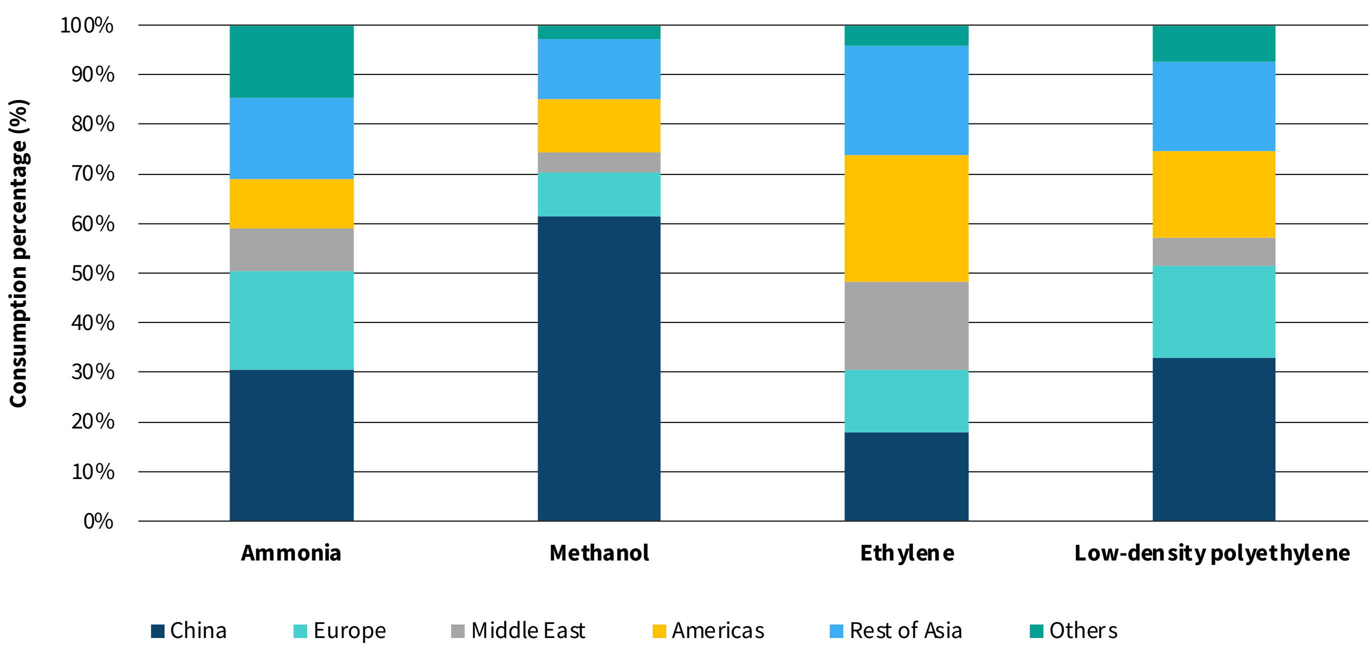
iv Industrial added value refers to the balance of the total results of all production activities of an industrial enterprise after deducting the value of material products and services consumed or transferred in the production process, and is the newly added value in the production process of the industrial enterprise.

Exhibit 1 Sales and consumption of chemical products in different regions (2019)



Source: CEFIC, VCI

Exhibit 2 Consumption of major chemical products in different regions (2020)



Source: IHS Markit

Overall, China's chemical industry shows overcapacity for low-end products, while undercapacity for high-end products. Conventional chemical products including urea, calcium carbide, caustic soda, and soda ash have suffered from low-capacity utilization for a long time. The industry is trying to control the excess capacity of low-end products, driving structural optimization from the perspectives of land supply, energy optimization, and environmental impact assessment to improve the overall technical level and operational efficiency by using advanced processes under a policy framework. High-end products, such as high-end polyolefin, special engineering plastics, and high-end membrane materials, have a high level of external dependence and need further development of domestic production capacity to alleviate the import pressure and industrial chain security risks. Overall, the production capacity of most conventional chemical products in China will increase slowly or decrease, while advanced chemical materials and special chemicals continue to develop.

Challenges in the Zero-Carbon Transformation of China's Chemicals Industry

The chemicals industry is one of the heavy industries and its carbon emissions are mainly from reaction processes and energy consumption. Carbon emissions from China's chemicals sector are about 1.3 billion tons per year, accounting for 13% of the country's total CO_2 emissions and 20% of its industrial sector's total emissions. Non-CO_2 greenhouse gas emissions from the chemicals industry also increase carbon-equivalent emissions, such as nitrous oxide generated in the ammonia production chain and methane escaping from natural gas chemicals facilities. As one of the highest energy consumption and emissions industries, chemicals industry companies are expected to participate in the national carbon market in the coming years. The chemicals industry will be one of the key sectors of China's carbon neutrality vision.

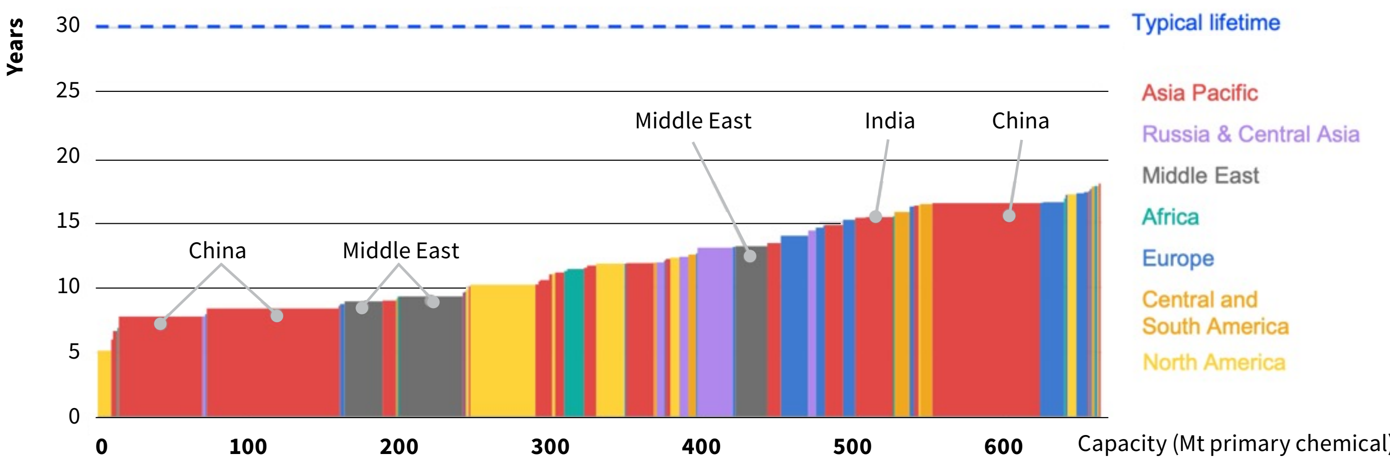
The zero-carbon transformation of China's chemicals industry faces several challenges.

From the demand side, the overall demand for chemical products is continuing to increase. In terms of total demand, the per capita consumption of chemical products in China is US$1,297, whereas the per capita consumption of chemical products in the United States is US$1,533 dollars, nearly 20% higher than that in China. With the growth of the domestic economy and quality of life, large expansion potential exists for China's total demand for chemical products. In terms of external dependence, the self-sufficiency rate of China's high-end chemical products is low. For example, the import dependence of solar photovoltaic ethylene vinyl acetate and metallocene polyethylene is 75% and 80%, respectively.[9] With the breakthrough of China's high-tech chemicals industry and the policy protection for high-end products' supply security, the external dependence of high-end chemicals will decline and high-end chemicals production capacity will increase.

From the supply side, China's chemical production is highly dependent on coal, and the carbon intensity associated with coal is much higher than that with other feedstocks. Due to abundant coal resources, China has a large coal chemicals industry. Taking methanol production as an example, 75% of China's methanol is from coal, although the global average is only 35%.[10] Neither the United States nor Europe produces methanol from coal on a large scale. Coal has a higher carbon content than other feedstocks and emits more carbon when producing products with a relatively low carbon content. For example, to produce 1 ton of methanol, the carbon emissions of the industrial processes using coal and natural gas as feedstocks are about 2.1 and 0.7 tons, respectively. The industrial process carbon emissions using coal and natural gas as feedstocks to produce 1 ton of ammonia are 4.2 and 2.1 tons, respectively.[11] China's large coal chemicals industry complicates its decarbonization pathway.

In addition, because chemical assets in China are relatively young, rapid transformation may bring higher risk of stranded assets. According to the International Energy Agency (IEA),[12] as shown in Exhibit 3, China's younger production assets account for more than half of the global total in the chemicals industry. For example, the average operating age of China's production facilities is only 13 years for ammonia, about 8 years for methanol, and 7 years for ethylene, with many new capacities being planned and built recently, but the lifetime of typical facilities after commissioning is 30 or even more than 40 years. Compared with other countries retiring chemical facilities, China's chemicals industry needs to comprehensively consider a combination of plans to properly phase out high-carbon capacity, process low-carbon retrofits based on existing facilities, and directly deploy new zero-carbon capacity in zero-carbon transformation. Therefore, the problem of how to properly dispose of existing assets, plan the transformation timeline, and avoid stranded assets as much as possible is even tougher.

Exhibit 3 **Age profile of primary chemicals production facilities (2020)**



Source: IEA

Opportunities in the Zero-Carbon Transformation of China's Chemicals Industry

Three major opportunities emerge in the zero-carbon transformation of China's chemicals industry.

First, the high ability to integrate technology, the huge market potential, and powerful policy tools, which enable the country to rapidly apply new technologies at scale, are China's major advantages. Ethylene set processing technology is one of the most sophisticated and complex technologies in the petrochemicals industry. From 2012 to 2013, the successful commission of the 600,000-ton ethylene project of China National Petroleum Corporation (CNPC) Daqing Petrochemical and the 800,000-ton ethylene project of Sinopec Wuhan marked the success of industrialization of localized large-scale ethylene set processing technology. In addition, with the improvement of the technology of equipment manufacturers such as Shenyang Blower Works Group and Shaangu Group, China has become the fifth country in the world that can produce three critical facilities at the million-ton level of olefin.[v] In the coal chemicals industry, following various technological advances, China has rapidly achieved large-scale breakthroughs including a 2,000 ton/day large gasifier, large converter, 120,000 m^3/h grade air separator, 80,000+ m^3/h grade air compressor, million-ton coal-to-oil reactor, and 600,000-ton methanol-to-olefin (MTO) reactor. At present, the initial development of green hydrogen; carbon capture, utilization, and storage (CCUS); and other technologies that can assist decarbonization is expected to achieve rapid cost reduction in the future due to China's ability to rapidly scale up new technologies.

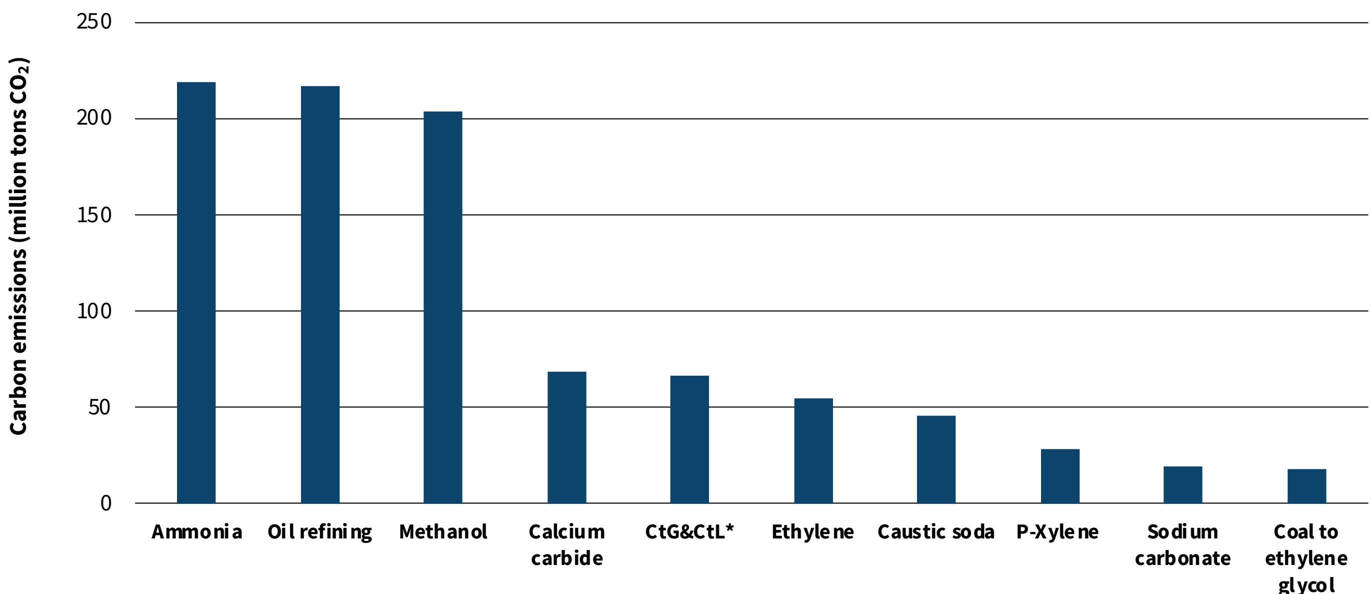
Second, China's chemicals industry is dominated by state-owned companies, which have sufficient willingness and resources to drive the zero-carbon transformation of the industry. Five Chinese mainland companies have been included in C*hemical & Engineering News'* top 50 global chemical companies in 2020.[13] Three are state-owned companies, namely, Sinopec, CNPC, and Syngenta, a subsidiary of Sinochem Holdings. Sinopec and CNPC are far ahead of other Chinese mainland companies with 2020 sales of US$61.6 billion and US$22.7 billion, respectively. State-owned companies dominate the Chinese chemicals market and are the key participants in carbon abatement actions. State-owned companies are subject to national policies to a greater extent, but they also play a leading role in demonstrating new technologies. For example, it was stated in the Notice of the State Council on the Issuance of Carbon Peaking Action Plan by 2030 that state-owned companies in key areas should create and implement carbon peak action plans and play a leading role.[14]

Third, the scale and integration trend of China's chemicals industry could fully utilize resources, energy, and economies of scale. Large-scale devices enhance energy-efficiency optimization. For example, the energy consumption cap of small ethylene devices with capacity lower than 300,000 tons per year is 830 kilograms of oil equivalent per ton (kgoe/t), equivalent to a carbon intensity of 2.56 tons of CO_2 per ton (tCO_2/t), but the energy consumption cap of large ethylene devices with capacity higher than 300,000 tons per year is only 720 kgoe/t, equivalent to a carbon intensity of 2.22 tCO_2/t.[15] Industrial clusters can give full play to the synergistic effect of chemical industrial aggregation and optimize electricity and heat utilization through resource coordination between energy consumption and production areas to form industrial chain links and standardize operation. According to the *Development Guide of Chemical Industrial Parks in the 14th FYP and Medium- to Long-Term Development Outlook 2035* issued by the China Petroleum and Chemical Industry Federation, China will focus on fostering 70 top-class chemical clusters during the 14th Five-Year Plan (FYP) period.

v The three critical machines for olefin equipment are three centrifugal compressor units, namely, cracking gas compressor, propylene compressor, and ethylene compressor.

Due to the wide variety of products and complex upstream and downstream chains in the chemicals industry, this report focuses on three representative products, namely, ammonia, methanol, and ethylene. From the perspective of carbon emissions, the total carbon emissions of ammonia, oil refining, and methanol are currently the highest among all the subdivisions of China's chemical industry.[16] Given the limited growth potential of refined oil demand in the future, the refinery capacity scale is expected to shrink in the long term. At present, the ethylene industry's equivalent self-sufficiency rate is about 60%, and the potential of capacity growth is high, leading to increased carbon emissions of the ethylene industry in the future. Ammonia, methanol, and ethylene will be the main focus of carbon emissions abatement in the chemicals industry. In addition, from the perspective of their positions in the value chain, ammonia, methanol, and ethylene are key basic chemicals in the chemicals industry, with numerous downstream products and high added value. For example, ethylene is one of the most important base chemicals in the petrochemicals industry. Final products derived from ethylene account for more than 75% of petrochemical final products.[17] Many of ethylene's downstream high-end plastics are also important products to promote overall social development.

Exhibit 4 **Carbon emissions of subdivisions of China's chemicals industry (2020)**



*Coal-To-Gas & Coal-To-Liquids

Source: China National Petroleum & Chemical Planning Institute

Chemicals Industry Demand Outlook under the Zero-Carbon Scenario

The chemicals industry is one of the few heavy industries and its overall demand is still growing. The chemicals industry has a long value chain, with a large number of different products. It involves complex supply-demand relationships among subdivided products. It is assumed in this report that the consumption of ammonia will decrease first and then increase in the future because the agricultural and industrial sectors are the main sources of demand and there is a long-term growth potential for ammonia as marine fuel. Methanol consumption will increase first and then decrease, with major demand including MTO, energy use, and traditional use. The demand from energy use and traditional use will gradually tighten up while the demand from MTO steadily increases. Ethylene consumption continues to grow, mainly supported by a large market for end-product plastics, but the pace is expected to slow as demand for primary plastics decreases due to maturing plastic recycling technologies and systems.

As industrialization and urbanization gradually approach the later stage in China, the country's demand for steel and cement will have a decreasing trend in the long run. **On the contrary, a major challenge in the chemicals industry's zero-carbon transformation is that the demand for related products continues to increase.** Therefore, the first step to analyze the zero-carbon transformation of the chemicals industry is to forecast the demand of major products and deeply evaluate their driving factors and the effect of the new carbon-neutral constraints on the supply and demand of products. This section analyzes and forecasts the demand of ammonia, methanol, and ethylene.

Ammonia

The demand volume of ammonia is mainly driven by the downstream market and is less affected by import and export. China's apparent consumption of ammonia in 2020 was 60 million tons, with a year-on-year growth rate of about 2%. Agricultural and industrial uses currently are the main consumers of ammonia, but in the future fuel use may become an important growth point for demand.

Agricultural use is the main driver of ammonia demand, followed by industrial use. In agricultural use, ammonia is mainly used to produce urea, which is directly applied as fertilizer or used to produce compound fertilizer. In industrial use, ammonia can be used to produce melamine, urea-formaldehyde resin, dynamites, and pesticides. At present, agricultural use consumes 70% of the total ammonia in China and industrial use consumes about 30%. Considering the background of reducing fertilizer use and increasing chemical use, **the share of agricultural use in ammonia will gradually decrease and the industrial use may show an increasing trend. In addition, for carbon neutrality, ammonia as a potential new fuel for shipping may appear as a new demand growth point apart from existing uses.**

The demand for ammonia in agriculture is decreasing, mainly due to the improvement of fertilizer utilization efficiency. Since the 13th FYP, China's total fertilizer consumption has been on a downward trend, achieving the goal set in the *Action Plan on Zero Growth of Fertilizer Use by 2020* by the Ministry of Agriculture in 2015, five years ahead of schedule. As China's population growth slows, stabilizes, and moderately declines, China's fertilizer consumption will gradually flatten and decline. China's fertilizer use per unit area of arable land is about twice the level of major developed countries, indicating a low use efficiency of only 35% in 2017, far lower than the 52% in the United States and 68% in Europe. Efficiency improvements will greatly reduce fertilizer demand in China. In addition, the consumption of ammonia for agricultural use will continue to decrease in the future due to multiple factors such as improved fertilizer efficiency, organic fertilizer substitution, upgrading environmental protection, and accelerated backward production capacity withdrawal. According to the National Bureau of Statistics, domestic fertilizer production in China has been declining for the past five years, with an average annual decline rate of 6.3%.

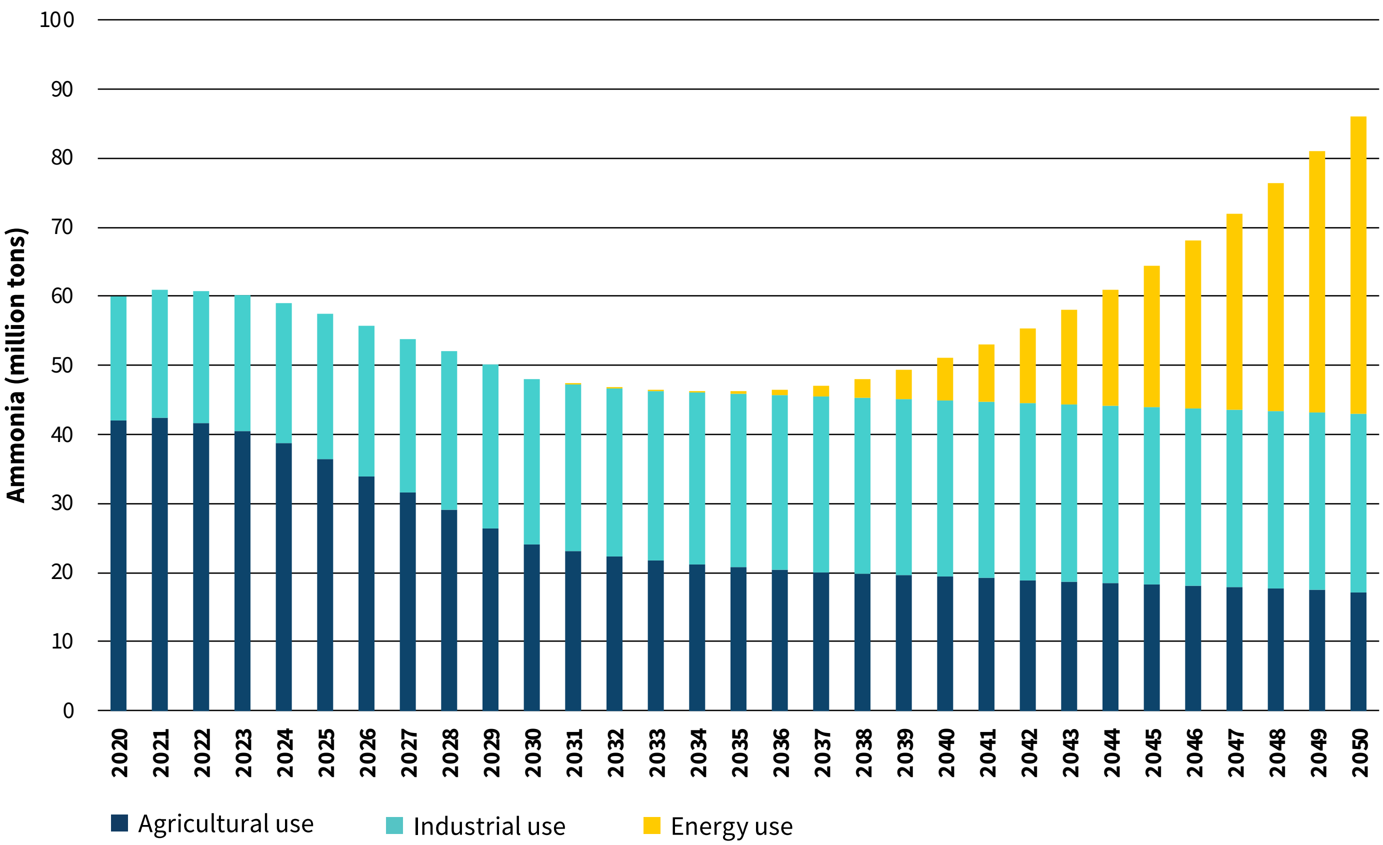
Industrial use for ammonia is likely to increase. In industrial use, the main products of ammonia, such as dynamites and urea-formaldehyde resin, are widely used in quarrying, mining, and civil construction. With the development of the economy and the improvement of domestic quality of life, the corresponding demand for ammonia will increase to a certain extent. However, considering that China's industrialization and urbanization are gradually approaching a later stage and the potential for relevant development and civil construction is limited, the demand for ammonia in these areas will not increase on a large scale.

In the future, demand may grow for ammonia as a new energy source in shipping and other fields. As an energy carrier, ammonia is stable and reliable, easy to liquefy, and convenient to store and transport, and can be made from hydrogen and converted back to hydrogen when necessary. It is an important medium for long-distance, efficient, safe, and low-cost transportation of hydrogen. In RMI's zero-carbon scenario, ammonia will become an important fuel option for long-distance heavy ships, which are currently switching from high-emissions bunker oil or diesel to low-carbon liquefied natural gas (LNG). According to DNV, ammonia could account for 25% of marine fuel by 2050 under the aggressive scenario.[18] Under RMI's zero-carbon scenario, 50% of China's shipping energy needs will be provided by ammonia by 2050. In addition, ammonia can be burned directly or mixed with other fuels for thermal electricity generation. For example, JERA, the largest electricity generator in Japan, plans to achieve an ammonia cofiring rate of 20% at the No. 4 unit of its Hekinan coal-fired power plant in Japan by 2024 or 2025, achieve the same cofiring rate in all its coal-fired plants by 2035, and gradually increase the cofiring rate to 100% for ammonia electricity generation by 2050.

Ammonia has a low dependence on import, and has long-term export potential. Ammonia is in a gaseous state at normal atmospheric temperature and needs to be pressurized or cooled to liquefy to be shipped over long distances, making it more difficult to import and export than solid or liquid products at normal atmospheric temperature. In 2020, 1.2 million tons of ammonia were imported in China, accounting for only 2% of the apparent consumption. In the short to medium term, the ammonia demand in China will decline, further reducing the amount imported. In the long run, the demand for ammonia energy use will increase, driving the development of advanced production capacity of domestic ammonia and promoting its export.

Based on the above analysis of three ammonia uses, RMI estimated the ammonia demand in the zero-carbon scenario. As shown in Exhibit 5, the demand for ammonia will go through three stages: before 2025, the total demand for ammonia will be stable at about 60 million tons, with agricultural use declining due to the influence of policies and industrial use increasing due to the development of downstream industries. From 2025 to 2035, the total demand for ammonia will decrease to about 46 million tons, mainly affected by the shrinking agricultural use caused by the significant improvement of nitrogen fertilizer efficiency, and the growth rate of industrial use will slow. Also, ammonia will be piloted as energy use in 2030 but will not be applied on a large scale. From 2035 to 2050, the total demand for ammonia will increase due to the expansion of the energy use demand and the large-scale commercial application of energy use will emerge. By 2050, energy use will account for 50% of total demand, with agricultural and industrial demand leveling off.

Exhibit 5 Ammonia demand projection in China



Methanol

Methanol demand volume in China is mainly affected by downstream consumption, with limited long-term influence from import and export, and the overall demand trend increases first and then decreases. In 2020, China's apparent consumption of methanol was 81.7 million tons, with a year-on-year growth rate of about 6%. Demand for methanol mainly comes from MTO, traditional use (acetic acid, methyl tert-butyl ether [MTBE], formaldehyde, etc.), and energy use, accounting for 51%, 34%, and 15%, respectively. In the future, demand from MTO will continue to expand, the traditional use will decline, and energy use will be stable and increasing.

The traditional use demand for methanol is stable and declining, and the long-term decline will continue to accelerate. Traditional use products of methanol include acetic acid, MTBE, and formaldehyde, which are mainly used in building materials, decoration, and refined oil blendstock. In the future, under the pressure of environmental protection, safety supervision, and carbon control, traditional use demand for methanol will be restrained.

MTO can use coal resources efficiently and relieve dependence on imported crude oil, with significant potential for growth. Using methanol to produce ethylene, which is an important basic chemical in the petrochemicals industry, will improve the economic benefit of methanol on the demand side. When the coal price is low and oil price is high, the cost advantage of methanol from coal-to-ethylene is greater than that of naphtha-to-ethylene. The share of new downstream demand for methanol, represented mainly by MTO, increased from 44% to 51% in 2020. In the future, methanol demand will increase if ethylene demand increases along with downstream demand for high-end plastics. However, because coal is used as feedstock for methanol production, energy consumption and carbon emissions issues will limit the demand for ethylene produced from methanol.

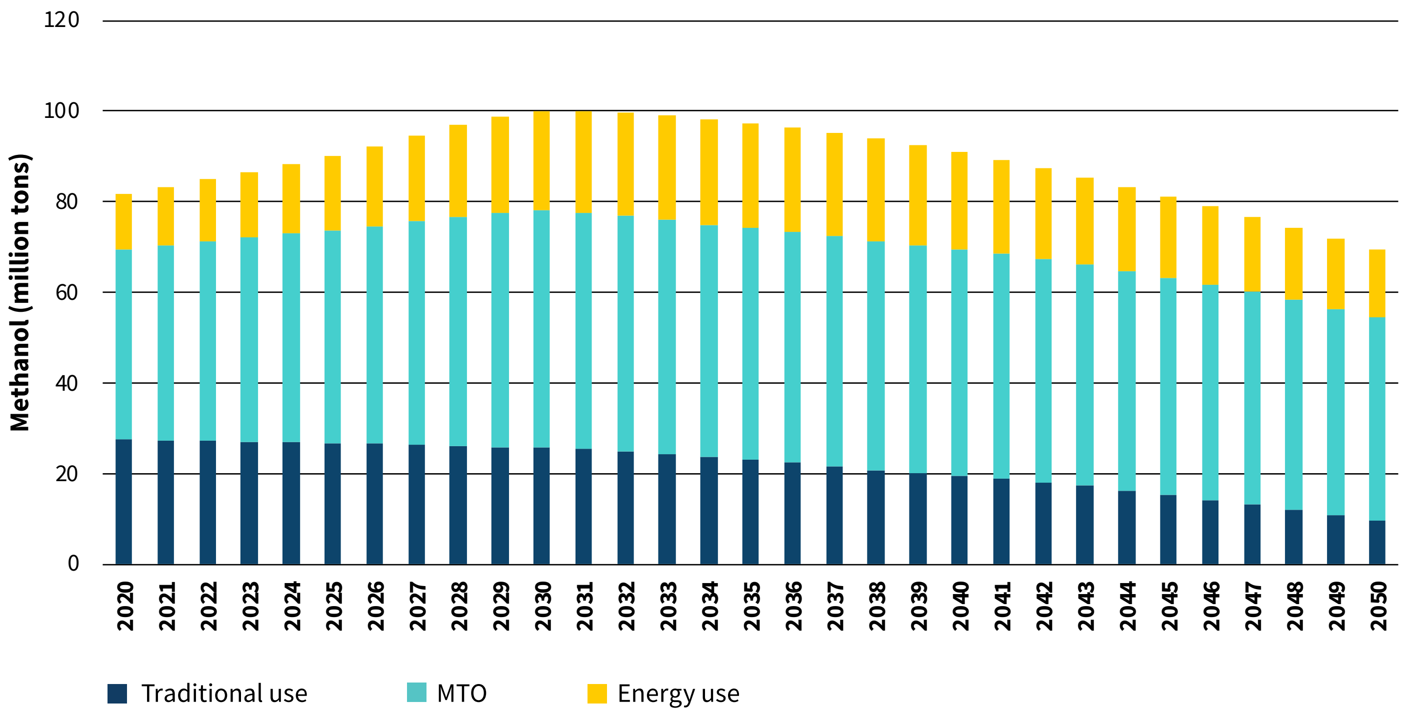
Methanol energy use is a relatively clean liquid fuel, and its demand is expected to grow to a certain extent, but the long-term demand is conservative. Using methanol instead of coal as fuel will reduce fine particulate matter (PM2.5) emissions by more than 80% and nitrogen oxides by more than 90%.[19] During the 13th FYP period, with the vigorous promotion of efficient and clean fuel and the implementation of policies such as coal-to-gas switching, methanol energy use was developed, and its application fields include methanol gasoline, methanol vehicle, methanol boiler, methanol stove, and ship fuel. In 2020, methanol fuel consumption was 12.2 million tons, accounting for 15% of total methanol consumption.

In areas where electrification applications are limited, methanol can play an important role as a relatively clean, easily stored fuel and has a more stable performance than batteries at low temperatures. Methanol has higher safety stability and volumetric energy density compared with hydrogen and can also be used as a hydrogen storage medium and converted into hydrogen in end-use applications. In addition, the ability to use methanol as liquid fuel also enables maximized use of existing infrastructure such as pipelines, oil terminals, and gas stations with minimal modifications.

Methanol import will decline slowly with the optimization of the domestic demand structure. In 2020, China imported 13 million tons of methanol, accounting for 16% of total apparent consumption, while export only occurred in small amounts when arbitrage space was occasionally available. Because planned and under-construction domestic production capacity continues to increase, methanol imports will decrease in the short term. The adjustment and optimization of capacity structure will stabilize methanol import volume in the medium term, and the decline in methanol demand may further reduce methanol import volume in the long run. In addition, the future demand for methanol is also affected by the development of green methanol production technology. Because the existing coal-based production route has high carbon emissions, if the low- and zero-carbon production routes can be promoted on a large scale, the development of the demand side can be promoted from the supply side to expand the market scale of the methanol industry.

As shown in Exhibit 6, RMI estimates that the change in methanol demand will go through two stages: the total apparent consumption of methanol will continue to increase until 2030, reaching about 100 million tons in 2030. In this stage, MTO and energy use demand will be the main drivers of methanol demand growth. Methanol consumption for MTO may reach nearly 52 million tons by 2030, and traditional use such as methyl ether will slowly decline. From 2030 to 2050, the total methanol consumption continues to decline after the peak year 2030, dropping to 69.5 million tons in 2050. MTO will decline slightly due to energy consumption and carbon emissions restrictions in the downstream olefin industry, and traditional use for methanol will continue to decline. For energy use, methanol boilers and cooking appliances will be phased out under the trend of electrification, reducing methanol demand; however, the zero-carbon transformation of shipping and road transportation may increase methanol demand. Overall, methanol demand as an energy use will basically remain stable after 2035.

Exhibit 6 **Methanol demand projection in China**



Source: 2020 data from *Early Warning Report of China Petrochemical Market,* China Petroleum and Chemical Industry Federation and Shandong Longzhong Information Technology Co., 2021.

Ethylene

Domestic ethylene production in China is mainly driven by downstream demand, import, and export; downstream demand is the focus of this study's analysis. Due to the difficulty in long-distance shipping of ethylene, countries generally trade in downstream derivatives of ethylene rather than in ethylene. At present, large import gaps of polyethylene, ethylene glycol, and styrene exist in the downstream demand of domestic ethylene; the import dependence rates were about 48%, 56%, and 26%, respectively, in 2019. The development of a domestic coal chemical route to produce ethylene may reduce ethylene import dependence. Therefore, because the import and export will be affected by product cost, resource availability, and the supply-demand balance of various products and other driving factors, the future ethylene development trend is uncertain. Assuming all ethylene demand comes from domestic self-sufficiency in the future, this study analyzes the future demand situation.

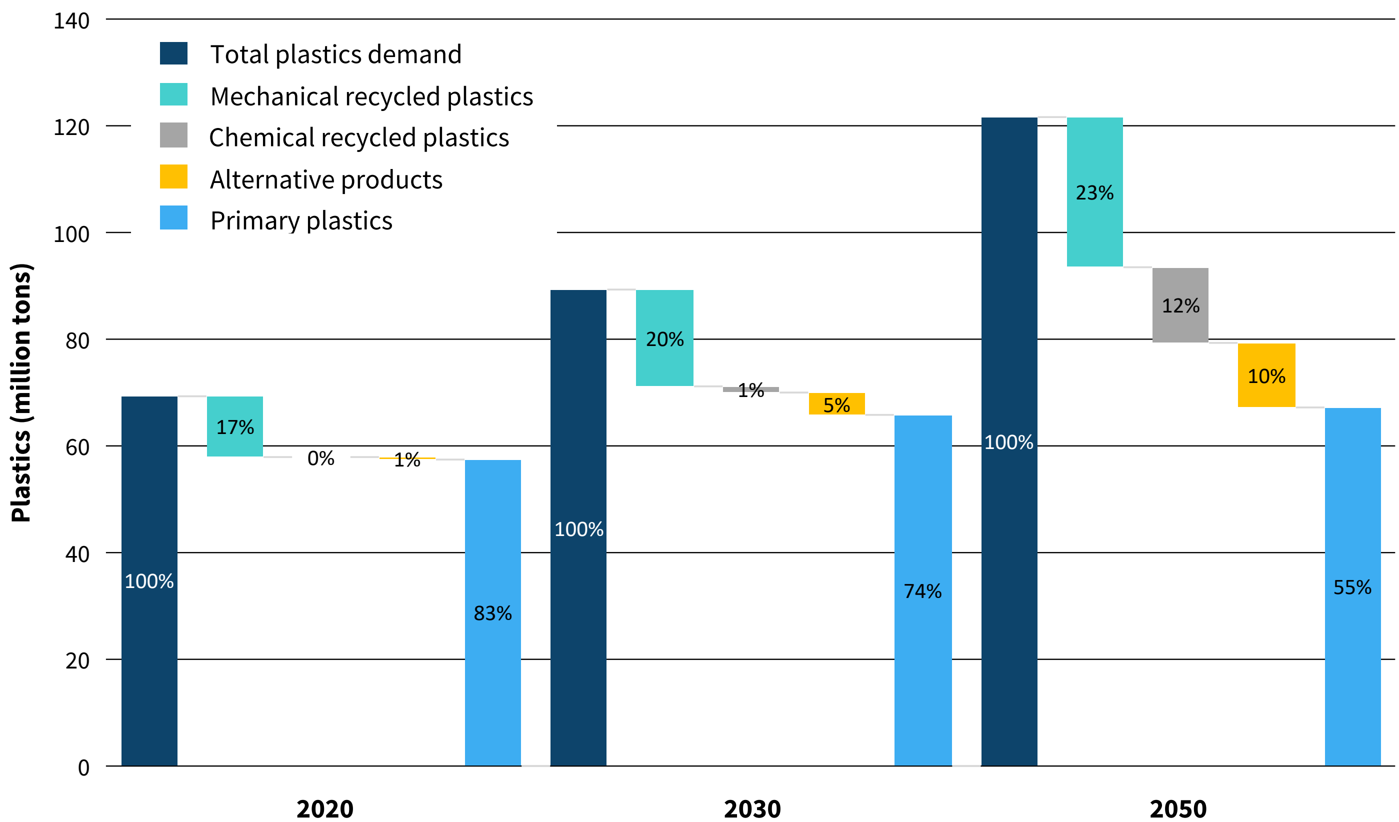
Ethylene is a vital basic chemical of the petrochemicals industry, and its products account for more than 75% of petrochemicals products. In 2020, China's ethylene production was 21.6 million tons, with apparent consumption of 33.7 million tons and equivalent consumption of 62.8 million tons. Polyethylene was the largest downstream product of ethylene, accounting for 61% of the total, followed by ethylene glycol at 17%, styrene at 6.5%, and ethylene oxide at 5%. **In the future, polyethylene will remain the biggest growth point in the downstream consumption of ethylene, while the consumption in other areas will be relatively stable.** Polyethylene is one of the most widely used plastics. Starting from analyzing the future demand of plastics, this study explores possible influencing factors of ethylene demand.

Plastics are a chemical end product with a large consumption and a growing demand. With the past decade's economic development, the scale of the global plastics market has steadily increased. In 2019, global production of primary plastics reached 370 million tons. With the rapid growth of demand, WWF forecasts that plastics production will increase by another 40% by 2030 without major development of waste treatment technology and management.[20] China is the world's largest plastics producer and consumer, with apparent consumption of more than 80 million tons annually. China's demand for plastics will continue to increase in the future as quality of life increases. At present, China's annual plastics consumption per capita is about 45 kg, about half that of major developed countries.[21] By 2050, assuming China's per capita plastics consumption reaches the current level of some developed countries, total plastics consumption in China will reach more than 120 million tons.

Plastics are the main driver of ethylene demand, and fully realizing their recycling potential can greatly reduce the demand for primary ethylene. Alternatives such as bio-based feedstocks may also reduce ethylene demand. Over the past five years, China has recycled about 18 million tons of plastic annually. Currently, the recycling rate of plastic in China is 27.8% of waste plastics production.[22] By reducing low-quality packaging plastics production, limiting packaging plastics export, and improving package plastics waste recycling, the recycling and disposal capacity of waste plastics is expected to increase by 10 million tons per year by 2030 and 15 million tons per year by 2035.[23] By 2050, if the plastics recycling rate reaches 60% through the development of new recycling technologies and the establishment of effective recycling models, and 10% of the total demand can be met by products from alternative feedstocks,[vi] plastics produced from ethylene will only account for 55% of the total plastics demand. If other factors such as improved consumer habits to extend the life of plastics are taken into account, the demand for ethylene from plastics will be even lower than that of the business-as-usual scenario.

vi According to the ETC and Material Economics, plastics from alternative feedstocks could account for around 10% of global demand by 2050.

Exhibit 7 Plastics demand projection in China



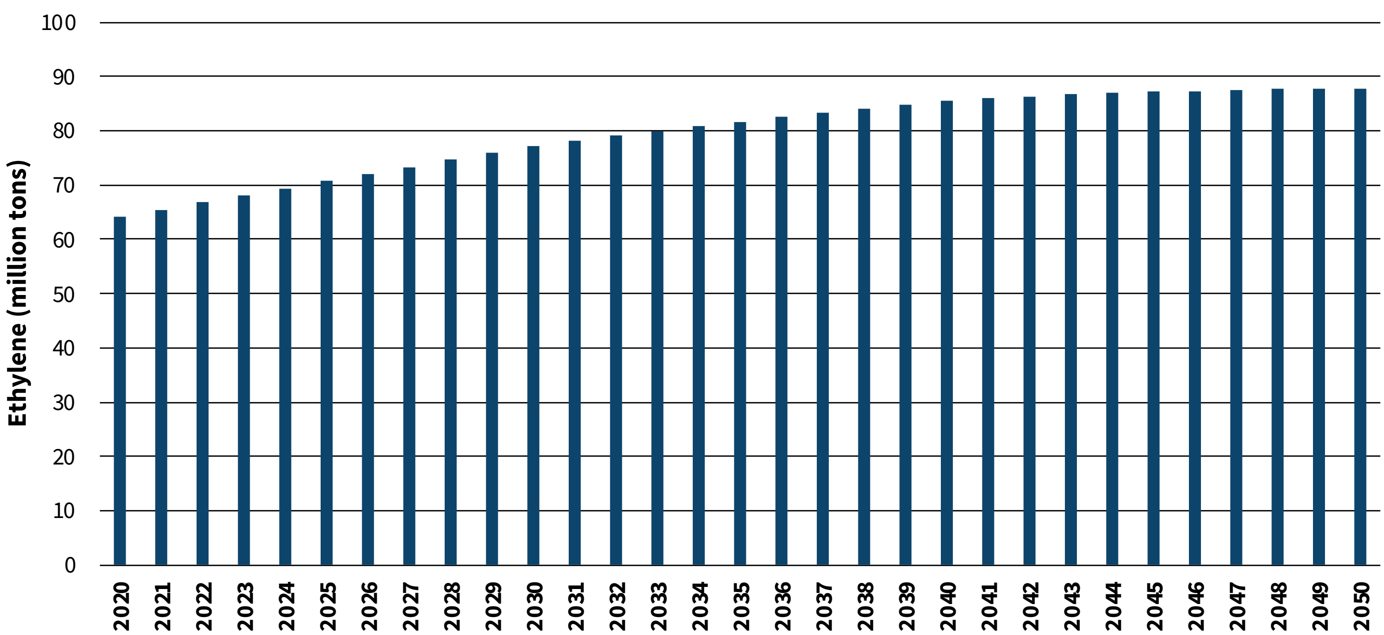
Overcoming the limits to recycling plastics mainly comes from two sources: the improvement of mechanical recycling driven by the mature recycling system, and the expansion of chemical recycling driven by technology advancement.[vii] Before 2030, the release of plastics recycling potential mainly comes from the improvement of mechanical recycling, while chemical recycling is expected to be applied on a large scale after 2030. The release of mechanical recycling potential mainly comes from the improvement of the front-end recycling, classification, and collection system. In the European Union, for example, of the 29.1 million tons of waste plastics collected in 2018, only 6% of the 15 million tons of mixed collected waste plastics were mechanically recyclable, while 62% of the 14 million tons of separated collected waste plastics were mechanically recyclable.

vii Mechanical recycling refers to processes by which plastics are collected, sorted, cleaned, ground into flakes, sorted, and then melted into pellets to be used to produce new products. Chemical recycling refers to the processes of converting waste plastics into components such as plastic monomers through a series of chemical processes, and then producing new plastics or other valuable chemical products.

In terms of chemical recycling, significant progress and breakthroughs have been made in relevant key technologies and technology sets, which have gradually entered the verification and demonstration stages. In the future, further technological breakthroughs and optimization of the industrial chain are needed to achieve rapid scaled development. At present, leading international chemical companies including BASF, Covestro, and Dow have increasingly entered plastics chemical recycling, while in China, CNPC and Sinopec have also been paying close attention to relevant fields. For example, during the 14th FYP period, CNPC is comprehensively working on relevant research, including unitary plastics material recycling and utilization technologies and new waste plastics optimization technologies. Sinopec has also started the development and industrial application of technology sets and started to research related product standards.

As shown in Exhibit 8, RMI estimates that ethylene demand in China will continue to rise to nearly 88 million tons by 2050, an increase of 37% compared with apparent ethylene consumption in 2020. The increase in ethylene demand is mainly due to the increase in the demand for end products represented by plastics. Compared with the business-as-usual scenario in which plastics recycling potential is not fully developed, China's ethylene demand level could be reduced by about 40% in 2050.

Exhibit 8 **Ethylene demand projection in China (equivalent)**



Source: 2020 data from *Early Warning Report of China Petrochemical Market,* China Petroleum and Chemical Industry Federation and Shandong Longzhong Information Technology Co., 2021.

Chemicals Industry Decarbonization Pathway: Leverage Resource Endowment, Develop Disruptive Technologies

Decarbonization of the chemicals industry can proceed from both the supply and demand sides, and the pathways include consumption reduction, high-end-product promotion, end-product substitution, efficiency improvement, fuel substitution, feedstock substitution, and back-end treatment. From a technical feasibility perspective, carbon reduction for chemical production can be concluded in three dimensions: low-carbon feedstocks, low-carbon fuels, and energy-saving systems. From an economic feasibility perspective, the cost reduction of green hydrogen, CCS, and other advanced technologies will also bring opportunities for low-carbon or zero-carbon chemical production. This chapter mainly discusses the technical and economic feasibility of zero-carbon transformation of China's chemicals industry using ammonia, methanol, and ethylene as examples.

Technical Feasibility: Decarbonization Pathways of the Chemicals Industry

The zero-carbon transformation of the chemicals industry should proceed from both the demand and supply sides, leveraging multiple drivers including consumption reduction, efficiency improvement, fuel and feedstock replacement, and back-end treatment to promote carbon reduction. Demand-side emissions reduction solutions include consumption reduction, high-end production, and end-product substitution, and supply-side emissions reduction solutions include efficiency improvement, fuel substitution, feedstock substitution, and back-end treatment (see Exhibit 9).

Exhibit 9 **Decarbonization pathways of petrochemicals and chemicals industries**

DEMAND SIDE		SUPPLY SIDE	
Consumption reduction	• Increase fertilizer efficiency, reduce fertilizer consumption • Plastic ban/restriction, increase recycling of waste plastics, rubber, and synthetic fiber	**Efficiency improvement**	• Reduce energy consumption through integrated method of production • Reduce energy consumption through coal-based cross-industry production and one-step production of hydrocarbon
High-end production	• Develop high-end products, increase share of advanced materials, special chemicals, and high-end fertilizer • Adjust product structure of oil refining industry, increase share of downstream chemical products, and reduce share of refined oil use	**Fuel substitution**	• Electrify low- to medium-temperature reactions • Substitute fossil fuels with biomass, hydrogen, etc.
End-product substitution	• Develop bio-based material, substitute or partly substitute synthetic materials produced from fossil fuel	**Feedstock substitution**	• Develop low- and zero-carbon feedstocks such as renewable hydrogen and biomass to replace fossil fuel feedstocks
		Back-end treatment	• Develop CCUS to reduce or eliminate carbon emissions from fossil fuel–based processes

Demand-side decarbonization pathways

The focus of demand-side decarbonization is to reduce dependence on energy-intensive chemical products. This includes reducing consumer demand while maintaining the same service quality by means of improving efficiency and recycling. However, it is also important to pivot to greener high-end products or alternative products. Specifically, demand-side decarbonization routes include consumption reduction, high-end production, and end-product substitution.

• Consumption reduction

Consumption reduction can reduce energy consumption and carbon emissions from the product demand side, and the consumption reduction potentials vary for different products. Applications aligned with future energy and social system needs will have higher demand growth, such as using methanol and ammonia to replace conventional fuels in the transportation industry. In some traditional fields, especially industries with high energy consumption and high pollution, consumption reduction has high potential. With the change of economic structure, the deepening of the circular economy, and the change of human habits, there are opportunities to explore consumption reduction of products such as formaldehyde slabs (methanol downstream), urea fertilizer (ammonia downstream), and plastics (ethylene downstream). Increased recycling of waste plastics, higher efficiency of fertilizer uses, and optimized materials for the construction industry will each contribute to reduced consumption.

• High-end production

High-end products can effectively eliminate backward production capacity and optimize low-end production capacity, reducing energy consumption and emissions. China's chemicals industry is at the forefront in terms of output and scale, but China's high-end product technologies are lagged behind comparing to developed countries. For example, China's olefin industry is highly homogeneous and at the middle and low end of the world petrochemicals industrial chain, lacking key technologies for high-end and high-performance polyolefin products.[24] China's domestic olefin industry still has a high equivalent import volume, which is concentrated in downstream high-end polyolefin products like metallocene polyethylene. The industrial chain of engineering plastic products such as polyformaldehyde also has high potential for further development.

• End-product substitution

Chemical products in end applications can be replaced by greener products to provide the same services. For example, the application of chemical products used as materials can be replaced by bio-based materials through further development and promotion. According to Nova Institute, the global production of bio-based structural polymers was 4.2 million tons in 2020, representing 1% of the production of structural polymers based on fossil resources.[25] The compound annual growth rate of bio-based polymers is up to 8% and is expected to continue to grow in the next five years. China's research on bio-based chemicals started late, but bio-based materials and bio-based chemicals have been listed as core research topics and the development of downstream materials application and business model have been vigorously promoted in the National Science and Technology Support Program during the 12th FYP period. The restriction and prohibition of nonbiodegradable plastics in provincial policies in China will facilitate the promotion of degradable bio-based materials.[26]

Supply-side decarbonization pathways

Supply-side decarbonization pathways may put forward higher technical requirements for chemical production. The chemicals industry's carbon emissions mainly come from reaction processes and fuel use. Different chemical production routes have different emissions structures. For example, the main source of carbon emissions from coal-to-methanol is the reaction process, but the main source of carbon emissions from ethane-to-ethylene is fuel use. Supply-side decarbonization pathways mainly involve reaction processes and energy consumption, supplemented by negative emissions technologies, to fully realize carbon emissions reductions in production processes. Specific solutions include:

- ### Efficiency improvement

Most chemical reactions occur under high temperature, high pressure, and catalyst, and have a high demand for fuel use. Effective management of thermal energy and improvement of catalyst efficiency are effective ways to improve energy efficiency in chemical reactions. Thermal management technologies such as steam recompression can improve thermal efficiency, and the application of new catalysts can reduce the temperature required for chemical reactions, thereby reducing fuel use and carbon emissions. For example, Linde Engineering's EDHOX technology, which reduces the reaction temperature for olefin steam cracking from 870°C to below 400°C, has been piloted in Germany.[27]

- ### Fuel substitution

Efficiency improvement reduces carbon emissions by reducing energy demand, but fuel substitution achieves carbon reduction and decarbonization by reducing or eliminating carbon emissions per unit of energy provided by the fuel itself. Specific measures can be taken to replace conventional high-emissions fossil fuels with low-carbon or zero-carbon clean energy, including:

- **Electric heating**

Electrification is an important means to replace fossil fuels. Most of the temperature and pressure requirements of chemical reactions can be met by reactors powered by electricity. For example, an electric cracking (e-cracking) furnace can be used as a reactor to produce olefin. BASF, SABIC, and Linde Engineering are working together to develop an electrically heated steam cracker furnace, aiming to achieve e-cracking commercialization by 2025.[28] At present, the bottleneck of e-cracking technology development mainly comes from the electricity grid, equipment, electric heating efficiency, and grid emissions factor. The use of green electricity for electric heating is essential for environmental property enhancement of the technology. China's electricity mix is dominated by coal-fired generation, which has a high carbon emissions level. With the promotion of new energy and the increasing green electricity market, zero-carbon electricity will be able to provide important green energy for chemicals industry decarbonization.

- **Biomass**

Biomass resources include straw, livestock manure, and forestry waste. Biomass fuels for industrial use are mostly biomass natural gas or biomass liquid fuels. Biomass fuels may provide heat through combustion and have high compatibility with conventional chemical heating furnaces. At present, the technology of biomass fuel is relatively mature, but its economics and resource availability are limited. To alleviate the problem of resource availability of biomass feedstock, companies and research institutions represented by ExxonMobil are investing in the research and development of advanced biomass fuels based on nonfood feedstock.[29] The prospects for domestic biomass development and biomass fuel availability for the chemicals industry will depend on future policy guidance, market conditions, and technological progress in advanced biomass fuels.

- **Hydrogen**

Hydrogen is an ideal clean energy source, with water as the only product after combustion. Hydrogen can meet the higher temperatures required for specific chemical reactions. Dow Chemical is collaborating with EcoCatalytic Technologies and Southwest Research Institute on "Integrated Hydrogen Combustion with Energy-Efficient Ethylene

Production." In the future, energy application of hydrogen in the chemicals industry will be mainly focused on chemical reactions with an extremely high temperature requirement, which are difficult for an electric furnace to run efficiently. Hydrogen could also be a primary or flexible heating energy source where hydrogen resources are abundant.

- ## Feedstock substitution

Feedstock substitution can reduce the carbon emissions of the reaction process. Improving the conversion rate of chemical products is the focus of feedstock substitution at present. For example, using ethane to produce ethylene can greatly improve the yield of ethylene products. In the long run, zero-carbon resources will become the main feedstock for chemical production. In the case that zero-carbon feedstock cannot be completely utilized, carbon emissions in the reaction process can be minimized by adjusting the proportion of feedstocks.

- **Green hydrogen and power-to-X (PtX)**

The application of green hydrogen can effectively solve the high carbon-hydrogen ratio problem of conventional fossil fuels. Taking the coal chemicals industry as an example, coal reacts with water through a water-gas shift reaction to produce synthesis gas (syngas), which is then used to produce methanol. Due to the high coal component of feedstocks, part of carbon is emitted as CO_2. Using green hydrogen to make use of emitted carbon reduces the carbon emissions in the chemical reaction process to a greater extent. PtX technology can dramatically mitigate fossil fuel resource dependence and uses CO_2 captured in the air or industrial sources to react with green hydrogen to produce chemical products. Both green hydrogen and PtX technologies have successful pilots. How to reduce costs through technological innovation and policy support will be the key challenge for future development.

- **Biomass**

The chemical utilization of biomass as feedstock mostly takes ethanol as an intermediate and uses it to produce high value–added chemicals such as ethylene, which is economical in some resource-rich countries and regions. The conversion rate of ethanol to ethylene is high. Due to the lack of biomass resources and the uncertainty about its future development in China, it is difficult to obtain biomass feedstocks on a large scale, and the cost of biomass-based chemicals will remain at a high level for a long time.

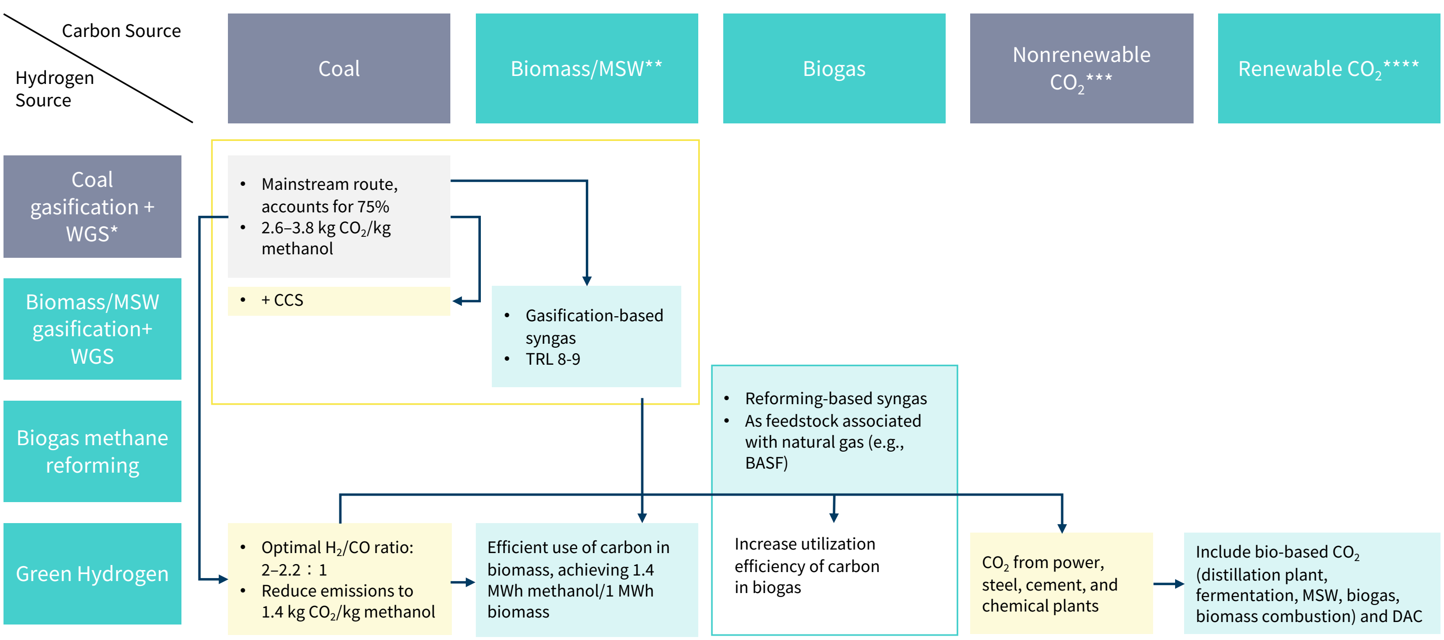
- ## Back-end treatment

For the remaining carbon emissions after various carbon reduction solutions from the feedstock and fuel use perspectives, negative carbon technology will become the back-end treatment of the chemicals industry for comprehensive decarbonization. CCS technology captures CO_2 and then compresses it and injects it into oil and gas fields or saline aquifers, where it is permanently stored underground. In the short to medium term, CCS can be combined with enhanced oil recovery (EOR) in mature oil and gas fields to improve the economics, while in the long term, saline aquifer storage should be used to enhance the storage capacity.

Overall, in chemical production, carbon emissions reduction can be considered in three aspects: feedstock substitutions, fuel decarbonization, and systematic energy conservation. Among them, carbon sources as feedstocks should gradually transition from fossil fuels to biomass, biogas, and CO_2, and hydrogen sources should gradually transition from fossil fuel hydrogen to hydrogen from biomass, biogas, renewable energy, etc. Even if fossil fuel feedstock cannot be eliminated immediately, feedstock with lower carbon intensity can be gradually increased. For example, in ethylene production, if available, the feedstock can transition from coal and naphtha to light hydrocarbons. In terms of fuel, processes that can be electrified should be electrified as much as possible, and there should be a gradual shift from fossil fuel energy to renewable electricity. In terms of system energy efficiency, the energy demand of the reaction should be reduced by making full use of thermal energy management and catalyst technology, thus reducing the overall system carbon emissions. Exhibits 10 and 11 list possible low- and zero-carbon transition pathways using methanol and ethylene as examples.

The carbon source of methanol feedstock can be gradually switched from coal to biomass, biogas, and CO_2. In the transition period, CO_2 can come from nonrenewable sources like industrial waste gas to reduce part of the carbon emissions. However, in the long term, to secure zero-carbon feedstock, CO_2 should be captured from the air or zero-carbon sources such as biomass or biogas combustion. Hydrogen sources can transition from water-gas shift to biomass, biogas, and green hydrogen. CCS can be used to eliminate emissions at the end of the process. In terms of fuel decarbonization, fuel used for methanol production can be replaced by electricity, and CCS could be added to deal with carbon emissions from burning while fossil fuels are still in use.

Exhibit 10 **Methanol decarbonization technology transformation pathways**

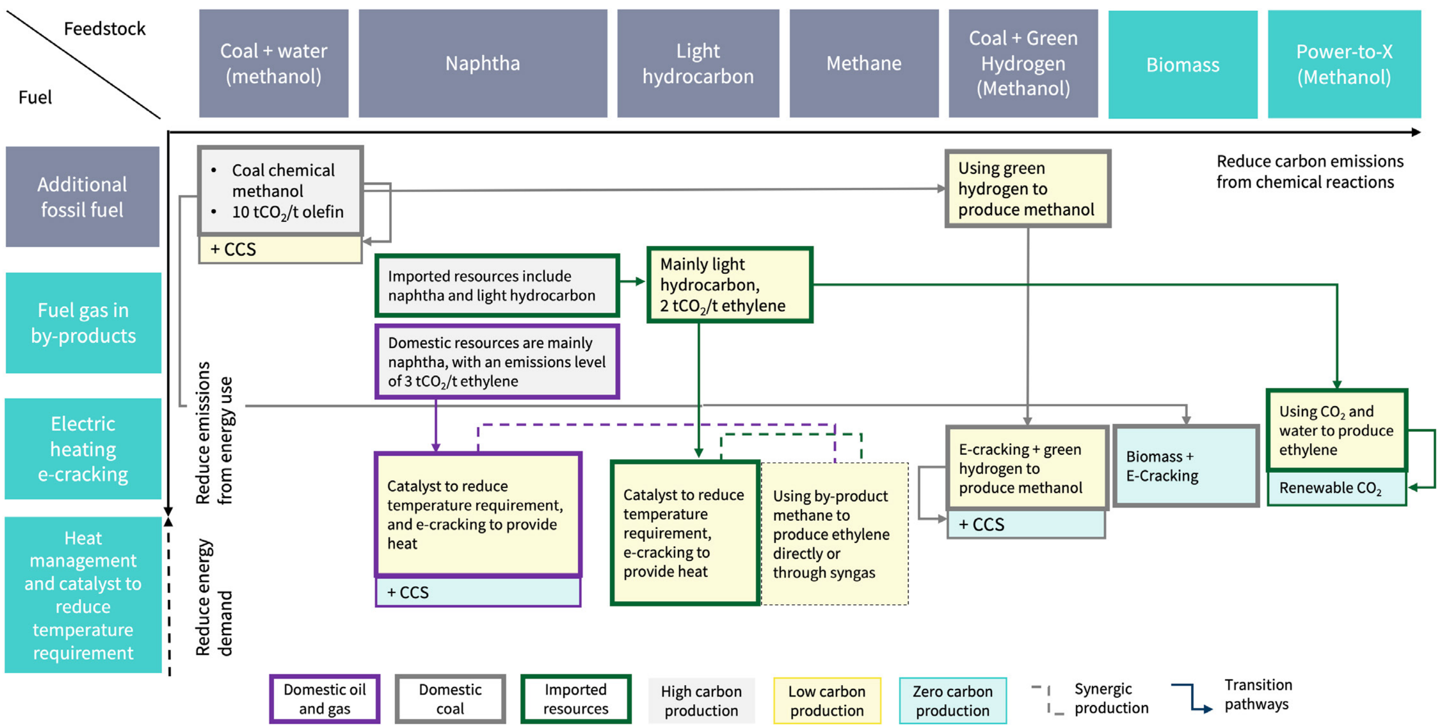


*WGS: Water-Gas Shift
** MSW: Municipal Solid Waste
***Nonrenewable CO_2 is from fossil fuel, industry waste gas, etc.
****Renewable CO_2 is from biomass or direct air capture (DAC)

High carbon production | Low carbon production | Zero carbon production | Transition path

In the zero-carbon transformation of ethylene production, the carbon and hydrogen sources of feedstocks should be gradually switched from coal and naphtha to light hydrocarbon, biomass, and green hydrogen plus CO_2, while the energy use should be gradually switched from fossil fuels to an e-cracking furnace, and heat management and catalyst technology could reduce the reaction energy demand during the transition. China's domestic olefin production can be divided into three modes according to different feedstocks: domestic oil and gas, domestic coal, and imported resources. According to the characteristics of different modes, appropriate transformation pathways should be developed to improve the product conversion rate by using by-product methane as feedstock. The ethylene industry chain should be promoted from high-carbon to low-carbon and then to zero-carbon production.

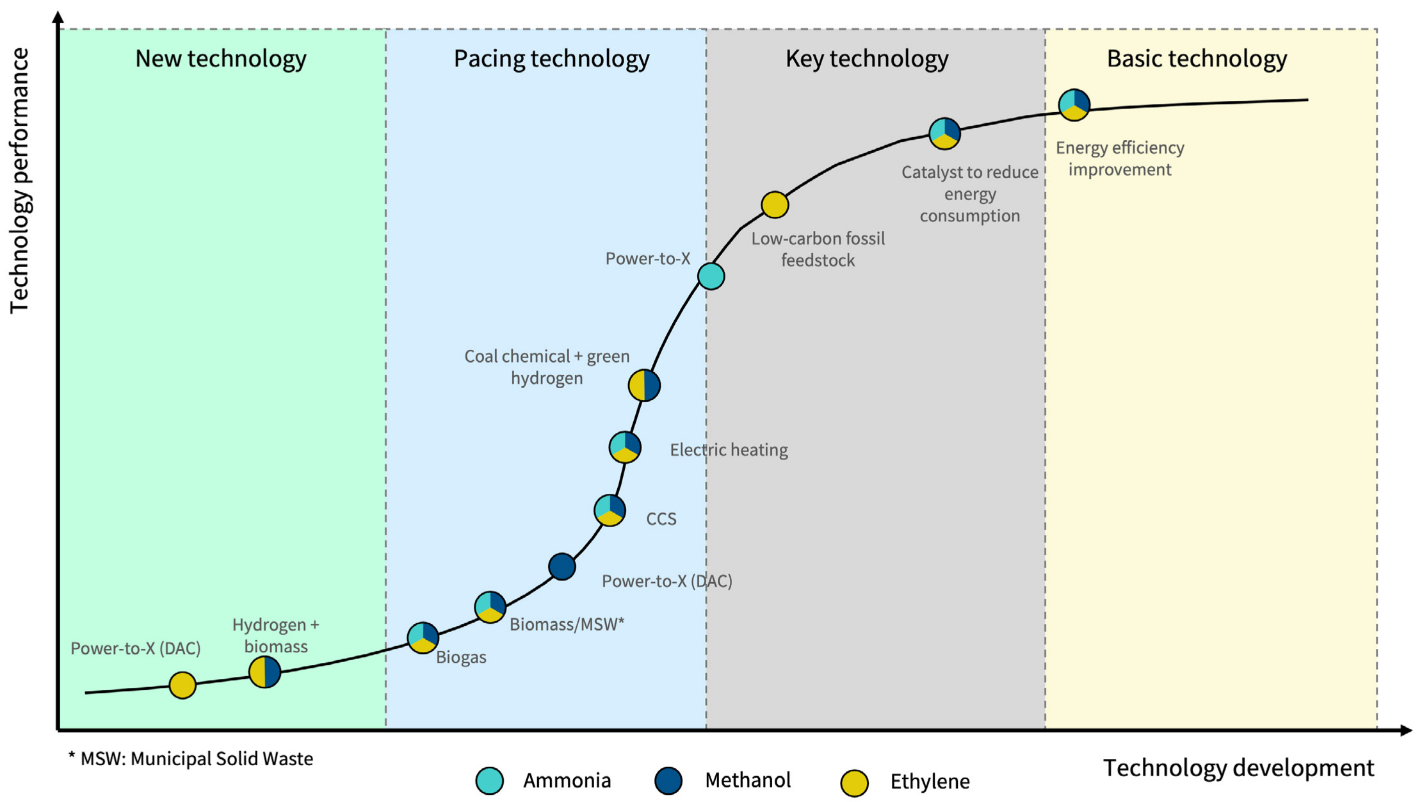
Exhibit 11 **Ethylene decarbonization technology transformation pathways**



By 2050, technologies that can drive a low-carbon and zero-carbon transition in chemical production will be mature enough to be deployed on a large scale. According to the technology readiness level of different technologies, the development and application time of the technology can be estimated. In terms of technology readiness, demand reduction represented by recycling and energy-efficiency improvement represented by process optimization and management improvement are highly feasible in the short and medium term. Such technologies have unlocked significant carbon abatement potential so far and could be further advanced. However, neither demand reduction nor energy-efficiency improvement could achieve complete decarbonization. Although disruptive technologies such as fuel electrification, green hydrogen utilization, biomass utilization, and CCS have greater carbon reduction potential, their technology readiness is relatively low. In general, available decarbonization technologies in the chemicals industry will basically achieve commercial application around 2035. Exhibits 12 and 13 show the related decarbonization technology curve and outlook.

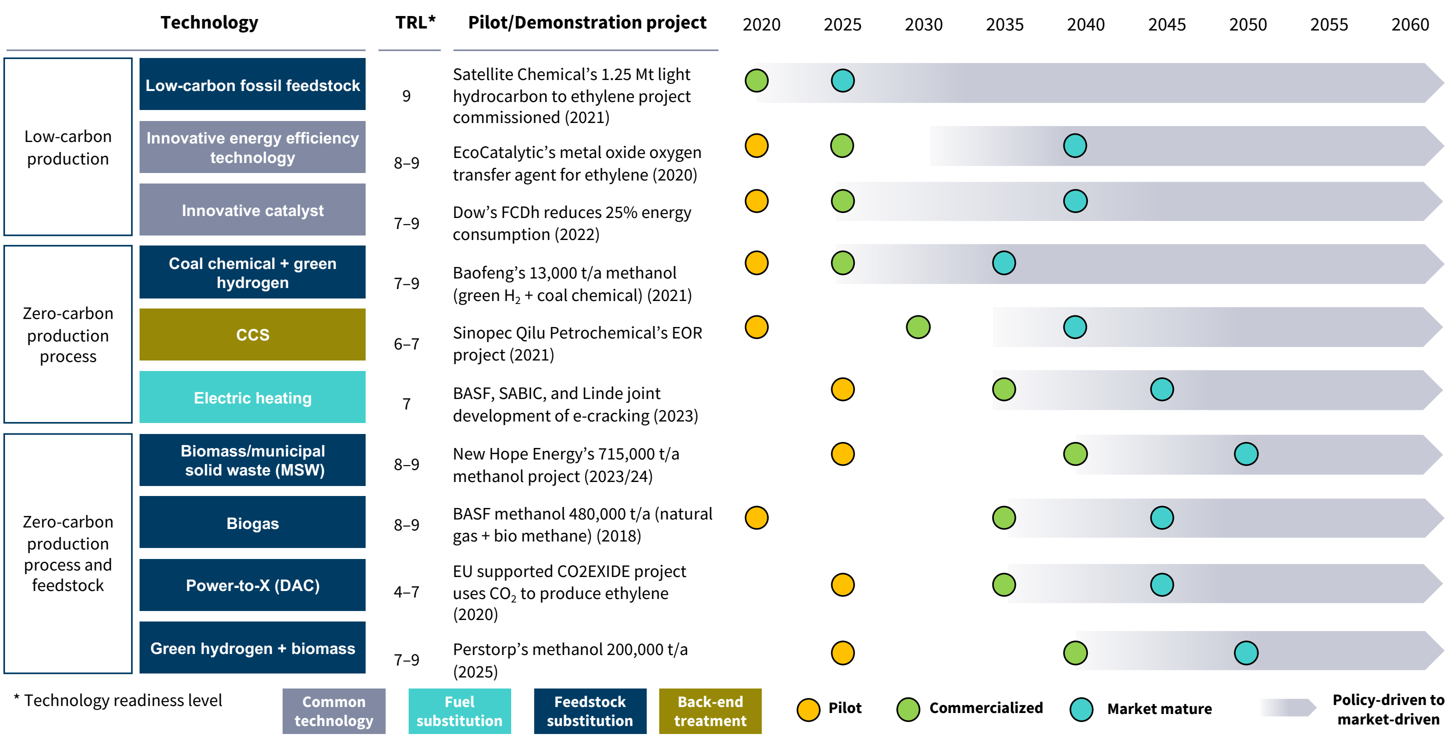
In addition, with the progress of technology, there will be more technologies with higher technology readiness that could accelerate the zero-carbon transformation of the chemicals industry. According to the IEA's Faster Innovation Case scenario, half of the carbon abatements needed to reach net-zero emissions by 2050 will come from technologies that are not yet commercially available today. The proportion of uncommercialized technologies is even higher in heavy industry and long-distance transportation.[30]

Exhibit 12 Chemicals industry decarbonization technology maturity curve



* MSW: Municipal Solid Waste

Exhibit 13 Chemicals industry decarbonization technology outlook



Economic Feasibility: Analysis of the Cost of Zero-Carbon Solutions

Economically, **because the cost of disruptive technologies such as green hydrogen and CCS is expected to drop significantly in the future (see Exhibit 14), the cost-competitiveness of low-carbon and zero-carbon chemical production will be dramatically enhanced.** The cost of low-carbon and zero-carbon production is largely determined by the costs of fuel and feedstock, although the impact of capital investment such as equipment is relatively small unless extensive retrofitting is required. In addition, the cost-competitiveness of various zero-carbon production routes is different across regions due to resource endowment and market status.

Green hydrogen is an important feedstock for zero-carbon chemical production, and its cost abatement mainly comes from the rapid cost reduction of renewable electricity generation and hydrogen production equipment, as well as the improvement of conversion efficiency. The cost of electricity accounts for a major part of green hydrogen cost at nearly 60%–70%. The declining cost of zero-carbon electricity in the future will significantly drive the cost reduction of green hydrogen. At present, the cost of hydrogen production in areas with abundant renewable resources in China is about US$2.6/kg. According to RMI's analysis, green hydrogen cost could drop to US$1.7/kg by 2050. And with cheap renewable energy, complete technology, efficient management, government support, etc., green hydrogen delivery prices can be further decreased. The green hydrogen cost could be as low as $1/kg according to India's Reliance Industry's statement.

In terms of equipment capital expenditures, the current cost of electrolyzers is around US$300/kW. As China's electrolyzer technology becomes more mature and scales up, there is a lot of potential for electrolyzer costs to fall in the future. Bloomberg New Energy Finance assesses China's electrolyzer prices at $300/kW. Foreign electrolyzer companies are also accelerating to strengthen their electrolyzer economics, such as Ambani in India and Fortescue Future Industries in Australia. The price is expected to drop to US$100/kW by 2050.

In terms of conversion efficiency, electricity consumption in hydrogen production could drop to 45 kWh/kg hydrogen by 2050, about 20% lower than current levels. There is a higher-than-expected potential for optimization processes for hydrogen production units, such as the technology from Hysata Australia that can increase conversion efficiency to 41.5kWh/kg. The cost of green hydrogen will depend on whether it is from on-site renewables or grid electricity. Electricity market reforms may create uncertainty about the future trend of electricity prices in different regions. Cost models have electricity and hydrogen prices at national average levels.

The high concentration of CO_2 emitted from chemical production creates excellent conditions for CCS applications at a relatively lower cost. In the future, the cost of CCS will continue to fall with technology iteration and as it takes advantage of economies of scale. The cost of first-generation capture technology is expected to drop 15%–25% by 2035, and as second-generation capture technology becomes commercially available, its cost will be 5%–10% lower than that of first-generation technology.[viii] By 2040, with the initial build-out of CCS clusters, the cost of second-generation capture technologies will be 40%–50% lower than current levels.[31] By 2050, the corresponding costs will drop even further.

Biomass resources are relatively limited in China. The cost of biomass-based zero-carbon chemical production is expected to decline through large-scale deployment in the future. However, compared with other zero-carbon

viii First-generation capture technologies refer to those technologies that can be demonstrated on a large scale at this stage, such as amine-based absorbers, physical solvents, and oxygen-enriched combustion. Second-generation capture technologies refer to new technologies that can significantly reduce energy demand and cost compared with mature first-generation technologies, such as new membrane separation technology and new absorption technology.

technologies, biomass will play a limited role and is only likely to be applied on a large scale in areas where biomass resources are particularly abundant.

This section analyzes the economics of different zero-carbon production routes for ammonia, methanol, and ethylene respectively.

Exhibit 14 Cost outlook of green hydrogen in China

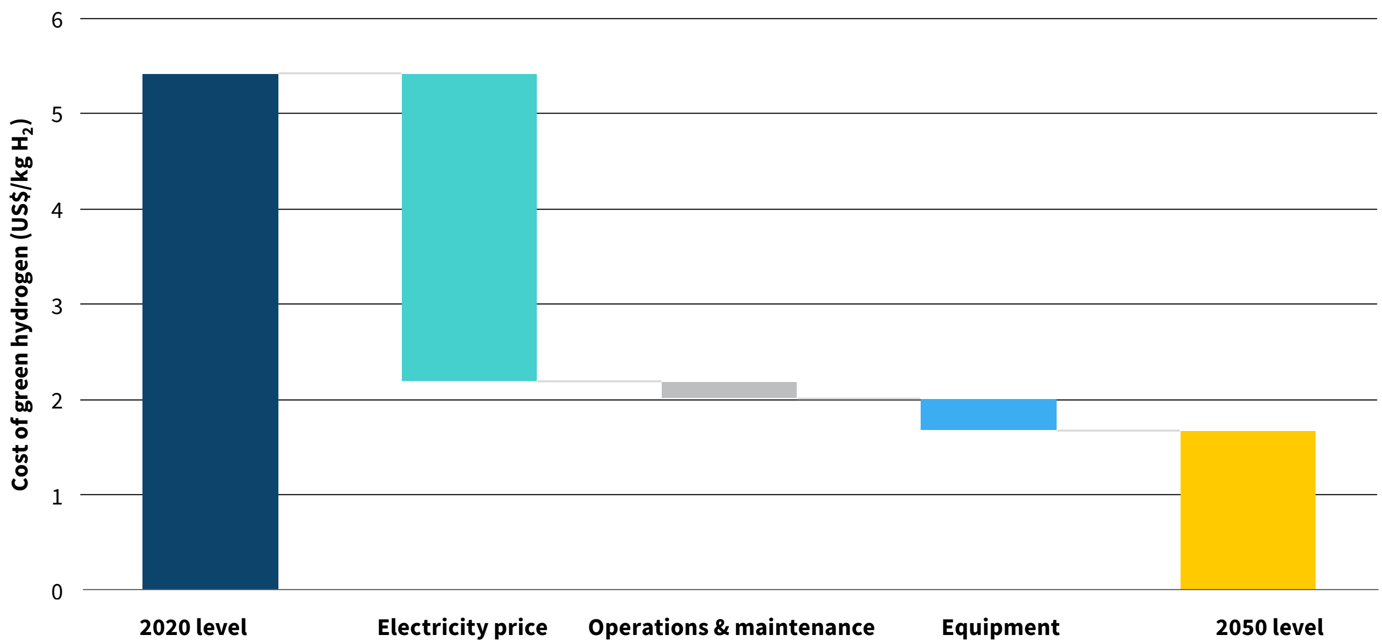
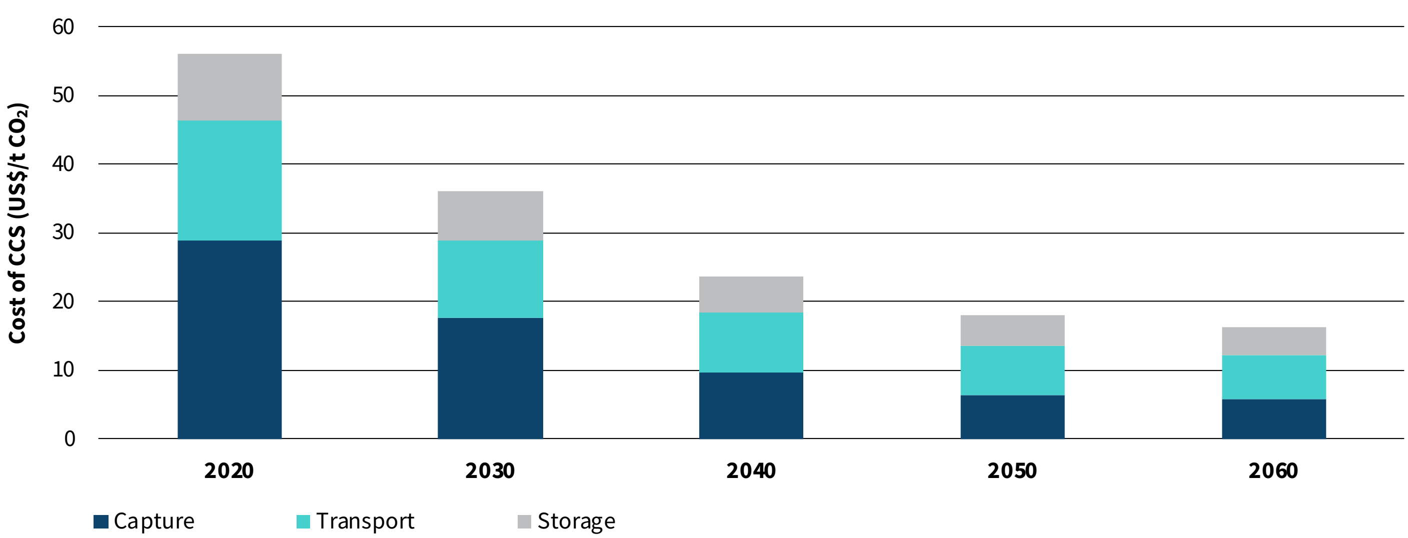


Exhibit 15 Cost outlook of CCS in China



Source: Chinese Academy of Environmental Planning, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, The Administrative Center for China's Agenda 21

Ammonia

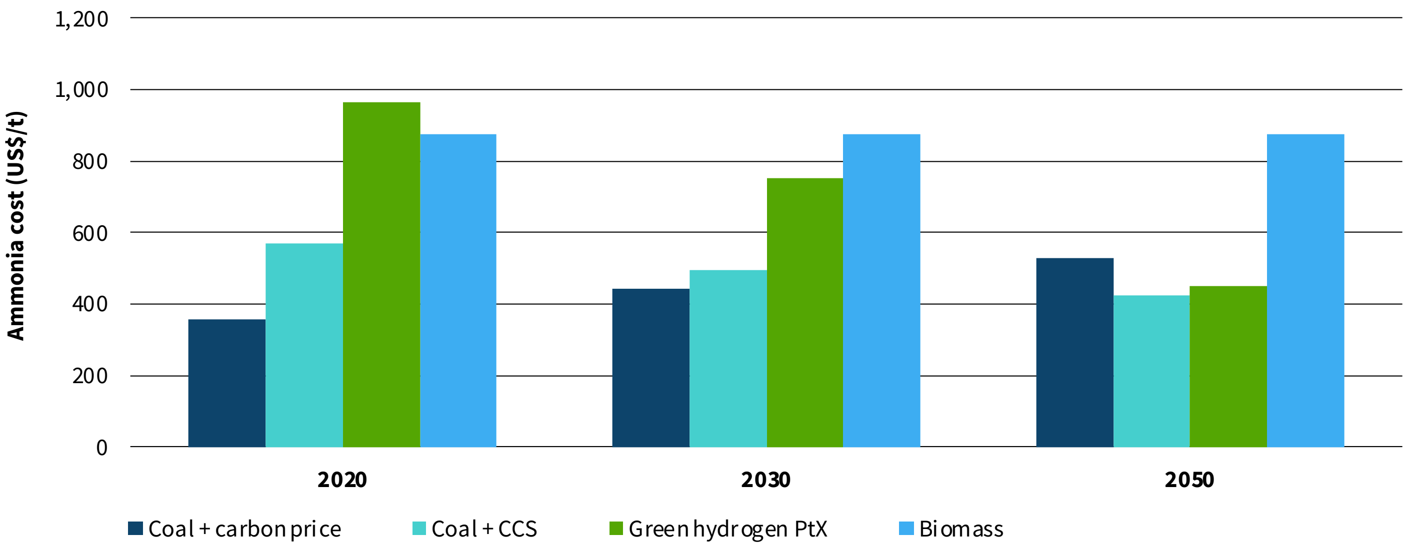
In the future, coal + CCS or green hydrogen will be most economical approaches to produce zero-carbon ammonia. Even now, with favorable renewable energy conditions, green hydrogen–based ammonia is already cost-competitive with conventional coal-based ammonia. According to an IEA report in 2019, the cost of green hydrogen–based ammonia in China could drop to about US$460/ton (t) through efficient integration of wind and solar resources, not far behind the cost of coal-based ammonia at about US$380 to US$410/t.[32] The cost of ammonia is sensitive to the variation of feedstocks (such as coal, natural gas, etc.) and their price fluctuation. In the future, carbon pricing will make fossil-based ammonia less cost-effective; however, the accelerated decline in the cost of CCS and green hydrogen will make zero-carbon production routes more competitive.

Exhibit 16 shows the cost comparison of ammonia production through various zero-carbon routes in the future. In the long term, zero-carbon production routes are likely to be more economical than conventional fossil fuels–based production routes due to the potential adoption of carbon prices. Under the assumption of a US$40/t carbon price in 2050, it would be more cost-effective to produce ammonia from CCS or green hydrogen than from coal, although current international estimates of carbon prices are much higher than that. Goldman Sachs, for example, believes a carbon price of as much as US$100/t is needed to effectively reduce emissions,[33] and Wood Mackenzie indicates a carbon price of US$160/t is needed to meet the 1.5°C target.[34] Due to the relative shortage and comparatively higher cost of biomass in China, the cost of using biomass to produce ammonia will remain high. Unless a low-cost and sustainable supply of biomass is available, the contribution of biomass to decarbonize the ammonia industry will be limited.

In the short term, it will be more economical to use CCS to decarbonize coal-based ammonia production. Currently, the production cost of ammonia with CCS is about US$570/t, with a zero-carbon premium of about 60%. However, the cost is expected to drop to US$490/t in 2030 and further reduce to US$430/t in 2050. By 2030, with an assumed carbon price of US$20/t, the cost of producing ammonia with CCS will only be 12% higher than the cost after paying the carbon price. By 2050, with an assumed carbon price of US$40/t, the cost of producing ammonia with CCS will be 19% lower than the cost after paying the carbon price. Due to the overall low cost of CCS applied in ammonia production, existing coal-to-ammonia plants could be equipped with CCS in the short term.

Although CCS is generally the cheaper decarbonization option in the short term, with the rapid decline in the price of green hydrogen the production of ammonia using green hydrogen may achieve even lower cost in the long term. By 2050, with delivery hydrogen at US$1.9/kg, the cost of green hydrogen–based ammonia will fall to US$450/t, 15% lower than the cost of coal-based ammonia with a carbon price of US$40/t. With higher carbon prices expected in the future, green hydrogen–based ammonia will be more cost-competitive. In addition, in regions with sufficient renewable energy and hence low zero-carbon electricity prices, the cost of green hydrogen–based ammonia will be more favorable and is expected to be lower than that of ammonia produced with CCS or even lower than that of fossil-based ammonia without CCS.

Exhibit 16 **Production cost forecast of ammonia zero-carbon production routes**



Assumptions: Electrolyzer costs US$320/kW in 2020, US$213/kW in 2030, and US$106/kW in 2050. Electricity prices are US$85/MWh in 2020, US$53/MWh in 2030, and US$32/MWh in 2050. Electricity consumption of hydrogen production is 55 kWh/kg in 2020, 51 kWh/kg in 2030, and 46 kWh/kg in 2050. Carbon prices are US$0/t in 2020, US$21/t in 2030, and US$43/t in 2050. CCS costs US$56/t in 2020, US$36/t in 2030, and US$18/t in 2050 for highly concentrated CO_2 capture.

The production cost of green hydrogen–based ammonia is highly sensitive to the cost of green hydrogen, which is highly dependent on the zero-carbon electricity price. Exhibit 17 shows the production cost of zero-carbon ammonia at different green hydrogen prices. By 2050, the cost of green hydrogen–based ammonia will reach parity with that of coal-based ammonia at a hydrogen price of about US$1.5/kg regardless of carbon price, and a hydrogen price of about US$2.4/kg with carbon price considered. Exhibit 18 shows the production cost of zero-carbon ammonia under different zero-carbon electricity prices when hydrogen is directly produced from on-site renewable energy. By 2050, the cost of green hydrogen-based ammonia will reach parity with that of coal-based ammonia at an electricity price of US$20/MWh regardless of carbon price, and an electricity price of US$38/MWh with carbon price considered.

Comparing the ammonia production routes through green hydrogen and CCS, green hydrogen–based ammonia will be more cost-competitive than that with CCS when the delivery price of hydrogen is less than about US$1.8/kg. If hydrogen is produced on-site using renewable electricity, the cost of green hydrogen–based ammonia will be lower when electricity price is below US$27/MWh. By comparing these cost conditions, early opportunities for CCS or green hydrogen–based ammonia pilots can be identified. The comparison can also help select the most competitive zero-carbon ammonia production routes in different regions.

Exhibit 17 Zero-carbon production costs of ammonia under different green hydrogen prices (2050)

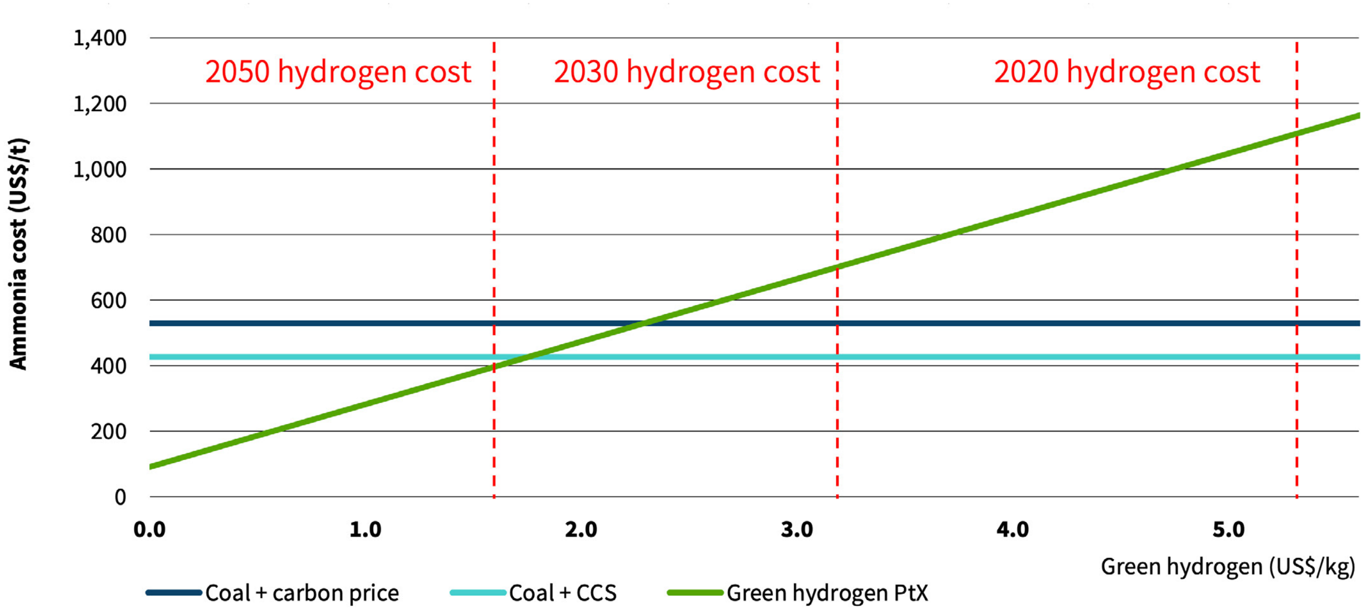
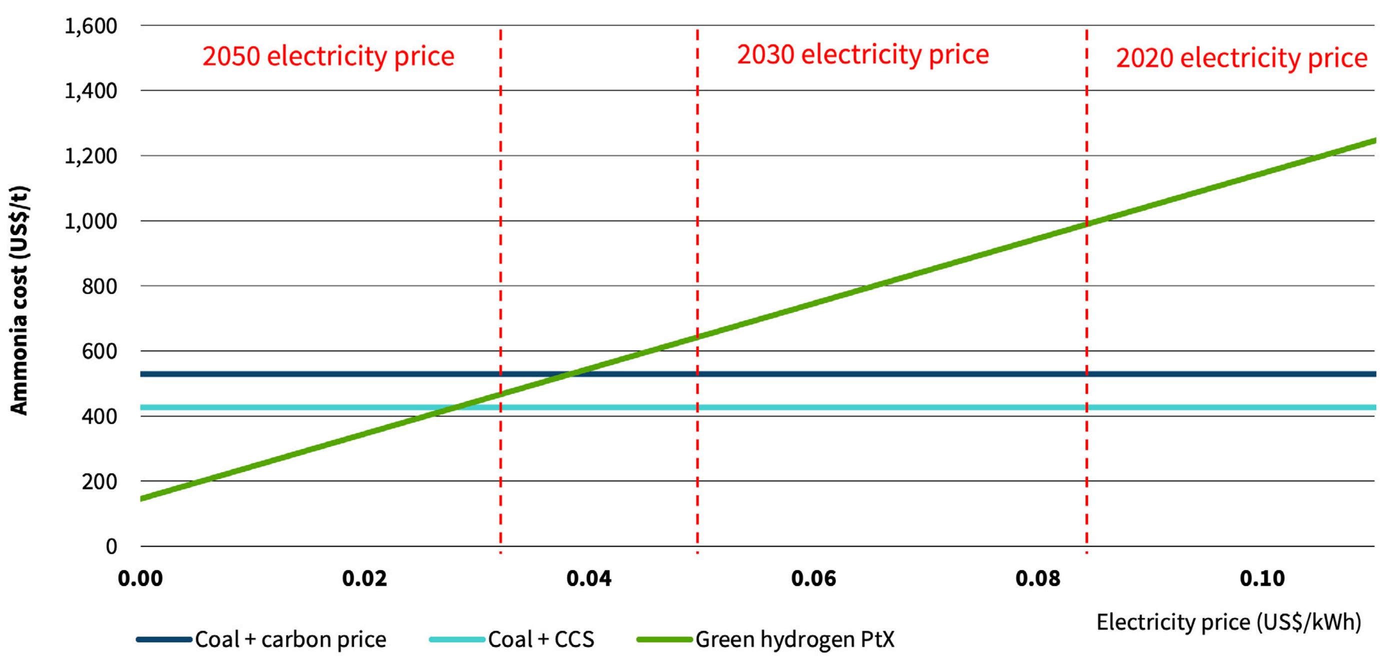


Exhibit 18 Zero-carbon production costs of ammonia under different electricity prices (hydrogen produced on-site, 2050)



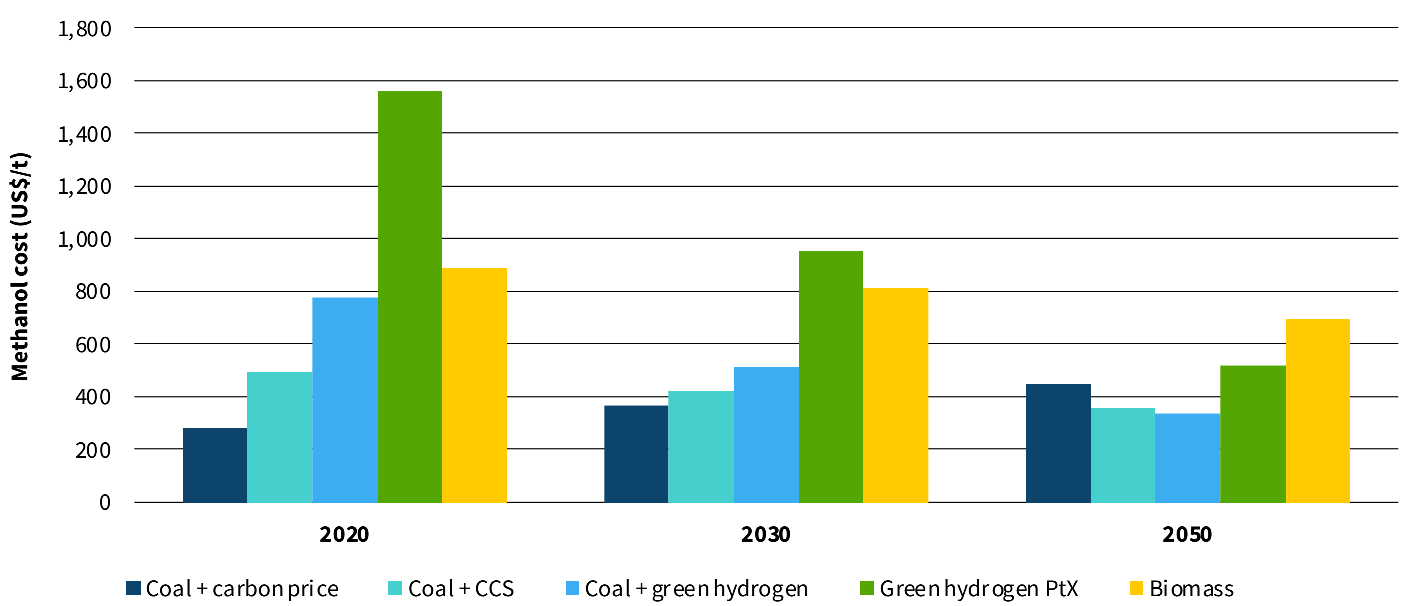
Methanol

Zero-carbon production routes of methanol can be classified according to feedstock sources into ones that still rely on fossil fuels (mainly coal) and ones that adopt new alternative feedstocks. The former routes are likely to release carbon into the atmosphere at the end of their life cycle because the carbon in their products still comes from fossil fuels. Therefore, this carbon still needs to be offset by means of carbon sinks to achieve life-cycle zero carbon.

In the above classification, former routes include conventional coal-to-methanol integrating with CCS and coal-to-methanol coupled with green hydrogen to avoid emissions during production. These two production routes can largely avoid carbon emissions in the reaction processes. Production routes adopting new alternative feedstocks mainly include green hydrogen–based PtX methanol production and biomass-to-methanol production. In addition to green hydrogen, the PtX route also requires CO_2 as feedstock. If the CO_2 comes from direct air capture or biomass, methanol production can be considered as life-cycle zero carbon. If the CO_2 comes from industrial waste gas during the transition to life-cycle zero carbon, it may still be released into the atmosphere at the end of the product's life cycle; therefore, achieving producing zero carbon could be the principle of the transition period.

Similar to the case of ammonia, the application of CCS in conventional coal-to-methanol is the most economical zero-carbon production route in the short term. Exhibit 19 shows the evolving cost of different zero-carbon production routes over time. In 2020, even with a green premium of more than 70%, the cost of the production route with CCS is still significantly lower than other zero-carbon routes. By 2030, even at a lower carbon price, the green premium for CCS could drop to less than 15%. By 2050, the production route with CCS will be more cost-competitive than the route to pay the carbon price. The competitiveness of the CCS-based production route comes from two aspects. First, the CO_2 concentration in coal chemical production is very high at close to 100%, so carbon capture could have clear cost advantages. Second, methanol production in China is highly dependent on coal, and the application of CCS enables the best use of existing production capacity and assets, avoiding uncertainties caused by large-scale transformation.

Exhibit 19 **Production cost forecast of methanol zero-carbon production routes**



However, with the rapid cost reduction of green hydrogen, methanol production routes using hydrogen — through either the conventional coal chemical process coupled with hydrogen or direct hydrogen-based PtX — could achieve ideal cost-effectiveness in the long term. Unlike ammonia that does not have a carbon component, the PtX route for methanol production also needs to take the cost of CO_2 as feedstock into account. However, RMI's analysis shows that, compared with the cost of feedstock CO_2, the cost of green hydrogen is still the bottleneck determining the cost-competitiveness of the PtX methanol production route. Industrial by-product hydrogen can be used as a transitional solution. By 2050, even if the cost of CO_2 feedstock is as high as US$100/t, which is equivalent to the current cost of direct air capture, the cost of green hydrogen still accounts for about 60% of the production cost of zero-carbon methanol at a hydrogen price as low as US$1.6/kg. If the hydrogen price drops to US$1.6/kg by 2050, the cost of green hydrogen-based PtX methanol production will be about US$520/t, with a 20% green premium compared with conventional coal-to-methanol plus carbon price. If hydrogen price could go even lower, the cost-competitiveness of PtX could be more compelling.

The cost of conventional coal-to-methanol coupled with green hydrogen is also highly dependent on the cost of green hydrogen. Although this route still relies on coal, green hydrogen is also needed to supplement as feedstock for the syngas that meets the carbon-to-hydrogen ratio requirement while avoiding process emissions. By 2050, methanol produced by this route will cost about US$320/t. Although the cost-effectiveness is relatively high, because the carbon element still comes from coal, terminal consumption or disposal of methanol may still cause carbon emissions in the life cycle.

The cost of biomass-to-methanol is lower than that of the green hydrogen–based production route in the short term. However, due to the shortage of domestic biomass resources and high feedstock cost in China, biomass-to-methanol could play a limited role in zero-carbon methanol production in the long term.

Exhibits 20 and 21 respectively show the cost comparison of different zero-carbon methanol production routes under different hydrogen prices and electricity prices (on-site hydrogen production). Assuming a carbon price of US$40/t in 2050, methanol produced from the green hydrogen–based PtX route will be more economical than methanol from coal when the delivery hydrogen price is less than about US$1.2/kg. The production cost of green hydrogen–based zero-carbon methanol is lower than that of coal-to-methanol with CCS when the delivery hydrogen price is less than about US$0.8/kg. If hydrogen is produced using on-site renewables, the required electricity price needs to be lower than US$22/MWh and US$16/MWh, respectively, to ensure the cost of green hydrogen–based zero-carbon methanol is more competitive than that of coal-to-methanol with carbon price and coal-to-methanol with CCS.

Exhibit 20 Zero-carbon production costs of methanol under different green hydrogen prices (2050)

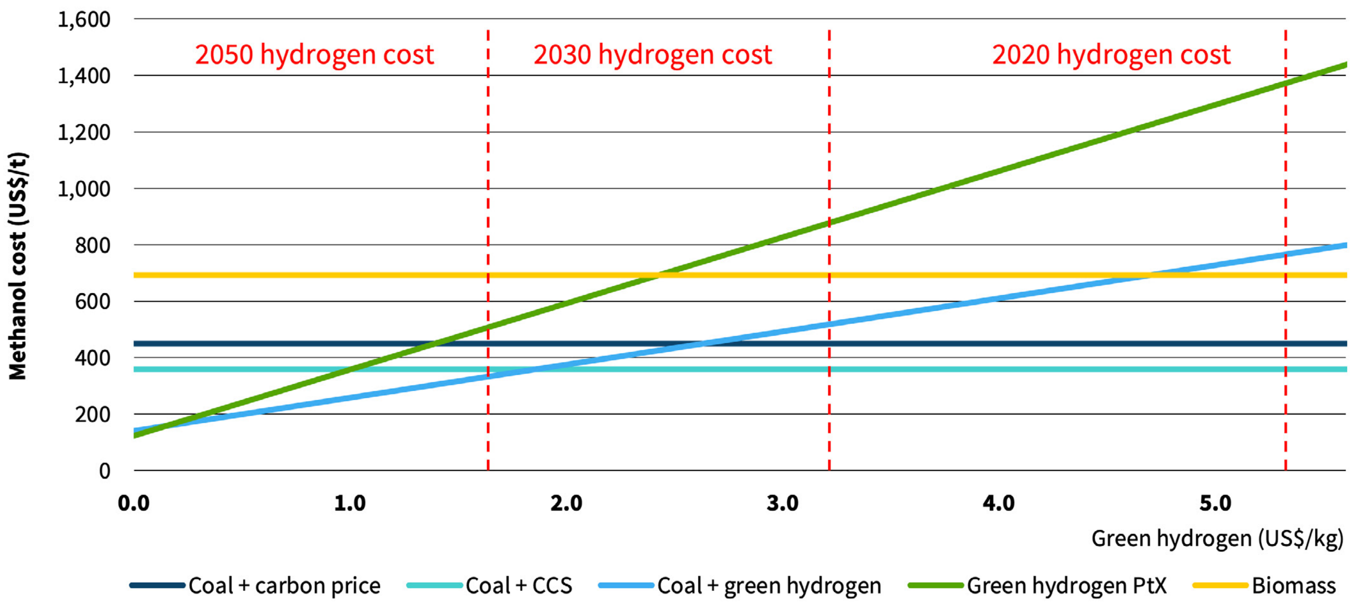
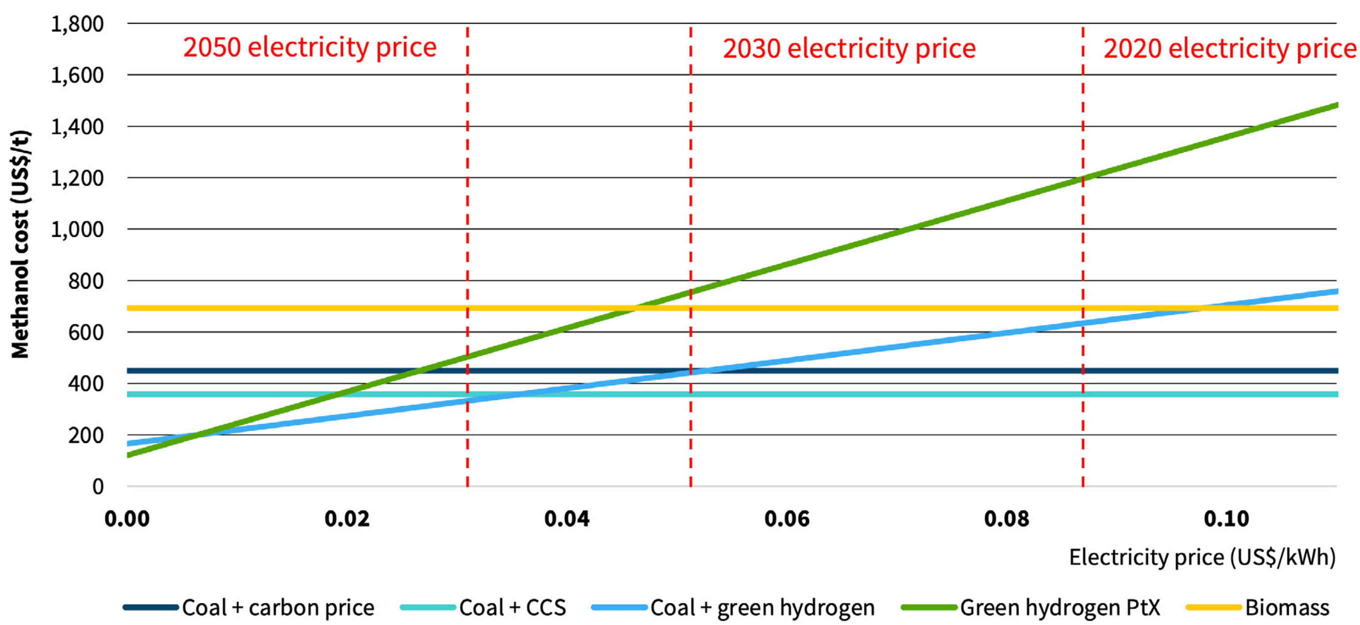


Exhibit 21 Zero-carbon production costs of methanol under different electricity prices (hydrogen produced on-site, 2050)



Ethylene

At present, the feedstocks for ethylene production mainly include coal, naphtha, and light hydrocarbon, and their cost constitutes an important part of the overall ethylene cost, accounting for about 25% for the coal-based route, about 75% for the naphtha-based route, and 39% for the light hydrocarbon-based route.[35] The prices of coal, naphtha, and light hydrocarbon play a significant role in the economics of ethylene production and affect the competitiveness of different feedstocks. Naphtha prices fell as oil prices fell in 2020, squeezing the market of the coal-based route in a low-oil-price environment. For every US$10/barrel (bbl) drop in oil price, the cost of olefin produced from oil will drop about US$128/t. The oil price parity for coal-to-olefins is around US$45/bbl, although low-cost coal-to-chemicals can push the oil price parity below US$40/bbl.[36]

Compared with coal chemical processes, petrochemical processes have less carbon emissions from feedstock reactions but more from the combustion of fuel to achieve the required reaction temperature. Zero-carbon ethylene can use naphtha, light hydrocarbon, green methanol, biomass, CO_2, and water as feedstocks. Naphtha- and light hydrocarbon–based routes require higher temperatures, with the former largely dependent on combustion of by-products and the latter supplemented by fossil fuels other than by-products. Produced CO_2 should be treated with CCS. E-cracking furnace technology can effectively replace fossil fuel combustion in naphtha- and light hydrocarbon–based routes and has a strong cost advantage when electricity price is low, and the equipment investment is only slightly higher than that of conventional cracking furnace. The energy transfer efficiency of an e-cracking furnace is higher, but how to achieve temperatures above 800°C efficiently and economically with electricity is still a problem to be solved by large-scale applications. Methanol-to-olefin (MTO) technology is relatively mature, with methanol price accounting for more than 70% of the total cost. The reaction temperature of MTO is about 400°C, which is easier to achieve using electric furnaces, but under the zero-carbon scenario methanol as feedstock needs to be generated from a zero-carbon route. Various biomass resources could be used to produce ethylene, with bioethanol as a more commonly used choice, but this route has constraints such as high cost and limited feedstocks. Being a disruptive technology, PtX uses CO_2 and hydrogen to produce ethylene directly, but it is still in early development stages.

Exhibit 22 **Production cost forecast of ethylene zero-carbon production routes**

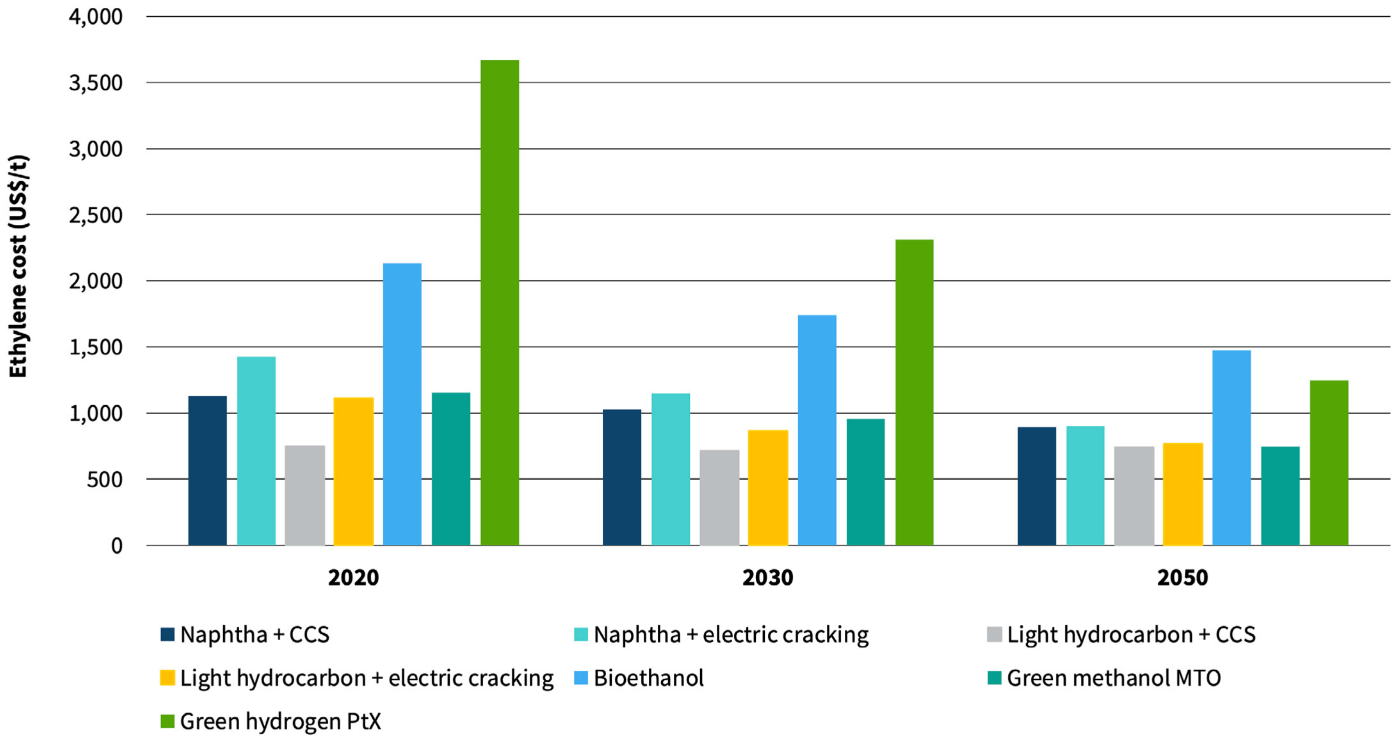


Exhibit 22 shows the production cost forecast of zero-carbon ethylene production routes. The cost reduction of naphtha- and light hydrocarbon–based routes is mainly due to the maturity of thermal energy management technology, the reduction of electricity price, and the decreasing cost of naphtha as feedstock. The trend toward low-carbon development will reduce demand for oil, and supply will lag to adjust the demand, keeping oil prices at low levels. As a product of the petroleum industry chain, the price of naphtha will be affected by the oil price and hover at a low level, creating an opportunity to develop the naphtha-based route. Producing ethylene from light hydrocarbon has a higher conversion rate, although the price of light hydrocarbon is expected to rise due to limited supply.

In general, the light hydrocarbon–based route still maintains a fast cost-reduction rate with the development of technology and the reduction of electricity price. Both routes need to integrate with CCS or e-cracking and their costs are expected to decline significantly, especially for e-cracking. The cost of the ethylene production route based on light hydrocarbon + e-cracking is expected to decrease nearly 50% from US$1,420/t to US$770/t in the next 30 years.

The cost of fossil fuel feedstock–based ethylene production coupling CCS or e-cracking will reach about US$800/t by 2050. However, the cost-competitiveness of the naphtha- and light hydrocarbon–based routes will be weakened if Scope 3 emissions are considered. In addition, production of ethylene from crude oil has developed rapidly in recent years. In this route, ethylene is produced directly from crude oil without oil refining and the conversion of naphtha and other intermediate materials, thus shortening the production process and reducing energy consumption. Due to the difference of crude oil components as feedstock, the required processes and product conversion rate are different and the cost of producing ethylene from crude oil could fluctuate widely and is difficult to estimate.

The cost of the green methanol–based ethylene production route has massive potential to decrease, mainly due to the declining cost of green hydrogen further decreasing the cost of green methanol. The breakthrough and maturity of PtX technology will also lead to cost reduction. The cost of green hydrogen–based PtX and green methanol–based MTO routes is expected to decrease to US$1,100/t by 2050, which will be competitive with fossil fuel–based routes. The cost of ethylene produced from biomass will still be expensive at nearly US$1,600/t in 2050 due to the limited supply of biomass as feedstock and high electricity demand. In the long term, biomass is unlikely to provide significant capacity for ethylene production.

Exhibit 23 analyzes the sensitivity of the cost of different ethylene production routes to the price of green hydrogen in 2050. Green hydrogen–based PtX and green methanol–based MTO routes are highly sensitive to green hydrogen prices; therefore, obtaining green hydrogen at low cost is the key to making them cost-competitive. Exhibit 24 analyzes the sensitivity of the cost of zero-carbon ethylene production routes to electricity prices in 2050. Green hydrogen– and biomass-based routes have higher demand for electricity and thus are more sensitive to electricity prices, but naphtha-based or light hydrocarbon–based routes are less sensitive. When electricity price is below US$48/MWh, the green methanol–based MTO route will be more cost-competitive, and when electricity price is above US$48/MWh, naphtha- and light hydrocarbon–based routes will be more cost-competitive. The green hydrogen–based PtX route will be more cost-competitive only in regions with extremely low electricity prices, and the bioethanol-based route will have relatively limited competitiveness with electricity prices at all levels.

Exhibit 23 Zero-carbon production costs of ethylene under different green hydrogen prices (2050)

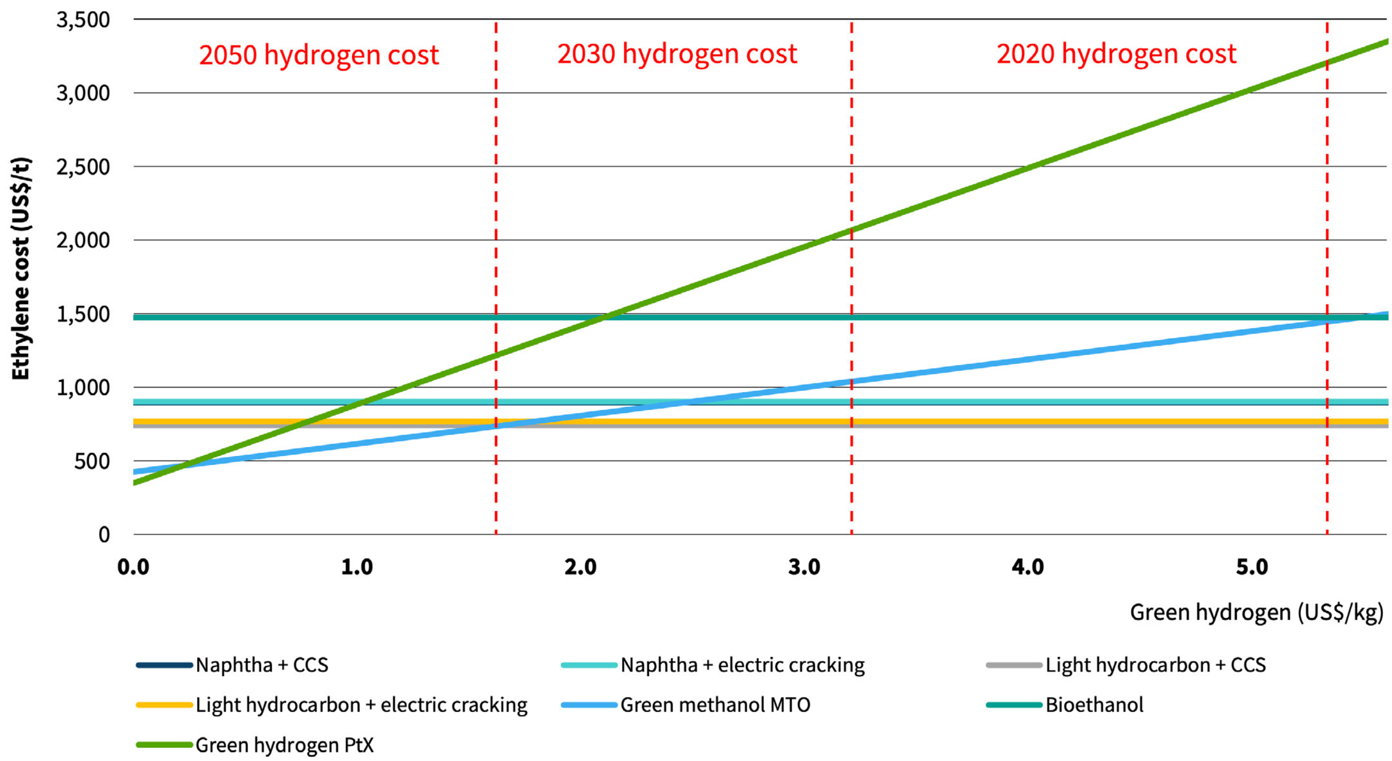
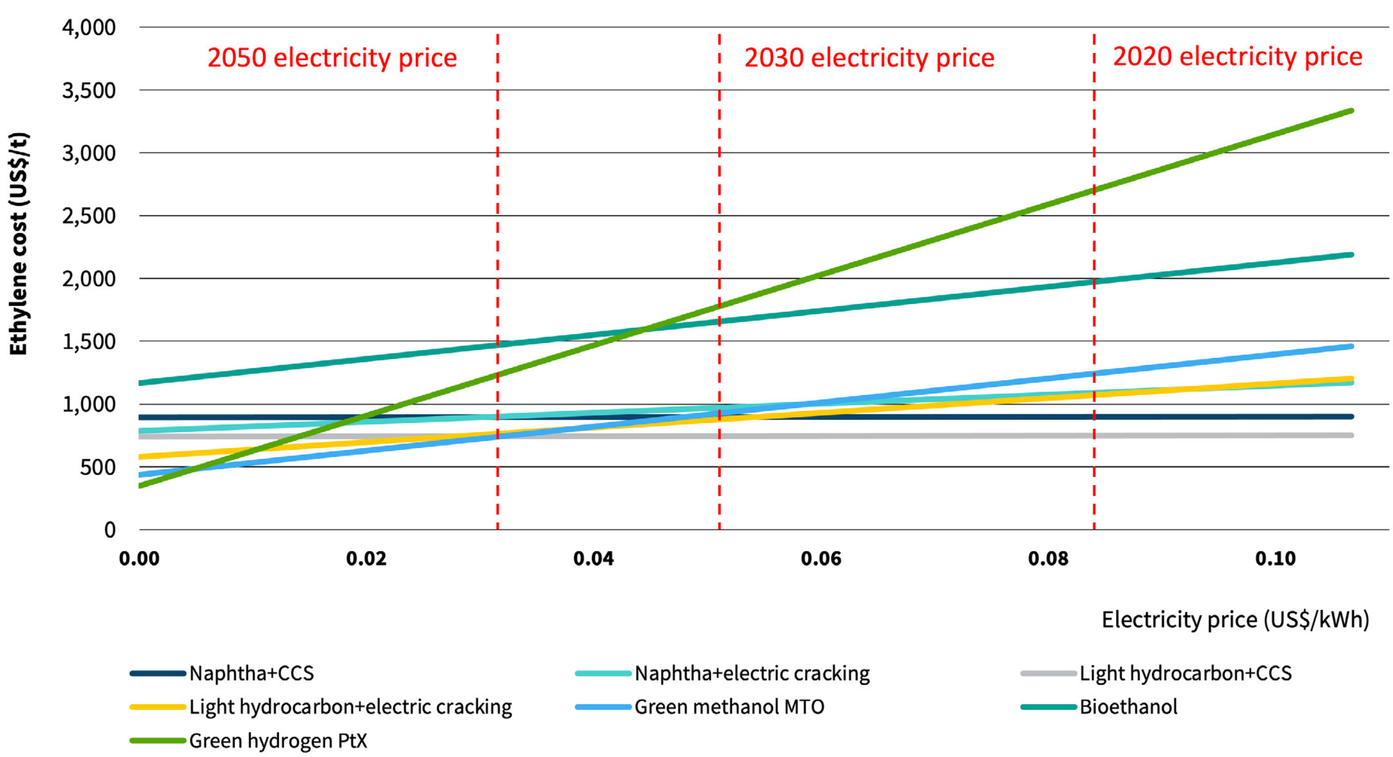


Exhibit 24 Zero-carbon production costs of ethylene under different electricity prices (hydrogen produced on site, 2050)



Emissions abatement cost

Exhibits 25–27 show the cost of the zero-carbon production routes per unit of carbon emissions abatement for ammonia, methanol, and ethylene in 2050. The cost of carbon abatement with CCS and electric heating routes will be about US$32/t. The biomass route cost remains expensive. The cost of carbon abatement through green hydrogen–based routes will vary significantly due to the different delivery prices of green hydrogen. This study analyzes the cost of emissions abatement under green hydrogen prices at US$3.2/kg, US$1.6/kg, and US$0.8/kg. The cost of emissions abatement could even be negative when the price of green hydrogen is low enough. In the future, when the carbon price is higher than the corresponding cost of emissions abatement, zero-carbon production routes will be more cost-effective than conventional routes.

Exhibit 25 **Emissions abatement cost of ammonia (2050)**

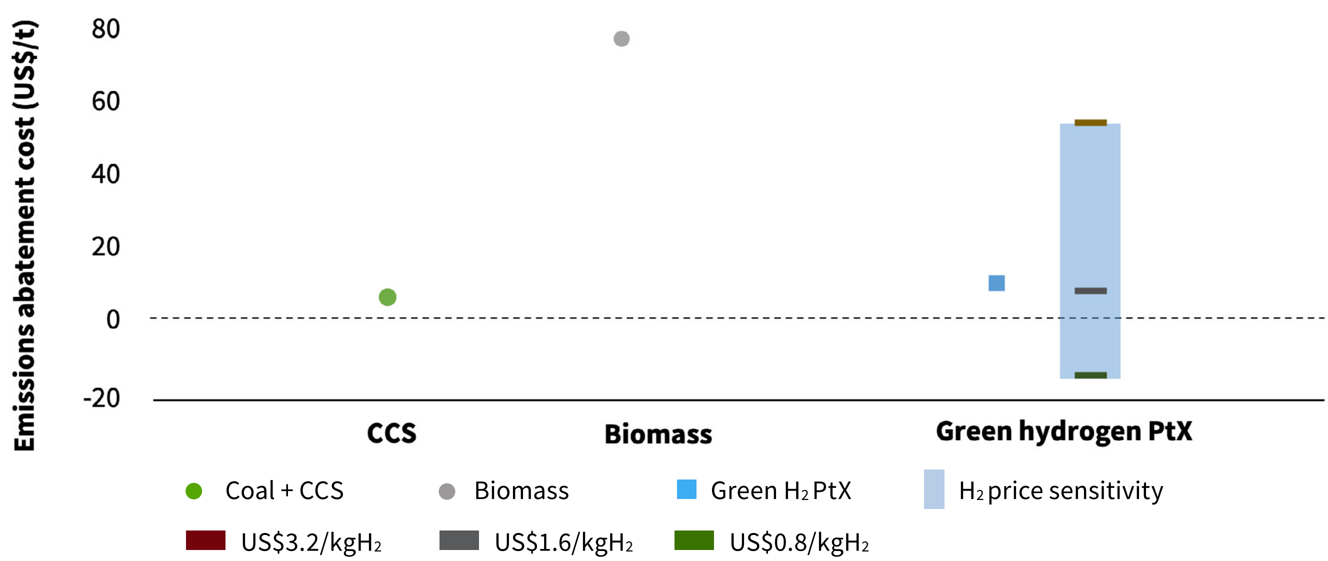


Exhibit 26 **Emissions abatement cost of methanol (2050)**

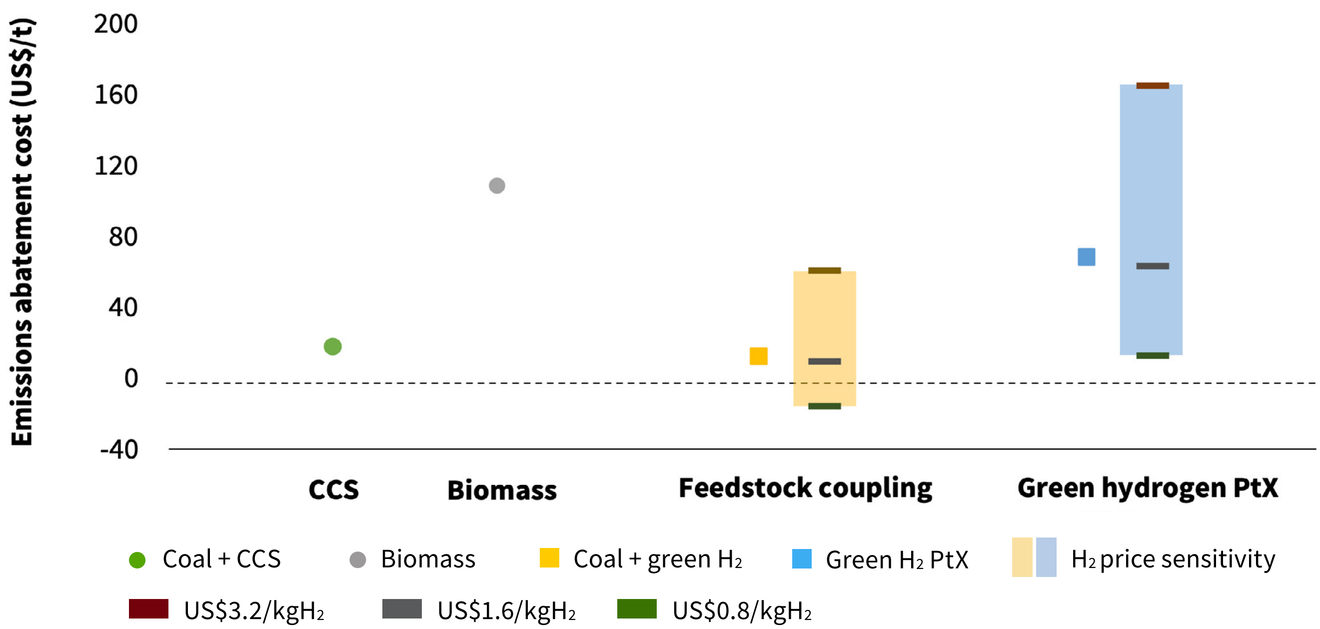
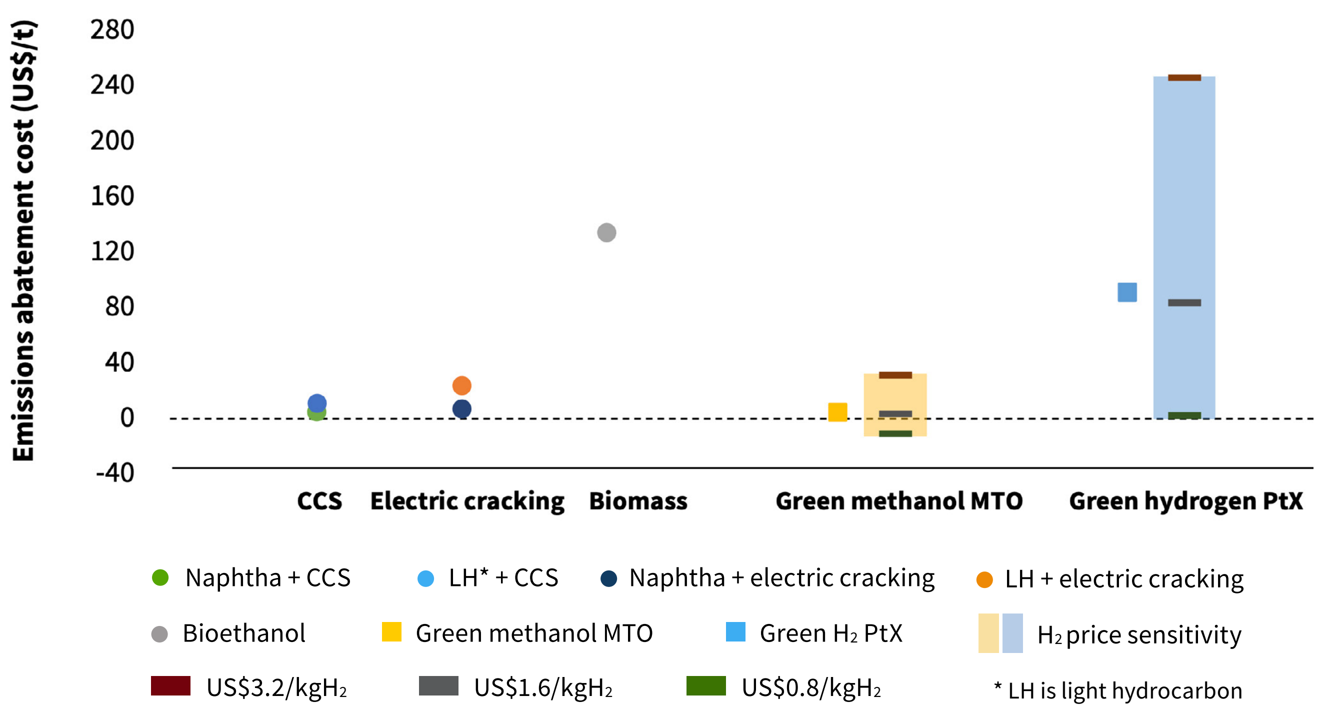
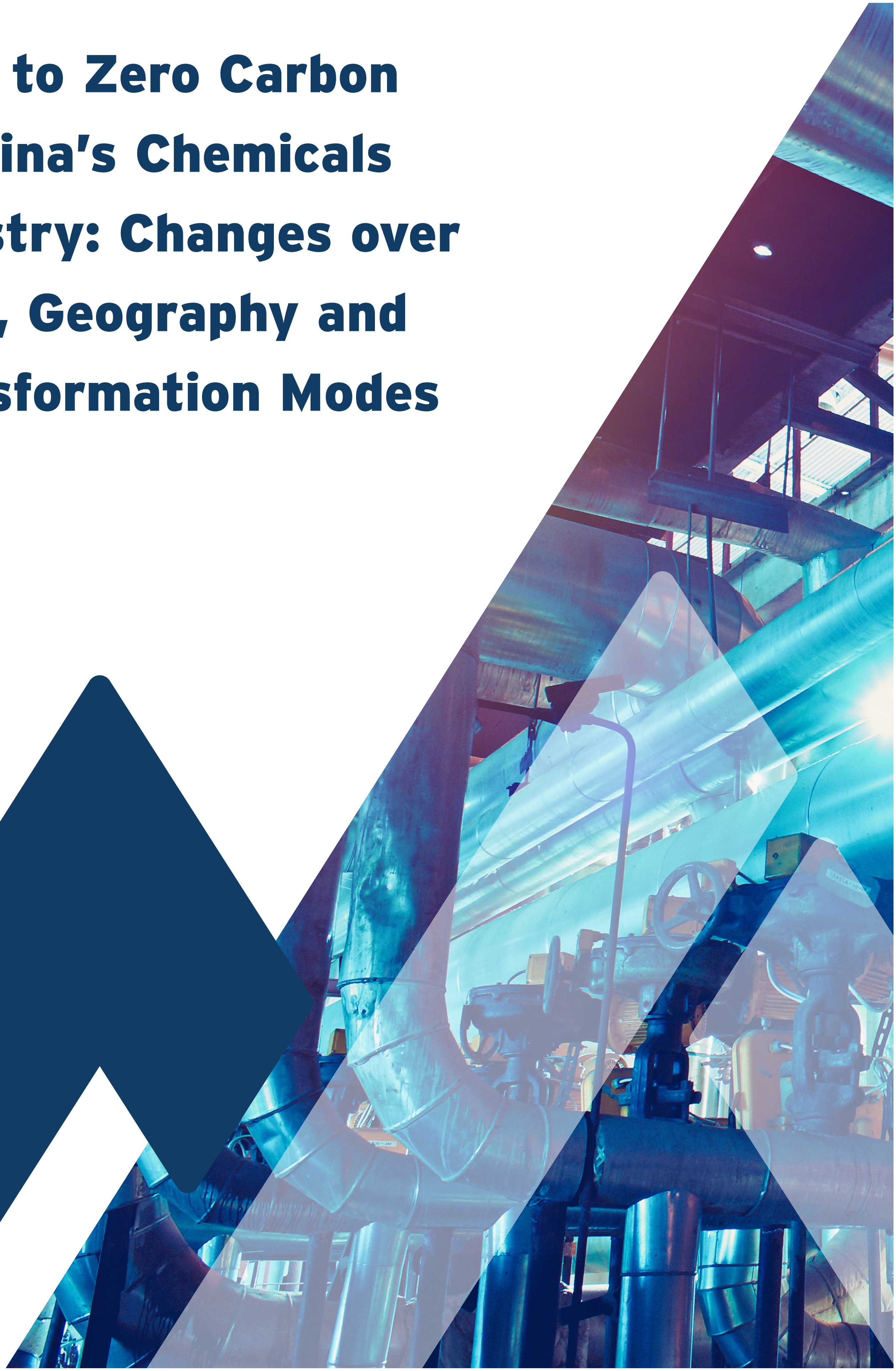


Exhibit 27 **Emissions reduction cost of ethylene (2050)**



Road to Zero Carbon in China's Chemicals Industry: Changes over Time, Geography and Transformation Modes



This chapter discusses the change of penetration rate of zero-carbon production routes of ammonia, methanol, and ethylene over the short, medium, and long term, demonstrating the development of China's chemicals industry to gradually achieve the zero-carbon target. This chapter also elaborates key regional zero-carbon actions and the possible layout of zero-carbon production capacities based on existing chemical production routes, zero-carbon resources distribution, and economics. Based on the characteristics of the industry, we also discuss the possible features and key actions of the large-base mode, distributed production mode, and import competition mode of the zero-carbon transformation of China's chemicals industry in the future.

Timeline of the Zero-Carbon Transformation of China's Chemicals Industry

Measures for the zero-carbon transformation of China's chemicals industry include industrial structure optimization, energy structure change (including feedstock structure change and fuel structure adjustment), energy-saving technologies, resource recycling, and CCS. These measures are in different development stages, with varying technology readiness levels, economics, and compatibility. Therefore, it is critical to establish an integrated plan that combines the best options of deployment time and solution penetration. Feedstock change is one of the most important carbon abatement levers for the zero-carbon transformation of China's chemicals industry. This study mainly discusses the timeline of the zero-carbon transformation of China's chemicals industry from the perspective of feedstock change and analyzes how other measures should be implemented at each time point.

In the zero-carbon scenario, the transformation of China's chemicals industry will present the following main features. First, the current production mode with coal as the dominant feedstock will gradually shift to one with more diversified feedstocks, and green hydrogen will replace coal as the most important feedstock due to the gradual expansion of the PtX production route. Second, because the existing assets based on fossil fuel feedstocks are relatively young, CCS could be installed on the existing facilities at a large scale in the short to medium term, and the scaled green hydrogen–based production routes will be deployed in the medium and long term. Third, even if fossil fuel–based production routes can be equipped with CCS, there will still be large-scale withdrawal of assets based on coal and gas, given the constraints of backward capacity phaseout and emissions control. In this study, the change of penetration rates and scale of different zero-carbon production routes of ammonia, methanol, and ethylene are analyzed.

Ammonia

In the zero-carbon scenario, with declining agricultural demand, slowly increasing industrial demand, and significantly expanding energy demand, the total domestic demand for ammonia will show a U-shaped curve from now through 2050. In terms of production routes, coal-based capacity will continue to drop, the proportion of operating coal-based capacity with CCS will gradually increase, and hydrogen-based PtX capacity will gradually expand and scale up more rapidly after 2040.

In 2020, ammonia produced from coal, natural gas, and coke-oven gas accounted for 77%, 21%, and 2% of the total, respectively. By 2030, with the withdrawal of 12 million tons of coal-to-ammonia capacity during the preceding decade, the proportion of coal-based ammonia will fall to 70%, while 20% of ammonia will come from the rapidly growing PtX production route and more than 30% of remaining fossil fuel–based production will be equipped with CCS. By 2040, coal-based capacity will be further reduced by 5 million tons, more than 60% of the remaining fossil fuel–based capacity will be equipped with CCS, and the further scaled PtX route will contribute 40% of total ammonia production. By 2050, PtX will be the largest source of ammonia, accounting for 70% of the total, and the remaining demand for ammonia will generally be met by the coal-based production route with CCS. Because the economics of producing ammonia from natural gas is generally low and China has prohibited the construction or expansion of new capacity of gas-based ammonia production, no more ammonia will be produced from natural gas in China after currently operating assets reach the end of their lifetime by 2040.

Methanol

In the zero-carbon scenario, methanol production in China will peak at 100 million tons around 2030 and gradually decline to 69.5 million tons in 2050, about 15% below current levels. Accordingly, during the capacity-expanding stage from 2020 to 2030, the increased capacity will mainly come from zero-carbon production routes such as PtX. However, part of the additional capacity will still be provided by the coal chemicals industry due to industry planning inertia, but CCS or coupling with green hydrogen will be required to minimize carbon emissions. During the capacity-declining stage between 2030 and 2050, coal-based capacity will be rapidly withdrawn; in particular, those assets not equipped with CCS or coupled with green hydrogen will be eliminated.

In 2020, coal-, natural gas–, and coke-oven gas–based production routes accounted for 75%, 12%, and 13% of China's methanol output, respectively. By 2030, in addition to the existing production routes, new routes such as PtX and biomass will also account for a certain proportion. Specifically, methanol produced from PtX will account for 20% of the total, reaching 20 million tons, but methanol from biomass will only account for 1% of the total due to the shortage of sustainable feedstocks and high cost. Coal coupled with green hydrogen and coal with CCS will account for 30%–40% of total coal-based capacity. By 2040, the PtX and biomass routes will further expand. Methanol production from PtX accounts for 40% of the total. Methanol production from biomass will account for 5%, reaching 5 million tons. More than half of coal-based production will be coupled with green hydrogen or equipped with CCS, and the remaining capacity that has not implemented carbon abatement measures will be rapidly withdrawn, reducing methanol's output by more than 22 million tons compared with 2030 levels. By 2050, the total amount of methanol produced by PtX will reach 60%, that produced by biomass will be further expanded to 10%, and the proportion of the coal-based production route will be reduced to 30%, all of which will be coupled with green hydrogen or equipped with CCS. At this point, coal-based methanol production will fall to about one-third of its 2020 level.

Ethylene

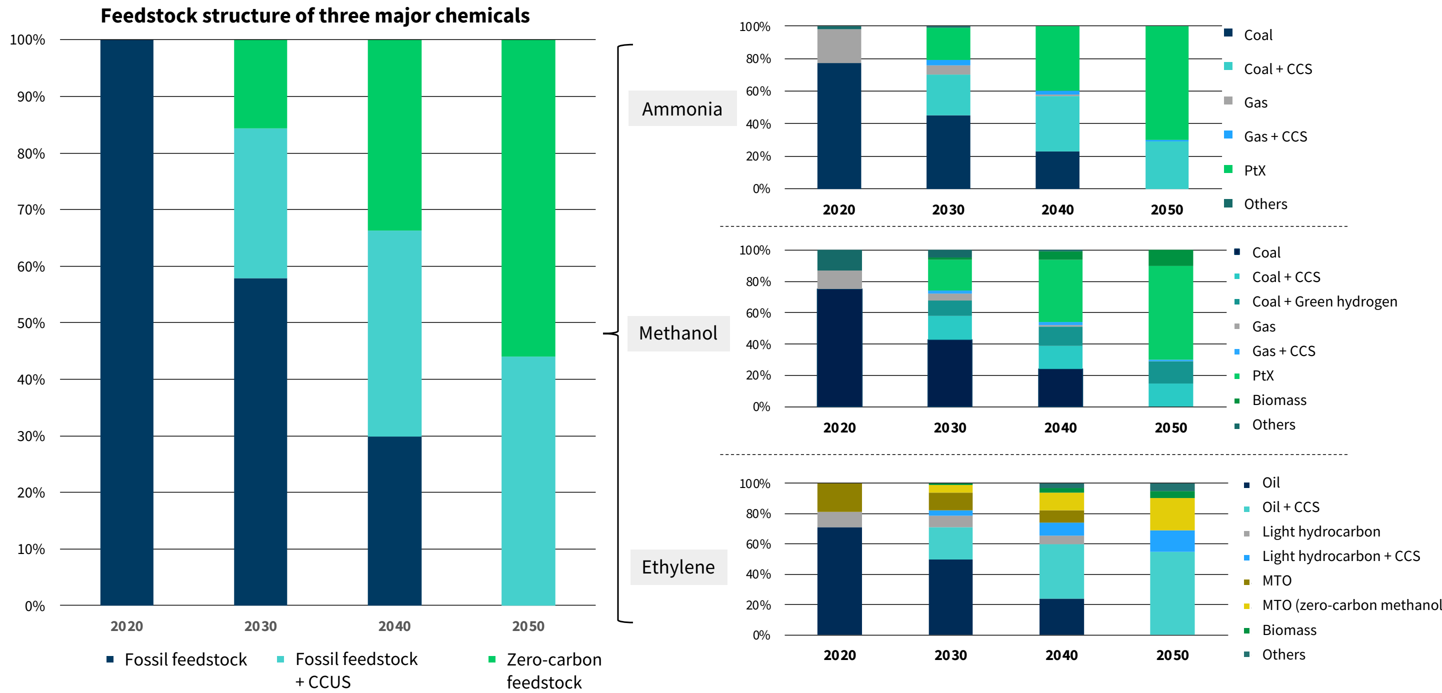
At present, the main feedstocks for ethylene production in China are petroleum products (mainly naphtha), accounting for 71% of the total output, ethylene from coal-to-olefin and MTO accounts for 19%, and the remaining 10% comes from ethane and other light hydrocarbons. The zero-carbon transformation of ethylene production in China will show the following characteristics: The source of feedstocks will shift from petroleum dominated to a more diverse combination. Due to the large potential of energy-efficiency improvement, which is beneficial for emissions reduction, the light hydrocarbon–based production route will expand to a certain extent. Due to the inertia of planned capacity, the naphtha-based route will maintain moderate growth in the short term, but its proportion will gradually decrease in the medium and long term. The MTO production route will also be developed, with methanol feedstock coming from a variety of zero-carbon sources in the medium and long term. Meanwhile, the use of CCS in fossil fuel–based production routes will gradually increase. In addition, new zero-carbon production routes, such as biomass-to-ethylene and PtX direct ethylene production, will also play a role in the long term.

By 2030, with the development of lighter feedstocks, light hydrocarbon–based ethylene will account for 14% of the total and the MTO route will account for 17%. Accordingly, oil-based ethylene production will be reduced to about 55%. Overall, 30% of fossil fuel–based ethylene production will be equipped with CCS by 2030. By 2040, there will be a small increase in light hydrocarbon–based production and more than 60% of MTO methanol feedstock will come from zero-carbon sources. The proportion of oil-based ethylene production will fall to 60%, with CCS penetration being more than 60% of fossil fuel–based capacity. By 2050, 14% of ethylene will be produced from light hydrocarbon, 20% from MTO (all zero-carbon methanol), and 55% from oil. From 2020 to 2050, the biomass-to-ethylene route will also develop gradually, although on a relatively small scale due to high costs and feedstock shortages. In addition, PtX direct ethylene production and other innovative routes will develop to a certain extent, but due to the relatively low technology readiness, the overall capacity will be low.

Exhibit 28 **Transformation roadmap for China's chemicals industry in the zero-carbon scenario**

		2020	2030	2040	2050	2060
Industrial structure optimization		Phase out backward capacity, increase share of high-end products, increase chemicals while reducing oil consumption, and strictly control added capacity				
Energy structure change	Fuel	30% electrified		Nearly 50% electrified	Almost 100% electrified where possible	
	Feedstock	Share of fossil fuel (mainly coal) to primary chemicals reduced to 80%		<60% coal-to-primary chemicals	<40% coal-to-primary chemicals, while zero-carbon feedstock accounts for 60%	
Energy conservation		Reuse of waste heat and pressure, advanced coal gasification technology, increased level of automation and intelligent production				
Resource recycling		Optimized plastic collection and sorting system, enhanced mechanical recycling, with a recycling rate of nearly 40%		Breakthrough in chemical recycling and optimized value chain, with a recycling rate of nearly 50%	Scaled plastic recycling industry with a recycling rate of over 60%, 1/3 of which comes from chemical recycling	
CCUS		Key pilots and demonstration, with over 30% fossil-based capacity equipped with CCUS		Scaled development with over 60% fossil-based capacity equipped with CCUS	Largely deployed with 100% fossil-based capacity equipped with CCUS	

Exhibit 29 Feedstock structure of three major chemicals in the zero-carbon scenario



Geographic Distribution of China's Zero-Carbon Chemicals Capacity

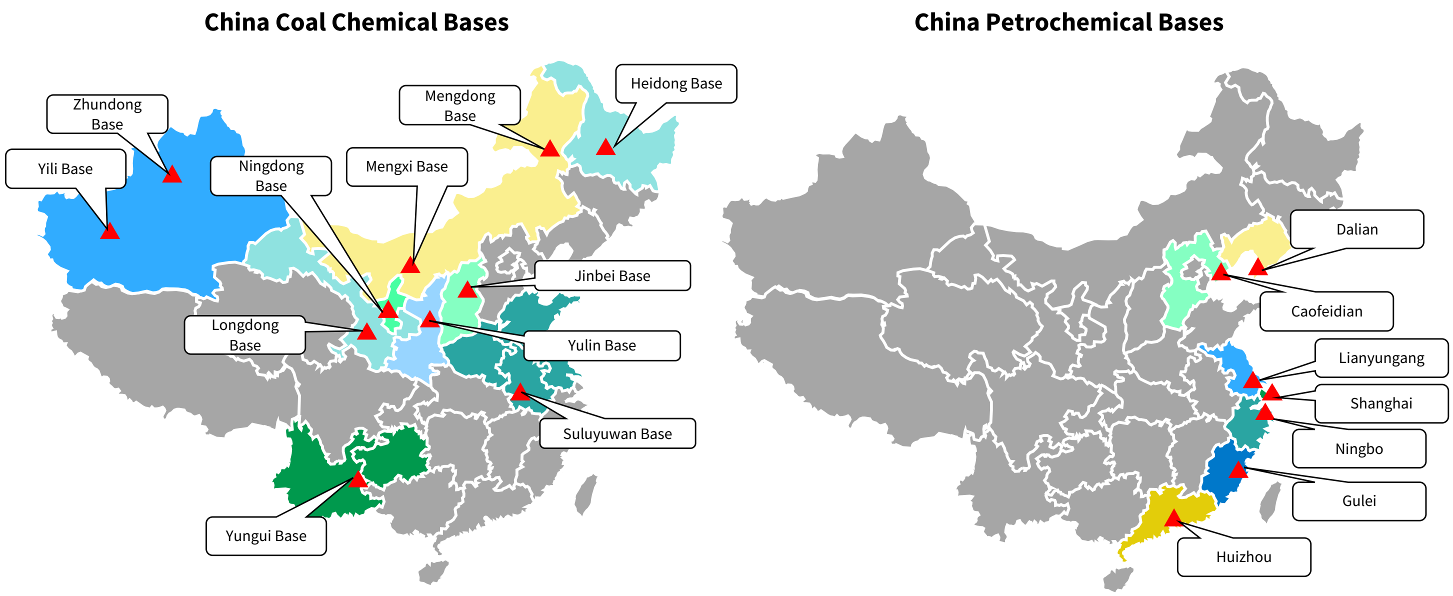
Zero-carbon chemical production relies on zero-carbon technologies and resources, including zero-carbon electricity, CCS storage capacity, and biomass resources. Based on comprehensive analysis of the technical feasibility, economics, and resource availability, zero-carbon chemical production capacity is more likely to be located in regions that have abundant zero-carbon technology and resources. Accordingly, the distribution focus of chemical production will likely pivot from places close to fossil fuels to places close to zero-carbon resources. In addition, the distribution of capacity will also depend to some extent on the distribution of the market.

Capacity distribution characteristics of China's chemicals industry

At present, the distribution of China's domestic chemical production capacity is close to fossil fuel resources. Specifically, China's coal chemical production is mainly concentrated in large coal chemical bases, with the Golden Triangle of energy and chemical industry as the core,[ix] supplemented by the Xinjiang and Qinghai regions, with extensions reaching the eastern coastal areas (see Exhibit 30-left). China's domestic petrochemicals industry is also mainly concentrated in large development bases. China's seven world-class petrochemicals industry bases, including Changxing Island in Dalian, Caofeidian in Hebei, Lianyungang in Jiangsu, Ningbo in Zhejiang, Caojing in Shanghai, Huizhou in Guangdong, and Gulei in Fujian, are all close to key development zones in coastal areas, relying on major crude oil import channels (see Exhibit 30-right). In terms of the capacity distribution, major ammonia and methanol facilities are all close to coal resources and distributed in and near large coal bases, but the capacity of naphtha and ethylene is mostly distributed in the seven petrochemical bases (see Exhibit 31).

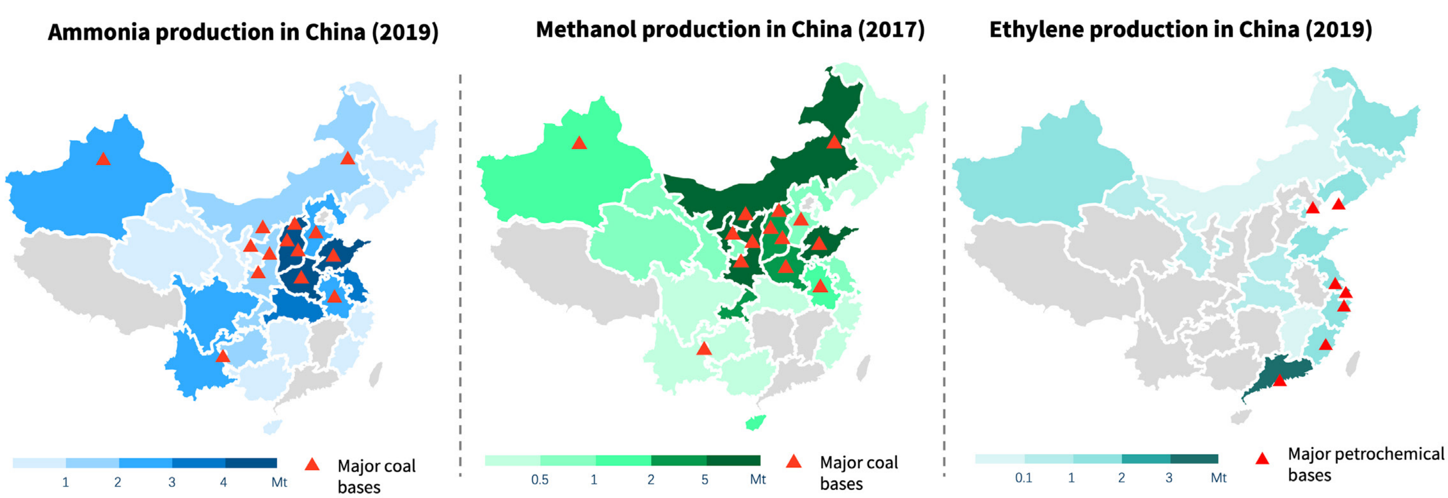
ix The area around Ningxia Ningdong Energy Chemical Base, Inner Mongolia Ordos City, and Shaanxi Yulin City is collectively called the "Golden Triangle" of energy because it constitutes a geometric triangle in geography.

Exhibit 30 Distribution of coal chemical and petrochemical bases in China



Source: China Coal Research Institute, Ping An Securities (left); Petrochemical Layout Scheme (right)

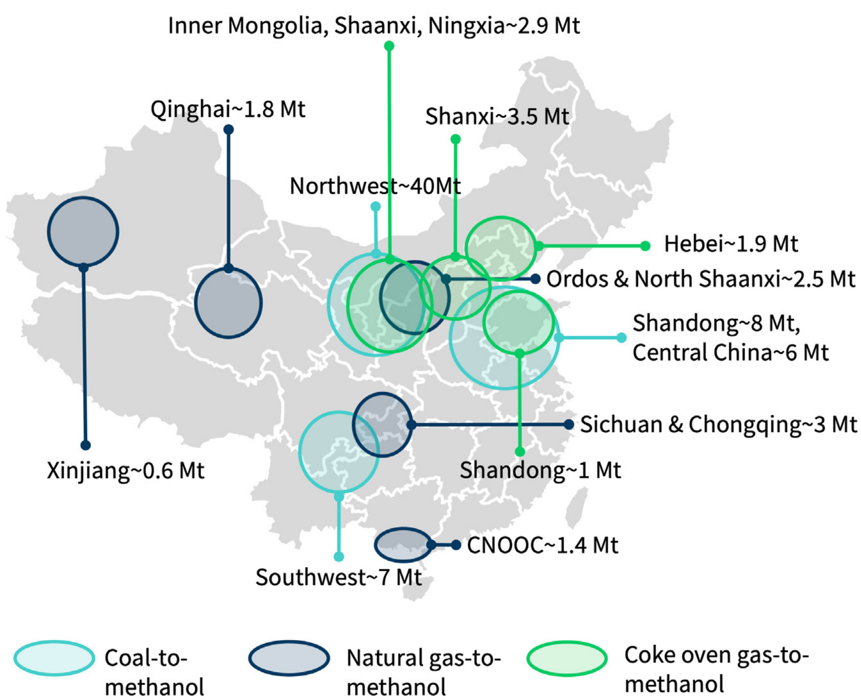
Exhibit 31 Distribution of chemical production capacity in China



In addition to coal and petroleum, natural gas and coke-oven gas are also used as feedstocks to produce ammonia, methanol, and ethylene. Although these capacities could be distributed in areas outside large-scale production bases, the future focus of decarbonization will remain on areas rich in coal- and petroleum-based productions. Take methanol as an example: feedstocks of domestic methanol production currently include coal, natural gas, and coke-oven gas, of which the coal-based route accounts for more than 75%. Distribution of production capacities vary according to their different feedstocks.

In the future, methanol production from natural gas and coke-oven gas will be withdrawn even without the pressure of zero-carbon transformation due to resource constraints (Exhibit 32). For example, China has banned the construction or expansion of projects related to methanol from natural gas, and because transportation of large-volume natural gas needs a pipeline, there will be a cost advantage only when the feedstock resources are nearby. In the future, there will be a shortage of feedstocks to produce methanol from coke-oven gas. Therefore, the analysis of the geographical distribution of methanol production capacity in China mainly focuses on the change of the capacity distribution of coal-to-methanol and new production technologies.

Exhibit 32 **Distribution and trend of domestic methanol production capacity**



Coal-to-methanol:

- Methanol made from coal is increasing due to the effective structural adjustment based on feedstock advantages (9.4% up year-on-year in 2019).
- New coal gasification technology is driving larger-scale, more efficient, and cleaner productions.

Natural gas-to-methanol:

- New gas-to-methanol capacity is prohibited due to resource constraints.
- Methanol from natural gas must be close to feedstock sources as gas has to be transported through pipelines.
- Production in the southwest is more economic, thanks to its shale gas resources.

Coke oven gas-to-methanol:

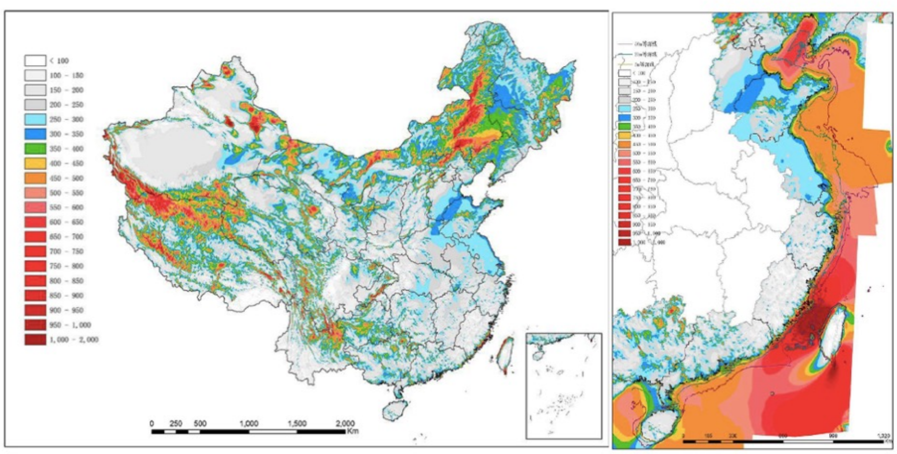
- Capacity is mostly 100,000–200,000 tons, and some may reach 500,000 tons, depending on feedstock supply.
- Capacity is concentrated in coke production areas and is likely to decline due to steel decarbonization.

Geographic distribution of zero-carbon resources

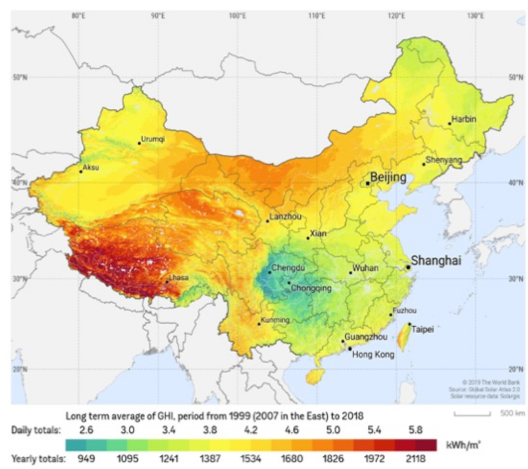
China's zero-carbon electricity resources are mainly distributed in western and northern regions. Specifically, wind resources in Northeast, Northwest, and North China regions account for more than 90% of the national total, and solar resources in the western and northern China regions account for more than 80% of the total.[37] In addition, most provinces in the west and north have introduced price mechanisms to reduce the cost of renewable energy due to the high curtailment rate. In addition to the west and north, the Southwest region also has rich hydro resources and a well-established price negotiation mechanism. About 80% of China's hydropower resources are distributed in the southwest, with favorable conditions in Tibet, Sichuan, Yunnan, and Qinghai. In eastern coastal areas, despite the current high electricity prices, zero-carbon electricity prices are likely to decline more due to further development of offshore wind and electricity market reform in the future.

Exhibit 33 **Geographic distribution of wind and solar resources in China**

Onshore wind at 70 m height (left) and offshore wind at 100 m height near coastal area with 5–20 m water depth (right)



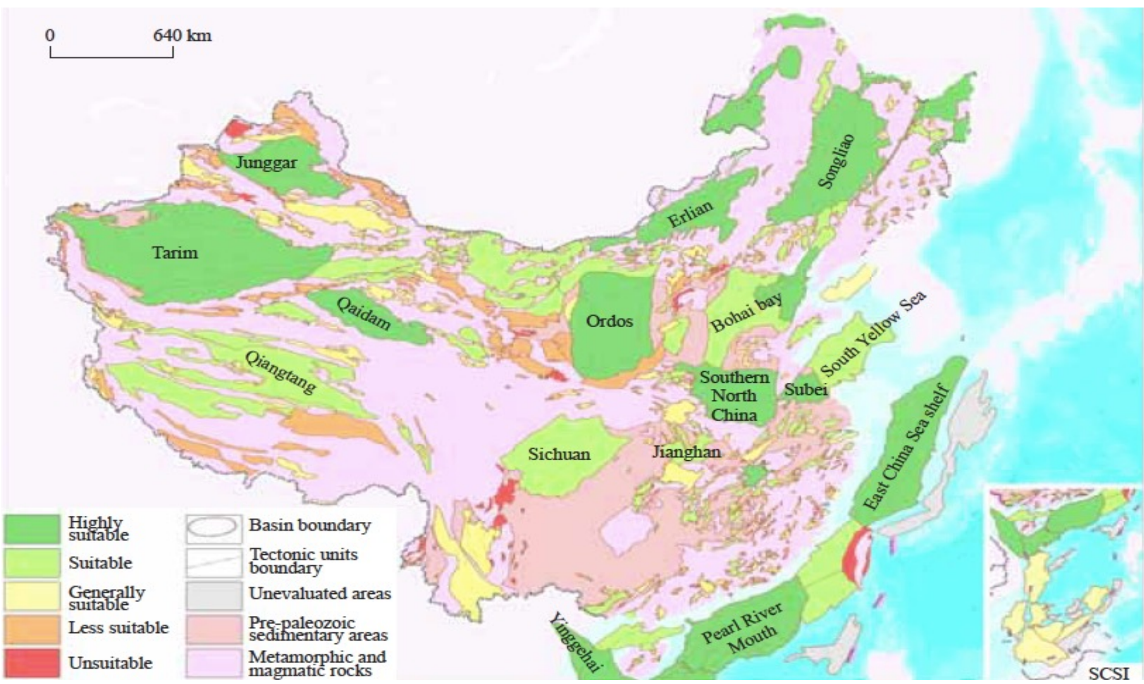
China's solar resources based on global horizontal irradiation



Source: National Development and Reform Commission, *Development Roadmap for China's Wind Power 2050* (left), IEA, Solargis dataset (right)

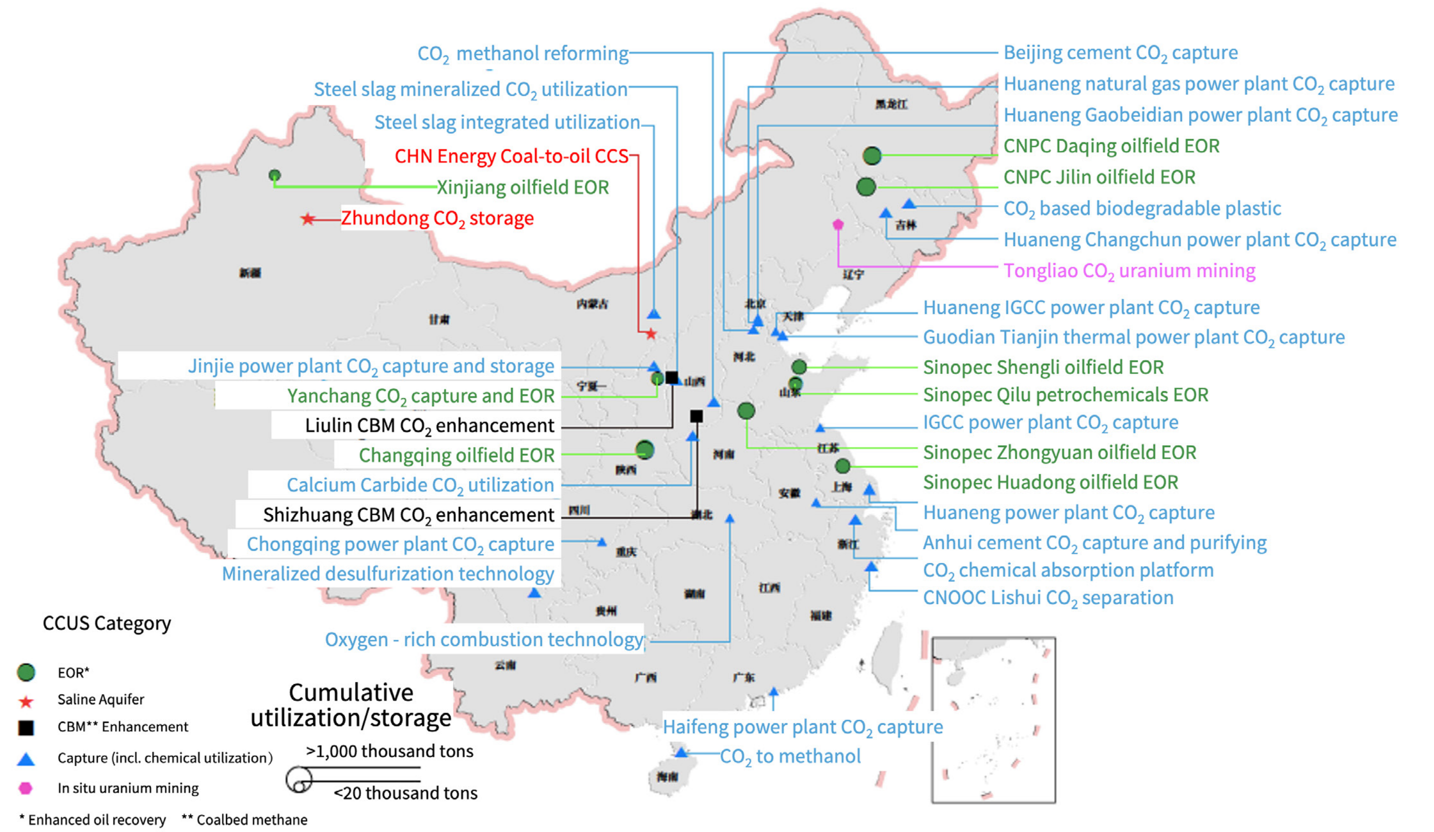
The geological storage potential of CCS in China is about 1.21–4.13 trillion tons. Suitable sites for CCS are mainly located in the northeast, northwest, southern North China, and Sichuan Basin, where there are large saline aquifers, oil fields, coal-bed methane fields, conventional natural gas, and shale gas fields (see Exhibit 34). Domestic oil fields in China are mainly concentrated in Songliao Basin, Bohai Bay Basin, Ordos Basin, and Junggar Basin, and 5.1 billion tons of CO_2 storage can be realized through CO_2-EOR technology. Gas fields in China are mainly distributed in Ordos Basin, Sichuan Basin, Bohai Bay Basin, and Tarim Basin, where about 15.3 billion tons of CO_2 can be stored in depleted gas reservoirs, and about 9 billion tons of CO_2 can be utilized by CO_2 enhanced gas recovery technology. The CO_2 storage capacity of deep saline aquifers in China is about 2.4 trillion tons, and its distribution is basically the same as that of oil and gas basins. Among them, Songliao Basin, Tarim Basin, and Bohai Bay Basin account for about half of the total storage potential, and the deep saline aquifer layers in Subei Basin and Ordos Basin also have great potential for storage.[38]

Exhibit 34 **Suitable locations for CO_2 storage in China**



Source: KAPSARC

Exhibit 35 Distribution of CCUS projects in China



Source: Chinese Academy of Environmental Planning, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, The Administrative Center for China's Agenda 21

Biomass resources are generally limited in China and are mainly used in areas where other decarbonization options are unavailable (e.g., aviation) or where there is a local supply of low-cost sustainable biomass resources. Biomass resources are distributed unevenly in China, with more than half concentrated in Sichuan, Henan, Shandong, Anhui, Hebei, Jiangsu, Hunan, Hubei, and Zhejiang provinces, and relatively few resources in northwest China and other areas. In areas with abundant biomass resources, with the reduction of biomass feedstock costs due to large-scale, centralized, and automated agricultural, forestry, and animal husbandry development, some localized biomass-based chemical production may be established in China.

Potential distribution of zero-carbon chemical capacities

The constraints of geographical distribution of zero-carbon chemical capacity include inertia of current capacity distribution, existing base planning, and distribution of zero-carbon resources. Based on a comprehensive analysis of these factors, the potential geographical distribution of China's zero-carbon chemical capacity in the future is estimated. Taking zero-carbon methanol as an example (see Exhibit 36), its capacity distribution presents the following characteristics:

In coal chemicals industrial bases represented by the Golden Triangle region in northwest China, a combination of coal chemicals coupled with green hydrogen, coal chemicals with CCS, and green hydrogen–based PtX methanol production routes can be developed simultaneously due to the abundant renewable resources and carbon storage capacity in this region. A considerable portion of the coal-based chemicals industry still exists in this region for the following reasons: First, abundant coal resources make the coal-based chemicals industry highly cost-competitive even with the application of zero-carbon measurements. Second, because the average age of domestic methanol production capacity is only about 8 years and the typical life is up to 30 years, this part of capacity may still be in use in the next 20 years or so to avoid stranded assets. Furthermore, although coal remains an important resource for chemical production, carbon emissions from the production process can be largely mitigated through coupling with green hydrogen or the application of CCS, but coal is used more as a feedstock and carbon will become a component of the product rather than as CO_2. Therefore, in the future, especially in the short and medium term, the coal chemicals industry combined with zero-carbon technology will remain a typical feature of this region, and distributed PtX capacity could be developed as well due to the abundant renewable resources.

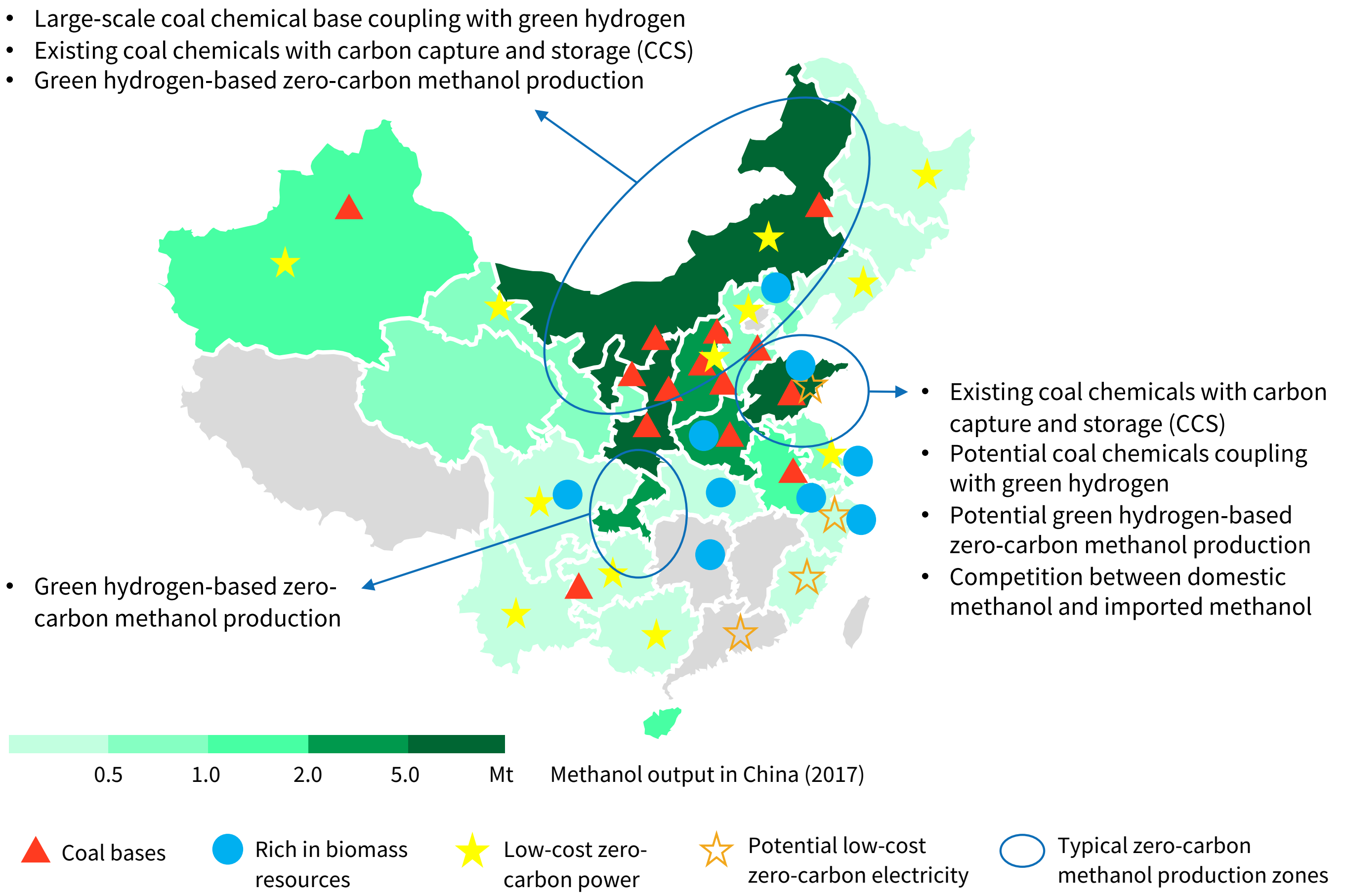
Southwest China, such as Yunnan, Sichuan, and Chongqing, could become a typical region for green hydrogen–based PtX methanol production in the future due to its rich hydro resources and relatively high cost of methanol production from fossil fuels. Methanol production from natural gas is concentrated in southwest China thanks to the abundant gas resources in this region. However, in general, the economics of methanol production from natural gas is relatively unfavorable due to the infrastructure requirements, such as pipelines and China's prohibition of constructing or expanding methanol production from natural gas . Therefore, the economic advantage of existing methanol production capacity from fossil fuels in this region is not obvious. In contrast, there are abundant hydropower resources in southwest China, enabling the low cost of hydrogen production from renewable energy. Even at present, in regions with favorable conditions, green hydrogen–based PtX chemical production could compete with conventional routes.

In coastal regions with superior coal resources, such as Shandong province, the potential zero-carbon production mode has great uncertainty. Although this area is close to the carbon storage site of Bohai Bay and has good offshore wind electricity resources, it remains uncertain whether better offshore wind resources could ensure a lower zero-carbon electricity price due to the high demand for electricity in coastal areas. In addition, the coastal location makes the region's zero-carbon chemical products face competition from imported products, especially for methanol, with olefin production being one of its major downstream modes of consumption. If the production cost of zero-carbon methanol is high, local users may choose to import methanol as feedstock for olefin production instead of using local methanol production, where olefin's carbon emissions are mainly concentrated.

In provinces with abundant biomass resources, only relatively small methanol capacity could emerge. This is mainly because the total amount of domestic biomass resources is relatively small in China, making it difficult to form a large-scale and sustainable biomass supply. In addition, the transportation cost of biomass feedstock is high, so concentrated capacity is more likely to be formed only in places near biomass resources.

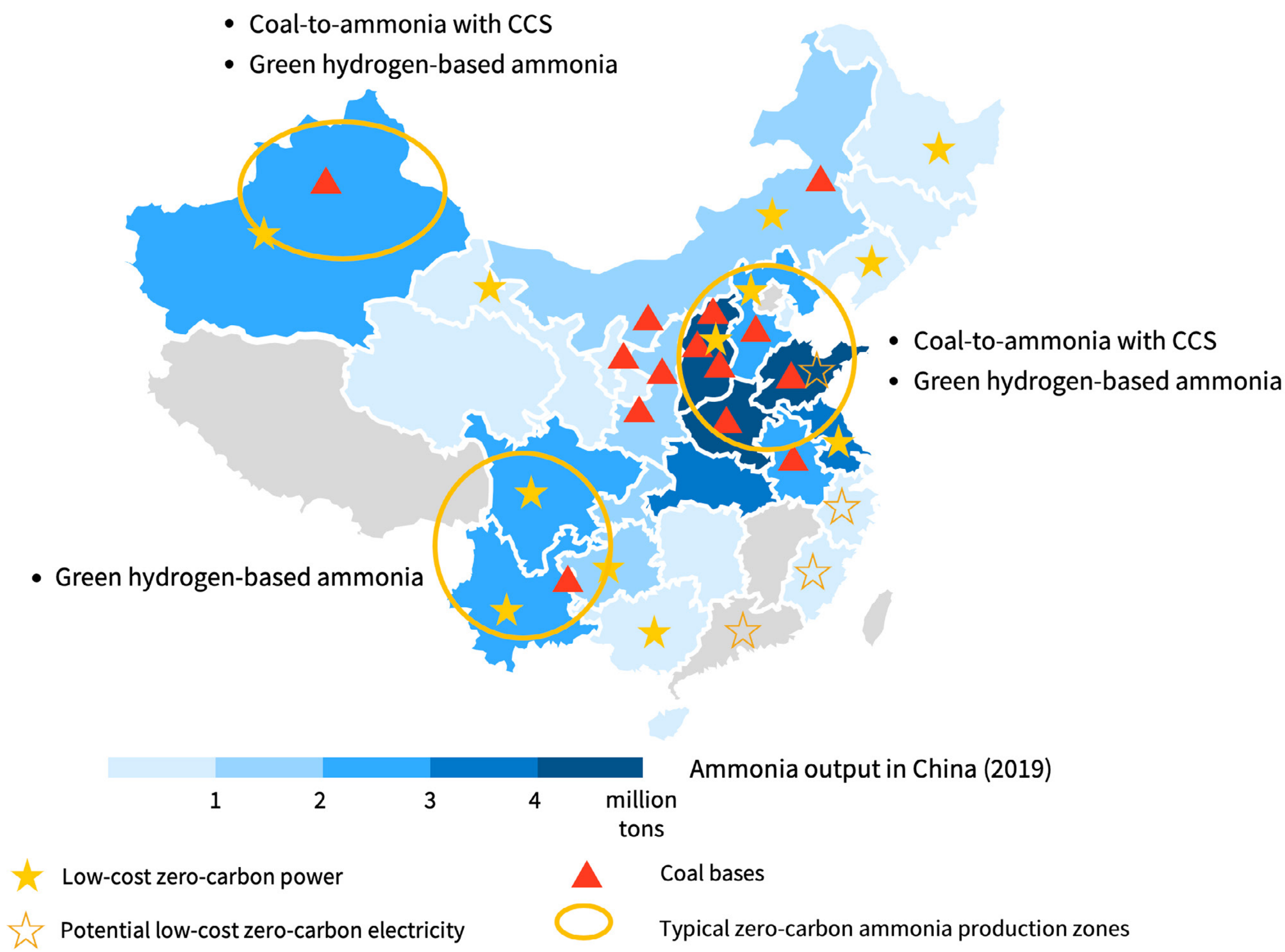
The above discussion is only about typical zero-carbon methanol capacity distribution, rather than an exhaustive conclusion. For other regions, zero-carbon methanol production capacity distribution can also be comprehensively considered according to the existing production inertia and zero-carbon resources. In addition, the distribution of zero-carbon methanol capacity is related to locations of downstream demand and transportation costs, which are not covered in this study.

Exhibit 36 Typical zero-carbon methanol production areas and possible production routes in China



Similarly, Exhibit 37 shows typical zero-carbon ammonia production areas and their possible production routes in China. Conventional areas with large capacities of coal-to-ammonia can be equipped with CCS in the future because they are also close to carbon storage sites. The regions with better renewable resources will be the main areas with concentrated green hydrogen–based ammonia production. Unlike methanol, ammonia is less affected by import and export because its downstream demand mainly comes from agricultural fertilizer, which is a more localized application. However, as mentioned in the *Chemicals Industry Demand Outlook* under the *Zero-Carbon Scenario* section, if ammonia's role as a fuel becomes more significant in the future, it will also be affected more by import and export issues. Broadly speaking, the future cost advantage of green hydrogen in China will lead to the cost advantage of ammonia, and hence the capacity of domestic zero-carbon ammonia will be less affected by imported ammonia.

Exhibit 37 Typical zero-carbon ammonia production areas and possible production routes in China



Oil-based feedstocks are highly dependent on imports, so the geographical distribution of oil-based ethylene capacity with zero-carbon solutions is not expected to be much different from present conditions. In addition, because ethylene production based on zero-carbon resources mainly uses methanol as the intermediate product, better economic benefits could be achieved for ethylene production capacities that are close to or even integrated with methanol production facilities. Therefore, the distribution of zero-carbon methanol production capacity could be relevant to the ethylene capacity condition. The overall geographical distribution of zero-carbon ethylene production is not further discussed in this study.

Due to the abundant renewables in the west and the relative lack of renewables in the east, China may have more country-level policy support to mitigate the imbalance of regional energy endowment, such as "west-east power transmission," and increase the construction of energy infrastructure across the east and west. The renewables in the west can be transported to the east in the form of electricity through extra-high voltage power lines or hydrogen through pipelines. Chemical enterprises in the east can use the cheap and stable electricity or hydrogen energy from the west to promote the energy-saving transformation and low-carbon transition of the existing equipment on the coast. It could avoid the stranding of eastern production equipment assets due to the control of carbon emissions.

Zero-Carbon Transformation Modes of China's Chemicals Industry

There may be three modes of zero-carbon chemical production in China in the future: (1) large-scale and centralized production mode supported by chemical production bases; (2) smaller-scale distributed production mode; and (3) competition with imported chemical products.

A series of practical problems need to be solved in the transformation process of different zero-carbon production modes. The key challenges and action plans in each of the transformation modes are discussed in this section.

Large-scale production base mode

Due to the land constraints of large-scale green hydrogen application, the intermittent issue of on-site hydrogen production from renewables, and the availability of suitable distribution and scale of CCS, the large-scale and centralized zero-carbon production mode supported by chemical production bases needs to combine multiple measures to form a comprehensive solution in the actual transformation.

In the zero-carbon transformation of a large-scale coal chemical base, if zero-carbon process emissions are achieved through the coal-based production route coupled with green hydrogen, a large amount of continuous green hydrogen supply must be secured. To meet the requirements, sufficient land area for on-site renewables installation, on-site hydrogen storage capacity to overcome the issue of intermittent hydrogen production from renewables, and the possible supplementary hydrogen production using grid electricity should be considered simultaneously. If CCS is used to achieve zero carbon, the distance between the chemical production site and the storage site and the carbon storage capacity of the storage site are the two major issues that need to be considered. In addition, due to various constraints, a combination of the green hydrogen– and CCS-based routes may be required.

This study analyzes the constraints between different conditions by discussing the following three schemes and trying to provide a reference for mode selection in real life. The reality may be one of the three schemes, or a combination of any of the three. The three schemes are (1) on-site hydrogen production + CCS; (2) on-site hydrogen production + hydrogen transportation and storage; and (3) on-site hydrogen production + grid electricity-based hydrogen production. The characteristics of the three schemes are shown in Exhibit 38.

Exhibit 38 **Typical schemes of the large-scale chemical production base mode**

On-site hydrogen + CCS	On-site hydrogen + hydrogen transportation and storage	On-site hydrogen + grid electricity-based hydrogen
• Hydrogen is produced on site using local renewables and coupled with coal chemical production as a supplementary hydrogen source • Scale of on-site hydrogen production is limited due to land constraints, and remaining coal chemical production capacity needs to be equipped with CCS • Traditional production route is used to supplement the intermittent hydrogen-based production route to ensure continuous production	• Hydrogen is produced on site using local renewables and coupled with coal chemical production as a supplementary hydrogen source • Scale of on-site hydrogen production is limited due to land constraints, and remaining hydrogen demand is met by off-site hydrogen that needs transportation and storage infrastructures • Sufficient hydrogen storage needs to be built to supplement intermittent on-site hydrogen production to ensure continuous production	• Hydrogen is produced on site using local renewables and coupled with coal chemical production as a supplementary hydrogen source • Scale of on-site hydrogen production is limited due to land constraints, and remaining hydrogen demand is met by water electrolysis using grid electricity • Grid electricity is used to supplement on-site renewable electricity to ensure continuous hydrogen production

Taking zero-carbon methanol production as an example, the three typical schemes of the large-scale production base mode are analyzed.

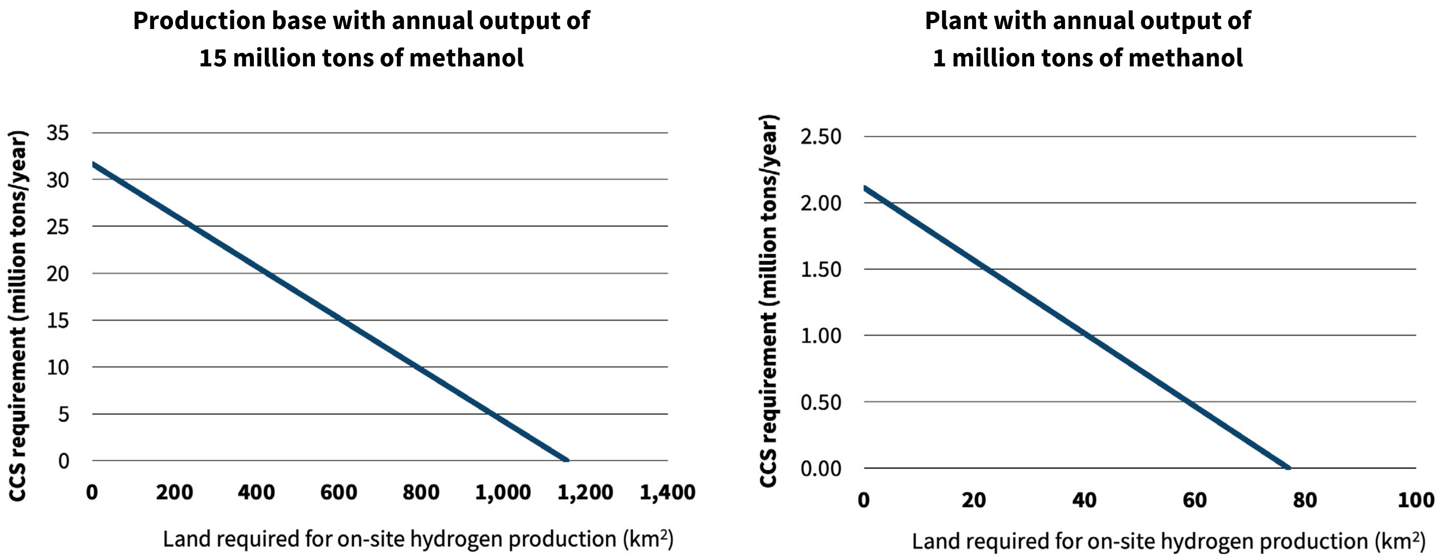
In the on-site hydrogen + CCS scheme, the sole use of hydrogen produced on site is to adjust the carbon-hydrogen ratio of coal-based syngas so land constraints for sufficient renewables installation need to be considered. For the methanol production process that cannot be coupled with green hydrogen, CCS is required to achieve zero carbon. As shown in Exhibit 39 (left), the land area required for on-site hydrogen production is inversely correlated with the demand for CCS capacity in a production base with annual output of 15 million tons of methanol.[x] The larger the area of land available for on-site hydrogen production, the smaller the additional CCS capacity required. Assuming that the maximum land area available for on-site hydrogen production at the site is 350 km^2 (about 10% of the area of the Ningdong base), the required CCS capacity would be about 22 million tons per year, which is equivalent to 55% of the annual capture and permanent storage capacity of CCS facilities currently in operation worldwide.[xi] As shown in Exhibit 39 (right), in a plant with an annual output of 1 million tons of methanol, if the available land area for hydrogen production is 40 km^2 (about 5% of the core area of the Ningdong base), the CCS capacity required by the plant is about 1 million tons per year, but the maximum capacity of the current domestic pilot CCS project is less than 1 million tons.[xii]

x Based on the current total methanol production in Inner Mongolia and Ningxia, close to 15 million tons/year, it is assumed that the methanol production within the large base is comparable to that level.

xi According to the *Global Carbon Capture and Storage — Status Report 2020* by the Global CCS Institute, about 40 million tons of CO_2 are captured and permanently stored per year by CCS facilities currently in operation.

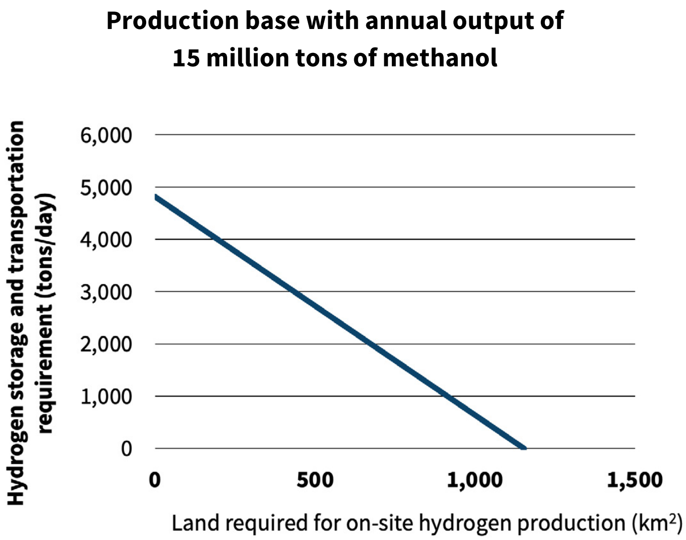
xii At present, domestic methanol production units above 1 million tons/year capacity account for about 40%, and this proportion will continue to grow due to the access scale requirements and supporting industries, thus assuming 1 million tons/year as a typical single

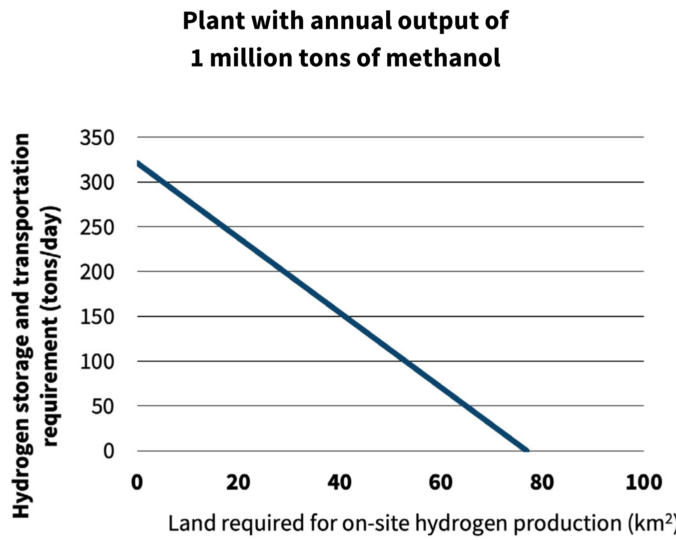
Exhibit 39 Relationship between required land area for on-site hydrogen production and CCS capacity for zero-carbon methanol production



In the on-site hydrogen + hydrogen transportation and storage scheme, on-site hydrogen could only meet part of the hydrogen demand due to land constraints. The remaining green hydrogen demand can be met by hydrogen produced off-site that is then transported to the chemical base. At the same time, due to the intermittence of renewable energy, achieving continuous production requires surplus hydrogen that is produced when renewable energy is available and off-site hydrogen that is transported and stored, which is used when locally sourced renewable energy is not available. Exhibit 40 shows the relationship between the land area required for on-site hydrogen production and the demand for hydrogen transportation and storage based on a region with an annual output of 15 million tons of methanol and a single plant with an annual output of 1 million tons of methanol, respectively. For the region, if the maximum land area for on-site hydrogen production is 350 km^2, the hydrogen transportation and storage demand of the region will be about 3,400 tons per day. For a single plant, if the land for local hydrogen production is 40 km^2, the demand for hydrogen transportation and storage will be 150 tons per day, meaning that 30 tank trucks are needed daily assuming one truck could transport and store 5 tons of hydrogen per day.

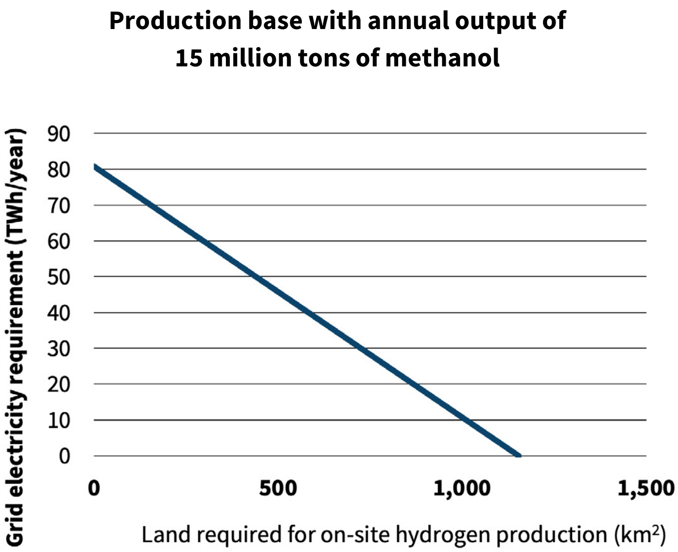
Exhibit 40 Relationship between the land area required for on-site hydrogen production and the demand for hydrogen transportation and storage

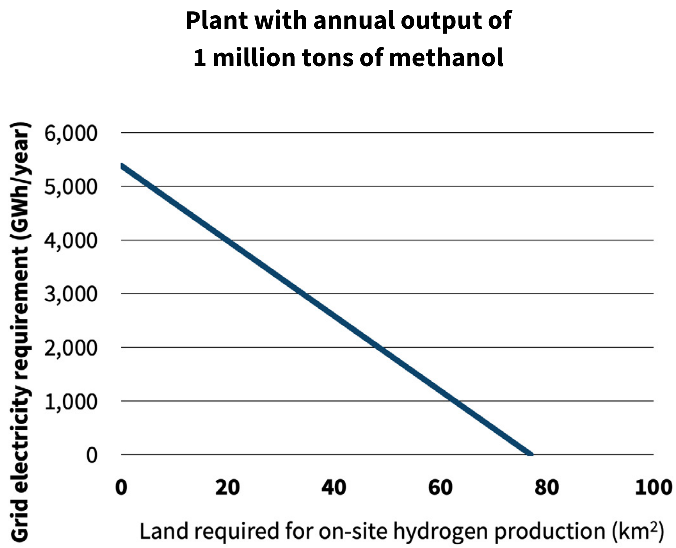




In the on-site hydrogen + grid electricity-based hydrogen scheme, to ensure sufficient hydrogen supply and continuous production, grid electricity is needed to produce additional hydrogen because on-site hydrogen production is insufficient due to land constraints. Exhibit 41 shows the relationship between the land area required for on-site hydrogen production and the demand for additional grid electricity. In a chemical base with an annual output of 15 million tons of methanol, if the land area for hydrogen production is 350 km^2, an additional 56 TWh/year of grid electricity will be needed for hydrogen production. In a single plant with an annual output of 1 million tons of methanol, if the land area of on-site hydrogen production is 40 km^2, an additional 2,600 GWh/year of grid electricity will be needed.

Exhibit 41 Relationship between the land area required for on-site hydrogen production and the demand for additional grid electricity

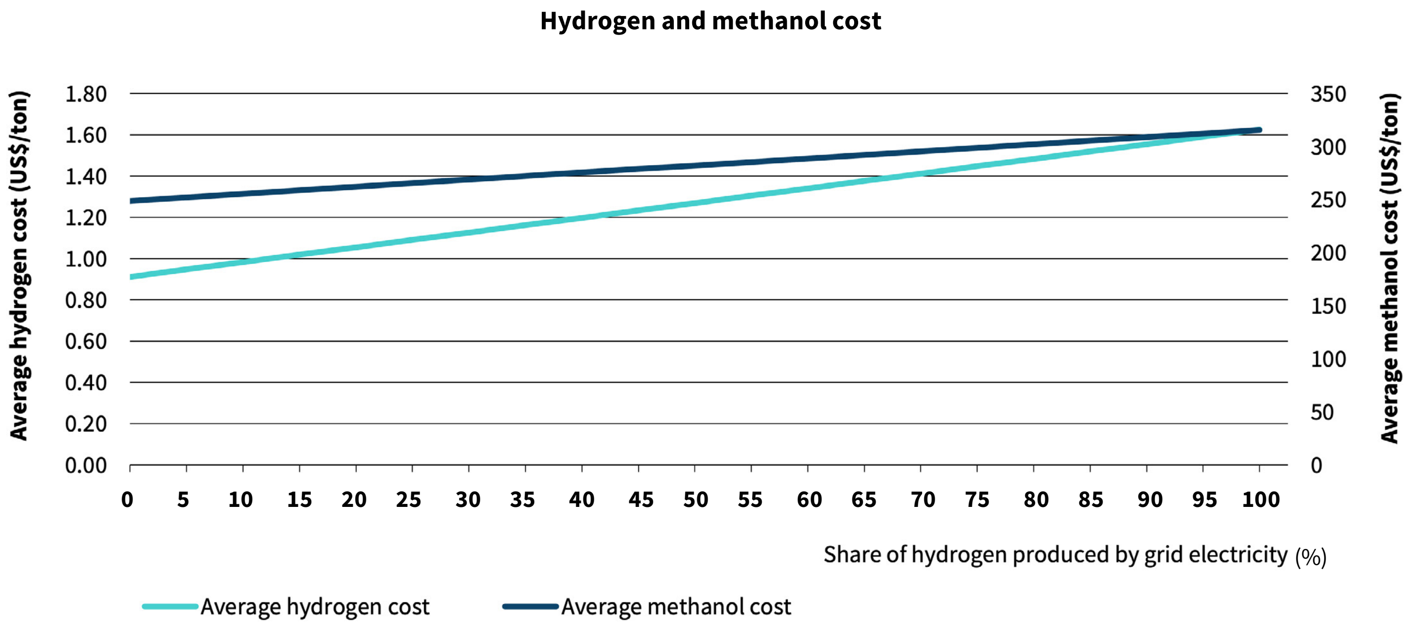


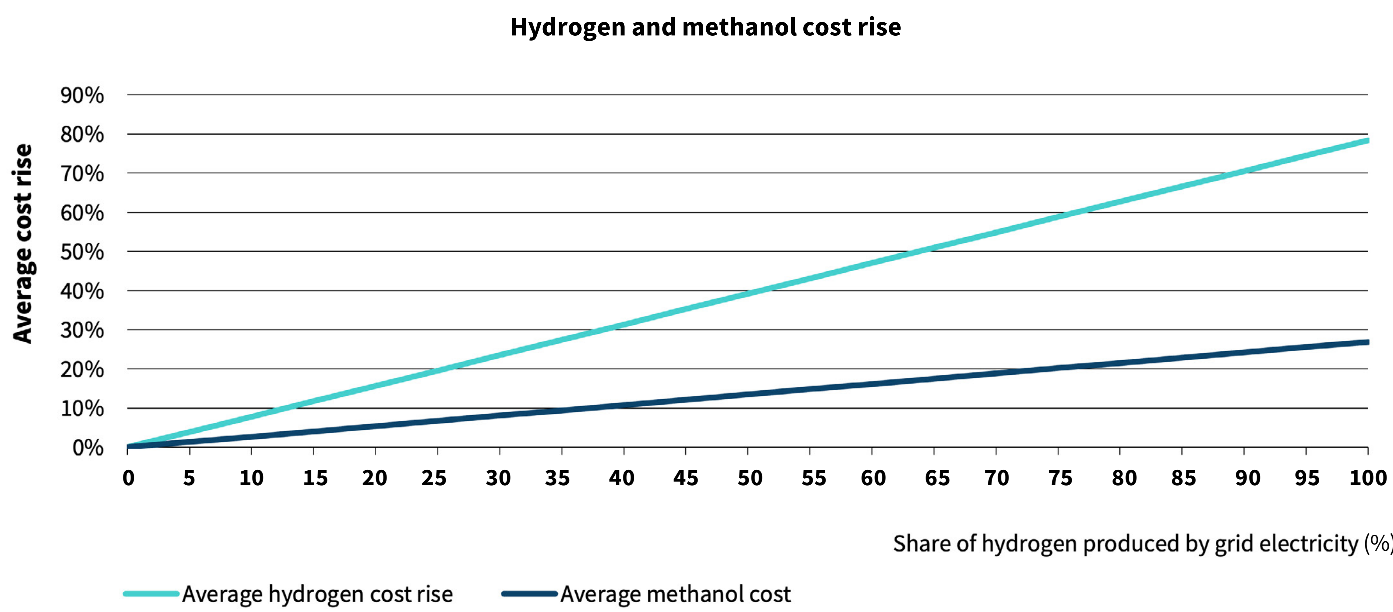


Meanwhile, because the cost of on-site renewable electricity is lower and the cost of grid electricity is higher, the increase in the proportion of grid electricity usage in hydrogen production will lead to the higher overall cost of green hydrogen and zero-carbon methanol. Exhibit 42 shows the relationship between the proportion of grid electricity usage and the average cost of hydrogen and methanol. For every 5% increase of the proportion of grid electricity usage, the cost of hydrogen and methanol will increase by 4% and 1.3%, respectively.

At present, production supported by a large-scale chemical base is the typical mode of chemical production in China. Green hydrogen and CCS will be gradually introduced and expanded in fossil fuel–based chemical production bases as a transitional method in the zero-carbon transformation. In the zero-carbon scenario, the actual zero-carbon production mode used by either a region or a single plant that is supported by a large-scale chemical base is likely to be a combination of on-site hydrogen + CCS, on-site hydrogen + hydrogen transportation and storage, and on-site hydrogen + grid electricity-based hydrogen due to various practical constraints discussed above. The discussion of each constraint factor in this section could provide a reference for resource allocation in the actual transformation depending on the actual situation.

Exhibit 42 Relationship between the land area required for on-site hydrogen production and the demand for additional grid electricity





Assumptions: Electricity price for on-site hydrogen production is US$0.015/kWh, electricity price for grid-based hydrogen production is US$0.030/kWh, and electricity consumption of hydrogen production is 46 kWh/kg.

Distributed mode

The green hydrogen–based PtX route is a typical distributed zero-carbon chemical production mode. Unlike the large-base mode, which relies on fossil fuel resources, distributed zero-carbon chemical production is more flexible in location and scale. Regions with abundant renewable energy resources are the first choice for distributed zero-carbon chemical deployment. In the actual transformation, the sources of hydrogen and carbon are major issues to be considered in this mode.

In the zero-carbon scenario, the hydrogen source of distributed chemical production mainly comes from green hydrogen produced by water electrolysis using renewable electricity. If this part of renewable electricity comes from solar PV or wind energy, similar to the large-base mode, land area constraints will need to be considered in practical production. However, the scale of the distributed production mode is relatively small, making it less impacted by land constraints, so it is a favorable development option when the green hydrogen–based PtX route is more cost-effective. Hydropower-based pilot projects have mostly been established in southwest China. For example, a hydropower-based hydrogen-to-ammonia project was planned in 2018 in Leibo County, Liangshan Prefecture, Sichuan Province. The first phase of the project completed the demonstration of renewable electricity–based hydrogen-to-ammonia with a capacity of 200,000 tons per year. The production output could be expanded in the future. In addition, grid electricity–based hydrogen production or hydrogen transportation and storage facilities need to be considered to achieve continuous production.

The carbon source of distributed chemical production can be provided by adjacent industrial waste gas CO_2 during the transition period. Providing a carbon source for chemical production using waste gas CO_2 from adjacent industries is an important means of CO_2 utilization. For example, CO_2 produced by steel, cement, and many chemical plants can be used as feedstock for chemical production. In a methanol plant with a capacity of 400,000 tons per year, assuming the conversion rate of CO_2 feedstock is 80%, the annual CO_2 feedstock demand will be about 690,000 tons. Because the carbon emissions factors of steel production and cement production are 2.01 and 0.88 tCO_2/t, respectively, a steel plant with an annual output of 340,000 tons or a cement plant with an annual output of 780,000 tons can easily provide the required carbon source. In the process of the zero-carbon transformation of various industries, CO_2 utilization realized through cross-sector synergy coupling can dramatically reduce carbon emissions. However, in the long term, carbon from biomass waste gas or direct air capture could be used as a carbon source for PtX chemical production to achieve zero carbon.

Case study:
CO_2 combined with hydrogen to produce methanol pilot project in Anyang, Henan

The CO_2 +hydrogen to produce methanol and LNG project located in Anyang, Henan Province, was jointly developed by Geely Technology Group, Henan Shuncheng Group Coking Co., Ltd., Meifenlong (Shanghai) Environmental Engineering Technology Co., Ltd., Henan Shunju Energy Technology Co., Ltd., and Anyang Shunfeng Chemical & Trading Co., Ltd.

The project introduced CO_2 + hydrogen to methanol technology from Icelandic company CRI, and will become the first CO_2 + hydrogen to methanol system in China, as well as the largest CO_2 to methanol plant in the world.

This project utilizes coke-oven gas produced by Shuncheng Group as feedstock and CO_2 captured from industrial waste gas as the carbon source to react with hydrogen to form methanol without any carbon emission. A total of 360 million normal cubic meters of coke-oven gas could be utilized annually to produce 110,000 tons of methanol and 70,000 tons of LNG, achieving direct and indirect CO_2 emissions reduction of 160,000 and 550,000 tons, respectively.

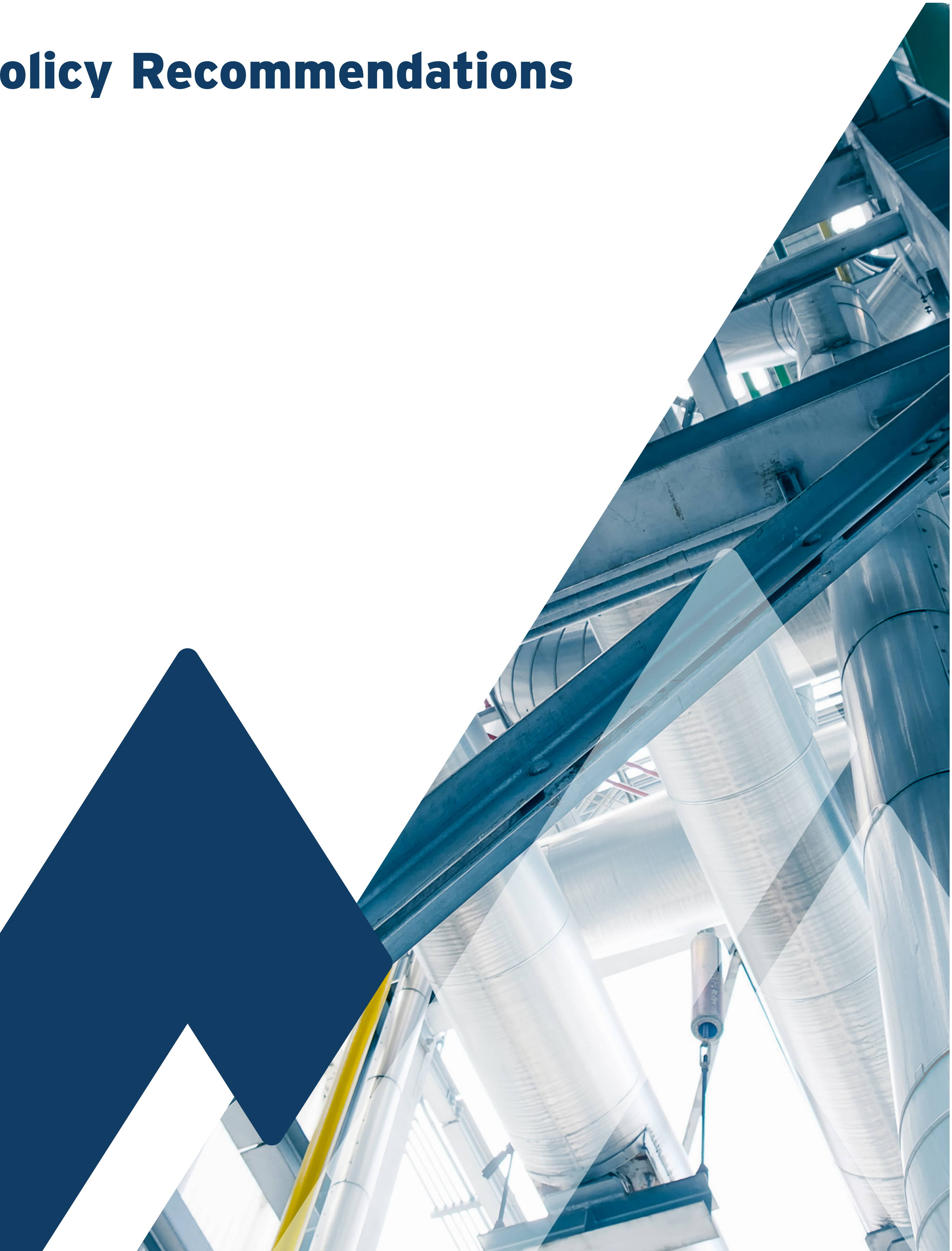
In addition to PtX, chemical production based on biomass will also be under the distributed mode. The reason is that biomass feedstock sources are dispersed and the cost of collection and transportation is high, making it more likely to be locally supplied with limited scale effect. Taking methanol production as an example, the scale of a single plant based on zero-carbon methanol production from biomass is expected to be in the range of 100,000–200,000 tons per year. However, more than 75% of existing methanol plants have a capacity of more than 400,000 tons per year, under the trend of large-scale development. Therefore, methanol production based on biomass will form a smaller-scale and distributed development mode.

Mode of competition with imported products

Under the global trend of zero-carbon transformation and China's carbon neutrality goal, the differences in the comparative advantages and timetables of national zero-carbon transformations may change the competitive landscape of domestic and imported chemical products. At present, China's coastal areas are major producers of chemical products due to their proximity to consumer markets and the convenience of importing feedstocks. In the future, under the pressure of zero-carbon transformation, domestic chemical production capacities may shift toward regions with abundant zero-carbon resources such as renewable energy and carbon storage capacity.

However, China is also likely to switch to imported chemicals rather than domestic production because there is still a green premium for zero-carbon chemicals. Even if both domestic production and imported products are subject to the zero-carbon constraint, domestic chemical products from zero-carbon production routes will also face competition from imported products because certain foreign producers may have better zero-carbon production resources. Furthermore, in addition to directly importing end products, China may choose to import products in certain segments of the value chain as feedstocks to produce end products domestically by comprehensively considering cost and carbon emissions of each segment, avoiding high-carbon-production segments.

Policy Recommendations



Under the goal of carbon neutrality, policy is needed to guide or even drive China's chemicals industry to achieve low-carbon or even zero-carbon transformation within a relatively short period in the next 40 years at most, and all stakeholders should be fully mobilized for concerted action. In view of the green premium issue, policies should focus on internalizing the carbon emissions cost of conventional high-carbon-production routes while promoting the cost abatement of zero-carbon production routes. To promote the participation of key stakeholders, policies should focus on encouraging leading firms as well as demand-side incentives and the effective use of international markets. In addition, key issues such as proper utilization of fossil fuels and recycling of end products should also be emphasized.

Specific recommendations are as follows:

Support innovation by leading players including state-owned enterprises (SOEs), with special focus on research, development, and demonstration of key technologies and equipment. The chemicals industry has a long value chain and complex products, with relatively independent subdivisions but interrelated products, making equipment and technical support particularly important. After years of development, China's chemicals industry has formed development patterns led by SOEs based on large-scale production bases, with large-scale technology, equipment, and production capacity leading the world. The government should effectively guide SOEs leading private participants, providing targeted support for key technologies and equipment in the industry, and strengthening cross-sector synergies. Examples include supporting pilot projects of conventional coal-to-methanol coupling with green hydrogen, deepening electrification of the chemicals industry, encouraging e-cracking furnace pilots, promoting catalyst technology, supporting the promotion of first-of-their-kind technologies, and eliminating concerns about the risks of developing cutting-edge technologies by means of policy support and financial subsidies.

Promote circulation and efficient utilization of end products and force elimination of backward production capacity on the supply side through demand reduction. At present, some end products still have problems with extensive and inefficient utilization, but the improvement of utilization efficiency can reduce the demand for primary chemical products, achieving emissions reduction. For example, problems such as low efficiency of current fertilizer utilization and high total consumption in China may affect upstream ammonia production, leading to excess capacity. In terms of policy, standardized management should be improved to guide rational control of chemical consumption and alleviate supply risks and pressure of emissions control. At the same time, recycling of chemical products should be promoted, such as vigorously promoting plastics recycling, including improving the management system of mechanical recycling and supporting technology breakthroughs in chemical recycling.

Leverage the international market to dynamically adjust the import and export policies of feedstocks while ensuring supply chain security. Although

climate change is a global issue, international cooperation can fully leverage each country's comparative advantages. On the premise of supply chain security, the structure of import and export products should be adjusted dynamically based on the characteristics of China's chemicals industry value chain and global resources. In the short term, attention should be paid to carbon reduction of feedstocks and importing light hydrocarbon feedstocks, to alleviate the problem of high emissions caused by the high proportion of feedstocks in the domestic market. In the medium term, green hydrogen could be imported from countries with abundant renewables to overcome the high-cost constraint of domestic hydrogen production. In the long run, capacity and structure of primary chemical products could be further optimized, expanding the production scale of high-end products and importing low-end products while exporting high-end products. In addition, global technological exchanges should be actively promoted, introducing advanced technologies adapted to China's industrial structure, integrating the advantages of existing technologies and imported technologies, and strengthening the continuous development of industrial technologies.

Advance support for carbon reduction technologies to reduce their costs and internalize carbon costs of conventional routes by policy methods such as carbon markets. By encouraging low-carbon routes and suppressing high-carbon routes simultaneously, the green premium of low-carbon and zero-carbon chemical production could be gradually reduced. As analyzed in the *Chemicals Industry Decarbonization Pathway* section of this report, zero-carbon chemical production has various routes, but they are currently less cost-effective compared with conventional production routes. Policy methods such as subsidies, tax credits, and reduced electricity prices could be used to encourage adoption of disruptive technologies such as green hydrogen to reduce costs of low-carbon and zero-carbon routes. At the same time, the integration of the petrochemicals and chemicals industries into the national carbon market and internalizing emissions costs of conventional production routes into production costs should be accelerated. The low-carbon and zero-carbon chemical value chain systems should be further developed by lowering the green premium of low-carbon and zero-carbon chemical production.

Guide the coal chemicals industry to proper utilization of coal, that is, using coal as a feedstock to provide carbon elements, not as fuel or a reaction agent to produce hydrogen. China is a country with abundant coal and limited oil and gas resources. Coal will still support the supply safety of chemical products. Policy should rationally control the transformation of the coal chemicals industry —coal as a fuel should be limited by coal as a feedstock for chemical products should not. China's Central Economic Work Conference pointed out that feedstock energy consumption should not be included in the total control of energy consumption. Policies should ensure that coal is used as a feedstock to provide the carbon component for chemical products, support industrial upgrading and technological progress, improve the conversion rate of coal as a feedstock, and reduce process emissions. In terms of energy source, coal should not be used as a fuel. Efforts should be made to promote the upgrading of heating systems for chemical plants, especially high-temperature reaction equipment, to get rid of excessive reliance on coal as a fuel and encourage the development of new energy sources. In addition, priority should be given to clean hydrogen production to avoid using coal as a reaction agent for hydrogen production, while orderly replacing gray hydrogen with green hydrogen. In the long run, to achieve complete zero-carbon emissions, Scope 3 emissions from chemical products could also be included in the assessment, and the zero-carbon production route should be promoted scientifically and orderly under the premise of supply security, achieving direct, indirect, and full-scope decarbonization of the entire value chain.

Establish industry standards, improve the certification system for zero-carbon products, and cultivate the demand market for zero-carbon chemical products by means such as tax credits. The end products of the chemicals industry involve all aspects of the economy and life, ranging from consumers' clothing to auto manufacturers' interior trim products to aerospace's high-end plastics, with diverse participants on the demand side. Industry standards and carbon emissions accounting and certification systems for low-carbon and zero-carbon chemical products should be established, encouraging procurement by governments at all levels and SOEs, and gradually expanding adoption. In addition, the consumption habits of low-carbon or zero-carbon chemical products should be gradually adopted by individual consumers through promotions by large-scale chemicals consumer companies as a starting point. For example, food packaging companies should be encouraged to establish their own decarbonization management system for the entire industry chain, and to gradually influence their end consumers, creating demand for low-carbon and zero-carbon chemical products and related consumption habits throughout society.

Promote the formation of a green hydrogen whole-value chain and integrate the application of green hydrogen in the chemicals industry into the green hydrogen policy system. The industrial application side and the production, storage, and transportation of green hydrogen will promote the continued maturation of each other. Green hydrogen is a necessary step for chemicals industry decarbonization, and the chemicals industry is also the largest downstream industry in hydrogen utilization at present. The huge demand for hydrogen from the chemicals industry should be leveraged to alleviate market maturation concerns for major players in other segments such as hydrogen production, storage, and transportation. The structure of the demand side should be optimized to synergize all segments of the hydrogen energy value chain. The chemicals industry can gradually transition the gray hydrogen to industrial by-product hydrogen in the short term, and gradually reduce the proportion of in situ coal-based hydrogen on the supply side of of the chemicals industry. Industry stakeholders need to promote synergy demonstrations of refining, coal chemical industry and green hydrogen, to form a complete industrial chain of hydrogen supply, storage and transportation and demand. Chemicals industry need to orderly grow the proportion of green hydrogen on the hydrogen supply side in the medium and long term.

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