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Prospects of the Chinese coal chemical industry in an increasingly carbon-constrained world

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Abstract

The coal chemical industry utilizes coal as both energy and feedstock to produce gases, liquids, and solids, which are then synthesized into various fuels and chemicals. In China the industry is generally classified into two categories: traditional versus modern coal chemicals. In 2020, the Chinese coal chemical industry processed nearly one quarter of national coal throughput, and accounted for about 5.4 per cent of national carbon dioxide (CO_2) emissions. The potential of coal chemicals to slow China's rising oil and gas imports bodes well with Chinese leadership's rising energy security anxiety amid geopolitical tensions. Due to this, coupled with strong political desire for investment-driven growth exaggerated by a sluggish post-pandemic economic recovery, especially at the local level, the coal chemical industry is the only major coal-consuming sector in China that could still see substantial capacity expansion as well as emissions spikes in the coming decades. Without an appropriate decarbonization strategy in place, further expansion of the industry is expected to contradict China's dual carbon goals of peaking national carbon emissions before 2030, and achieving carbon neutrality before 2060.

Despite its large industrial scale, the Chinese traditional coal chemical industry has long suffered from overcapacity, legacy assets, single product structure, and heavy pollution, among other chronic weaknesses. Thus, the coal chemical industry is continuously subject to increasingly stringent and sometimes disruptive energy and environmental regulations. In the above context, the modern coal chemical industry is prioritized by key stakeholders, especially local governments and the coal industry, to supplement petrochemical manufacturing and climb up the value chain. Nevertheless, unless the modern coal chemical industry can outperform its petrochemical counterpart in the net-zero transition once China enters the era of its post-2030 carbon neutrality goal, the long-term prospects for the Chinese coal chemical industry as a whole still look challenging.

1. Introduction

As the world's largest energy producer and consumer, as well as CO_2 emitter, China relies heavily on coal for power generation and heat provision, and coal currently accounts for more than half of the country's primary energy consumption. Unlike the rest of the world, China also increasingly utilizes coal as a raw material to manufacture chemical products.

Even so, the rapid ascendance of the Chinese coal chemical industry is a rather recent phenomenon. After China's accession to the World Trade Organization in 2001, the country's spectacular economic boom was soon translated into burgeoning demand for all sorts of chemical products, with its worldwide chemical sales growing at an astonishing rate of more than 18 per cent annually. Consequently, China's share in the global chemical market rose drastically, from a mere 6 per cent at the beginning of the millennium to 44 per cent in 2022.[1] This could be mostly explained by a large consumer base; favourable government policies, including a rather open attitude towards foreign direct investment; easy availability of low-cost capital and labour; government subsidies; and relaxed environmental norms.[2]

Because of its abundant coal resources—versus its limited conventional oil and gas endowment—in addition to rising investment in typical chemical manufacturing segments including organic and inorganic industrial chemicals, ceramic products, petrochemicals, agrochemicals, polymers, and fragrances, China has also become the only major economy to continuously invest heavily in both coal research and greenfield large-scale coal chemical facilities.

Following the high-profile international climate pledge in September 2020 to peak its national carbon emissions before 2030 and achieve carbon neutrality before 2060, in April 2021 China announced its aim to strictly limit the increase in coal consumption over the 14th Five-Year Plan (FYP) period (2021–2025), and phase it down in the 15th FYP period (2026–2030). As a result, major Chinese coal-consuming sectors (especially coal power and heavy industries such as iron and steel, and cement) face increasing scrutiny by various levels of government, with medium- to long-term sectoral coal demand growth potential severely dented.

In light of US–China frictions and other geopolitical tensions, rising anxiety over energy security among Chinese decision-makers has prompted Beijing rethink coal's role. This is evidenced by the State Council of China's announcement in December 2021 that newly added renewable capacity and 'feedstock energy' would be exempt from any energy consumption cap during the 14th FYP period, signalling a relaxation of restrictions on energy-intensive heavy industries, especially coal chemicals.[3] During its second quarterly press conference in 2023, the National Energy Administration (NEA) reiterated that coal remains the 'ballast stone' for China's energy security.[4]

Despite the short-term backlash against the dual carbon goals and the constantly changing regulatory environment, the coal chemical industry remains the only major coal-consuming sector in China that still possesses great potential for substantial capacity expansion as well as emissions spikes in the coming decades. As a result, it is necessary to take a deep dive to better understand the prospects of the industry in an increasingly carbon-constrained world. More specifically:

- What are the past and the status quo of the Chinese coal chemical industry?
- What are the major driving forces and constraints that affect coal chemical development in China?
- What will the Chinese coal chemical industry look like in the coming decades?
- How should the industry be appropriately regulated?

The following sections present the state of play of the Chinese coal chemical industry, followed by a proposed energy policy framework, and an assessment of major driving forces and constraints that affect coal chemical development. After a glimpse into the future of the industry, the paper highlights several pathways the industry could adopt to better adapt to an increasingly carbon-constrained world, aiming to inform both international audiences and Chinese decision-makers.

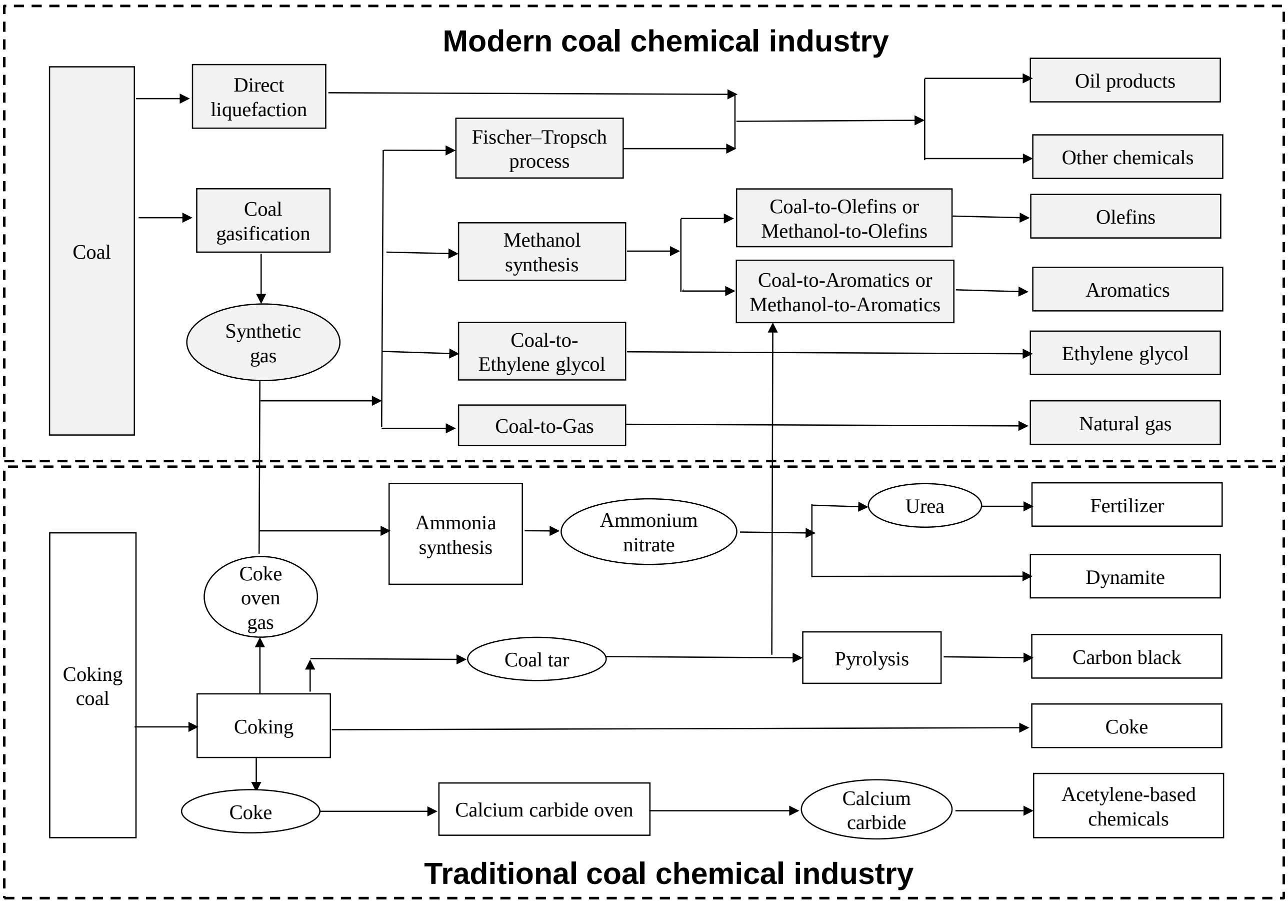
[1] CEFIC (n.d.).
[2] CRISIL (2019).
[3] Reuters (2021).
[4] NEA (2023).

2. State of play

2.1 An overview of China's coal chemical industry

The coal chemical industry utilizes coal as both energy and feedstock to produce gases, liquids, and solids, which are then synthesized into various fuels and chemicals. In China, the industry is generally classified into two categories: traditional versus modern coal chemicals (see Figure 1).

Figure 1: Simplified flow diagram of the Chinese coal chemical industry



Source: Author

In the Chinese context, the traditional coal chemical industry mainly consists of coke manufacturing, coal to ammonia and urea, and coal to polyvinyl chloride (PVC) via calcium carbide (CaC_2) manufacturing—uses of coal as raw material to produce coal-based derivatives through oxidation and solvent extraction processes.

- Coke manufacturing: Coke and coke by-products, including coke oven gas, are produced by the pyrolysis (heating in the absence of air) of suitable grades of coal (i.e., coking coal). The process also includes the processing of coke oven gas to remove tar, ammonia (usually recovered as ammonium sulfate), phenol, naphthalene, light oil, and sulfur before the gas is used as fuel for heating the ovens.[5] Coke, the main product of this manufacturing process, is primarily used as a reducing agent in smelting iron ore in a blast furnace.
- Coal-based ammonia: The basic processing in a coal-based ammonia plant consists of an air separation module for the separation of O_2 and N_2 from air, the gasifier, the sour gas shift module, the acid gas removal module, and the ammonia synthesis module. In the downstream end, ammonia is often used to produce urea as fertilizer or dynamite.

[5] World Bank (1998).

- CaC_2 manufacturing: CaC_2 is made by carbothermal reduction of lime (calcium oxide), or by heating calcium oxide with coke or coal in the presence of water at over 350°C. It is an important raw material in industries such as metallurgy, ceramics, synthetic fibres, and chemicals.
- PVC manufacturing: Unlike the rest of the world, where PVC is largely synthesized using the ethylene process, China produces PVC primarily through the CaC_2 process, in which hydrogen chloride is used to produce PVC after electrolysis of raw salt, and the remaining sodium is used to produce caustic soda. Therefore, there is a symbiotic relationship between chlorine and alkali, and the balance of chlor-alkali is also an important factor to be considered in PVC manufacturing.[6]

The modern coal chemical industry normally starts with large-scale coal gasification to produce synthesis gas, i.e., hydrogen (H_2) and carbon monoxide (CO). The synthesis gas is then used for supplying hydrogen in the hydrogenation of coal and synthesis of liquid fuels, including indirect coal-to-liquids (CTL). By comparison, direct CTL involves contacting coal directly with a catalyst at elevated temperatures and pressures with added H_2, in the presence of a solvent, to form a raw liquid product which is further refined into product liquid fuels. In the Chinese context, typical modern coal chemicals include, but are not necessarily limited to:

- CTL: consists of oil products produced by both direct and indirect CTL facilities.
- Coal-to-gas (CTG): a multiple-step process starting with coal gasification—coal is first burned with water vapor or oxygen to produce synthesis gas; after the cleaning process, a water gas shift/methanation process is followed to produce synthetic natural gas.
- Coal-to-olefin (CTO): the process always starts with synthesis of methanol, which is manufactured with syngas from coal gasification—as methanol is a feedstock for the methanol-to-olefins (MTO) process, coal-derived olefins could be produced by either integrated CTO facilities or MTO plants.
- Coal-to-ethylene glycol (CtEG): the process normally includes three steps: gasification of coal to syngas; catalytic coupling of CO with nitrite esters to dialkyl oxalates (e.g., dimethyl oxalate); and hydrogenation of oxalates to EG.
- Coal-to-aromatics (CTA): aromatics—more complex petrochemicals—can also be produced from (coal-derived) methanol, although this technology is at a much earlier stage of development.

Though the distinction between traditional versus modern coal chemicals is widely used in China, it is worthwhile to note that the rationale behind the boundary between traditional versus modern coal chemicals has not been clearly clarified in the literature. For instance, categorizing coal-to-methanol (CTM) as a modern coal chemical and coal-based ammonia as traditional coal chemical is rather arbitrary, as coal gasification, precursor of both processes, is long-established. Nevertheless, as industrial policies in China are often designed in accordance with the above usage, and government attitudes towards project development generally differentiate between traditional and modern coal chemicals, the above industrial categorization is used throughout this study.

2.2 Development of China's coal chemical industry

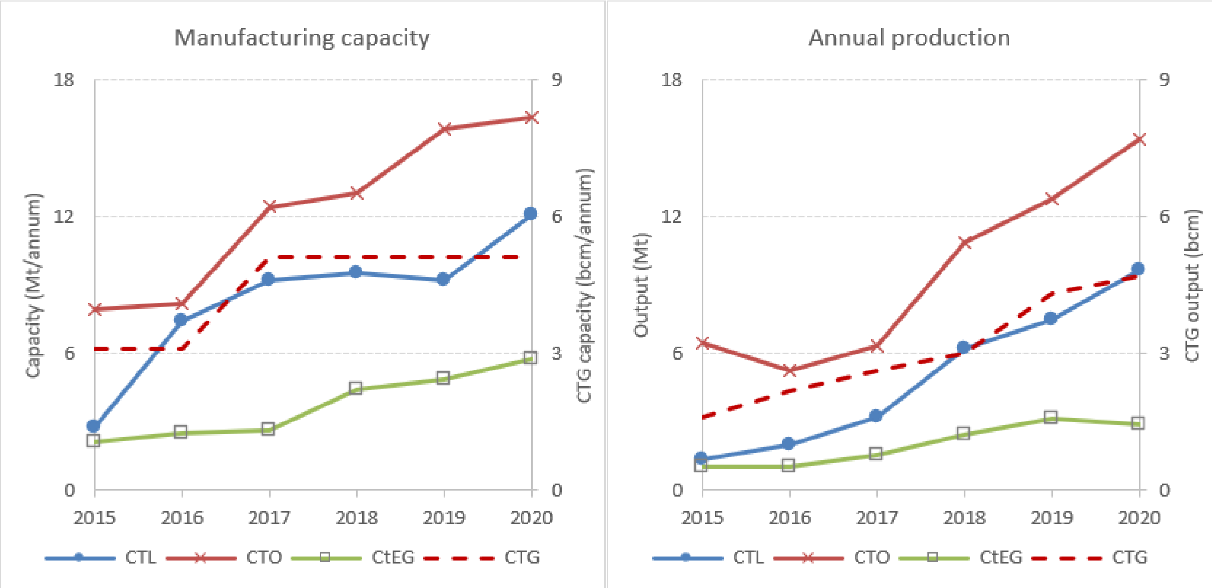
Since the inception of the People's Republic of China (PRC) in 1949, the Chinese coal chemical industry has developed from traditional coal chemicals with coke, synthetic ammonia, and calcium carbide as its main products, to modern coal chemicals with a scale of production not duplicated in any other part of the world. At the beginning of its development, the Chinese coal chemical industry mostly relied on imports of technology and equipment from developed countries; now it features some of the world's most advanced coal technologies and manufacturers.

Taking the traditional coal chemical industry as an example, China's coke output was only 0.54 Mt in 1949. Largely driven by the massive iron and steel capacity expansion in the past decades, China's coke output reached 492.6 Mt in 2023, accounting for nearly 70 per cent of global total, or the equivalent of more than

[6] NGO Chemical Group (2019).

911-fold output growth since 1949.[7] Similarly, many other traditional coal chemicals, including synthetic ammonia and calcium carbide, also rank first in the world.

Figure 2: Production capacity of selected modern coal chemicals in China during the 13th FYP period



Source: various sources.[8]

Note: According to China Coal Processing & Utilization Association, in 2021 China's CTL capacity reached 9.31 Mt/annum with actual output at 7.96 Mt; CTG capacity reached capacity reached 6.125 bcm/annum with actual output at 4.629 bcm; CTL capacity reached 16.72 Mt/annum with actual output at 15.75 Mt; and CtEG capacity reached 6.75 Mt/annum with actual output at 3.23 Mt. Please note that the 2021 statistics from CCPUA are not entirely compatible with data serials in this figure, which is likely to be caused by difference in statistical coverage.

After China lost its long-cherished status of energy self-reliance in 1993, the rising anxiety over the country's increasing dependency on oil imports prompted sustained interest in utilizing coal as a raw material to produce liquid hydrocarbon, synthetic natural gas, olefins, and glycol, among other fuel and chemical products. Following years of scientific and technological research, especially through the project demonstration during the 11th FYP period (2006–2010), the direct CTL process and catalyst developed by Shenhua Group have been successfully commercialized at a 1.08 Mt/annum demonstration project in Erdos, Inner Mongolia, which was commissioned in 2008.[9]

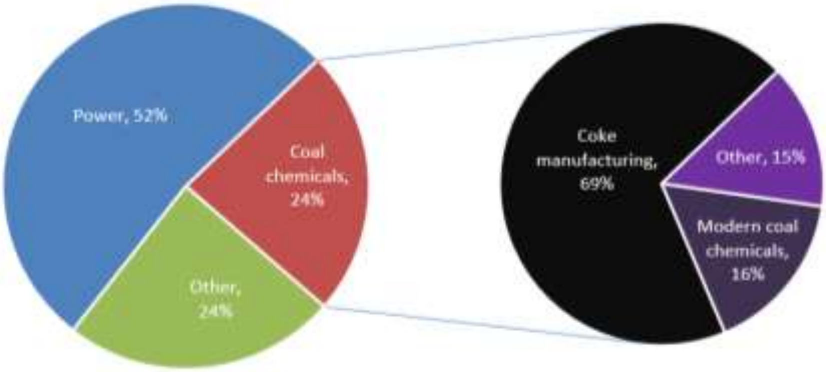
Since then, the Chinese modern coal chemical industry has witnessed substantial growth in both manufacturing capacity and annual output. As a result, the number of CTL plants reached 10 in 2020. Though annual CTL output reached 9.63 Mt in the same year, it accounts for no more than 1.5 per cent of China's national oil consumption. By comparison, CTG output reached 4.7 bcm in 2020, just under 1.5 per cent of China's national gas consumption. Meanwhile, CTO output reached 15.39 Mt in 2020. Taking polyethylene as an example, the CTO/MTO process represents about one-fifth of national production capacity. By comparison, CtEG output reached 2.35 Mt in 2020, and accounts for about 15 per cent of national EG consumption (see Figure 2).

As illustrated in Figure 3, coal power is the dominant coal-consuming sector in China, accounting for more than half of national coal throughput. Coal processed by the Chinese coal chemical industry represents about one quarter of national coal throughput. As most coal processed by the Chinese coal chemical industry is passed to other sectors as either chemical feedstock (e.g., coke) or fuel products (e.g., liquid

[7] NBS online database, available at https://data.stats.gov.cn/english.
[8] Cao Xute (2020); Chen Yang and Yang Qian (2022), Intelligence Research Group (2020); Liu Diandong and Wang Yu (2021), Xu Zhenggang (2020), Zhang Xin (2022), and anonymous industrial sources.
[9] NEA (2019).

hydrocarbon), so coal chemicals' share of national carbon emissions, which is estimated at about 5.4 per cent, is significantly lower than the percentage of coal processed by the industry.

Figure 3: Estimated breakdown of China's coal flow by sector in 2020



Source: National Bureau of Statistics, and the author's own estimation.[10]

Note: breakdown is based on approximate estimation, as both double counting and under-reporting are inevitable for this sector due to extremely complicated chemical reaction routes through the coal chemical value chain. For instance, coke consumption by the chemical industry is allocated as coal throughput only in the coke manufacturing industry to avoid double counting.

In the Chinese coal chemical industry, nearly 70 per cent of coal throughput is processed to manufacture coke, an important ingredient for the iron and steel industry and certain coal chemical products, followed by 16 per cent of coal processed by the modern coal chemical industry. Other coal chemicals, such as ammonia and CaC_2, account for the remaining 15 per cent.

2.3 From the 3E to SECTOR framework: Assessing the prospects of China's chemical industry

When the International Energy Agency (IEA) was established in 1974 with the objective of coordinating the response of participating states to the global energy crisis, it had long focused on three key pillars: economic development, energy security, and environmental protection, known as 'the 3E of IEA' or the '3E Trilemma'. As the global energy sector has become increasingly interconnected and complicated over time, not only does the definition of energy security need to be broadened, but additional criteria should also be incorporated into energy decision-making process. In the above context, this paper argues that prospects of the Chinese coal chemical industry could be assessed against a list of key criteria, with the acronym SECTOR (see Figure 4).

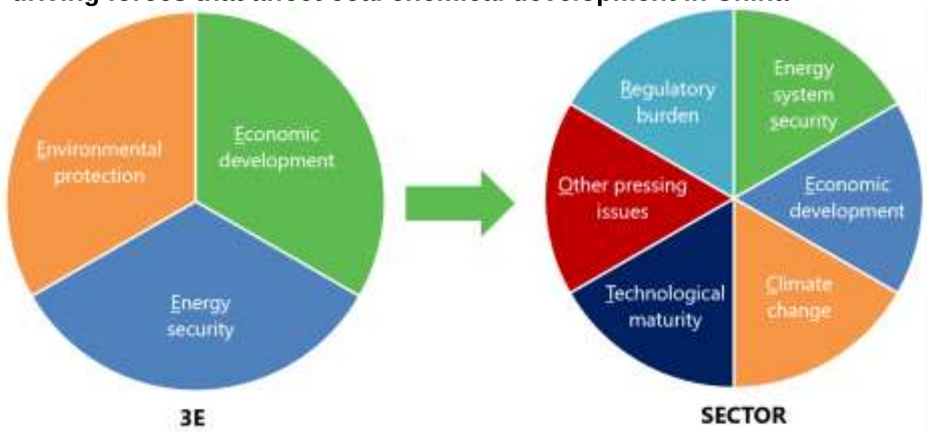
Energy (system) security: While the IEA defines energy security as the uninterrupted availability of energy sources at an affordable price,[11] and long focused its collective actions among member countries on oil supply security, the rising importance of gas supply security and electricity security prompted the agency to broaden its energy security-related coverage in recent years. As a result, security of the energy system is a more appropriate consideration for China's coal chemical development. Energy (system) security may be defined as reliable, affordable access to increasingly interconnected energy sources for all key energy stakeholders, including energy importing, exporting, and transition countries.

Economic development: A major goal of China's Reform and Opening policy is economic development or economic growth. The two terms are not identical. Growth may be necessary but not sufficient for development. Economic growth refers to increases in a country's production, as approximately measured by gross national product (GNP), or income per capita. Economic development refers to economic growth

[10] NBS (2023).
[11] IEA (n.d.).

accompanied by changes in output distribution and economic structure.[12] The consumption of energy fuels economic growth, so energy remains an important factor in the determination of economic development.

Figure 4: Key driving forces that affect coal chemical development in China



Source: Author

Climate change: As human-induced climate change is the largest, most pervasive threat to the natural environment and societies the world has ever experienced, consideration of environmental protection alone becomes increasingly insufficient to target this paramount global challenge. Climate change thus deserves to be categorized as an individual driving force underlying coal chemical development. The issue of climate change attracted virtually no public or political attention from China in the 1960s, and only a little during the energy policy debates of the developed world in the 1970s. Since then, Beijing bided its time in developing an increasingly proactive and comprehensive energy and climate policy, which culminated on 22 September 2020, when Chinese president Xi Jinping announced the dual carbon goals.[13] Given China's unique political system, climate change is expected to remain a key factor shaping China's energy policy, including coal chemical development, in the decades to come.

Technological maturity: The Chinese government recognizes that reaching carbon neutrality by 2060 will not be achievable without a major acceleration in clean energy innovation. According to IEA, reaching net zero emissions in China will require the widespread use after 2030 of technologies that are still at the prototype or demonstration stage today. To achieve the dual carbon goals, technologies that are available on the market today provide the bulk of the CO_2 emissions reductions required in 2030 relative to 2020; but in 2060, 40 per cent of the reductions will come from technologies that are under development today.[14]

Regulatory burden: As coal is at the center of enormous energy, environmental, social, and climate challenges in China and worldwide, coal is undoubtedly regulation-intensive throughout its entire value chain. A core challenge for effective regulatory governance in China is the coordination of regulatory actions, from the design and development of regulations at the central government level, to their implementation and enforcement at local levels: closing this loop requires painstaking institutional reforms that are always politically challenging to carry out. By comparison, China's transition away from coal is not only critical to addressing multiple regional and global challenges, but also beneficial to substantially lower regulatory burdens faced by both the government and the energy industry.

Other pressing issues: As coal chemical manufacturing often consists of water-intensive production processes with substantial wastewater discharge, **water availability and contamination** are major constraints faced by the industry. Since coal chemical projects are mainly located in water-stressed western regions with questionable environmental enforcement records, further expansion of China's sizable coal chemical industry is expected to exaggerate widespread water scarcity and water pollution in some affected regions.

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[12] Nafziger (2005).
[13] Tu (2022).
[14] IEA (2021).

Meanwhile, **air pollution** remains at an alarming level in China, and affects economies and people's quality of life. Thus, coal chemical manufacturing's impacts on air quality are hard to ignore. From coal mining and transport to end uses, the Chinese coal value chain has led to severe environmental and public health consequences. In particular, outdoor air pollution, which is largely caused by coal mining, transport, and combustion, has been a leading risk factor for mortality, contributing to an estimated 1.2 million premature deaths in China in 2017. Dispersed coal combustion from small burners and residential uses are the main cause of heavy pollution in many urban centers across China. In 2017, indoor pollutants emitted by Chinese households burning coal caused about 750,000 deaths from respiratory diseases.[15]

Another chronic policy challenge related to coal chemical manufacturing is **safety**. Coal chemical plants contain flammable materials, and face hazards related to the combustion or even explosion of these materials. On 5 January 2022, one explosion at a coal chemical plant in Henan killed three people.[16] As coal chemical manufacturing leads to sustained coal mining operations, the industry's connection with coal mining accidents is difficult to overlook. According to official statistics, more than 269,000 Chinese coal miners have died in numerous mining accidents since 1949.[17] Though China has made significant progress to improve coal mine safety in the past two decades, major accidents are still difficult to entirely eliminate. On 22 February 2023, an open-pit coal mine collapse in Inner Mongolia killed 53 miners.[18]

When examining the Chinese coal chemical industry, it is important to incorporate impacts of the above-mentioned policy drivers. Table 1 adopts a numerical rating scale, ranging from –5 representing the most negative impacts to +5 representing the most positive, and is utilized to assess prospects for the Chinese coal industry in the last section of this paper. It is recommended that a survey could be conducted in a follow-up study, ideally with weights of each drivers assigned explicitly.

Table 1: A sample survey on SECTOR's perceived impacts on the prospects of coal chemical development in China

Driving forces	Short-term (14th FYP)	Mid-term (Around 2030)	Long-term (Mid-century)
Security of energy system	++++	+++	+
Economic growth	++++	++	+
Climate change	–	– – –	– – – – –
Technological maturity	– – –	–	++
Regulatory burden	– – –	– –	–
Other pressing issues:	– – –	– –	– –
Water scarcity	– – –	– – –	– – – –
Water contamination	– – –	– –	– –
Air quality	– – –	– –	–
Safety	– – –	– –	–

Note: – – – – – (– 5) represents the most negative impacts on coal chemical development in China; +++++ (+5) represents the most positive impacts, and 0 represents no impacts at all.

[15] Gang He *et al*. (2020).
[16] Sina.com (2022a).
[17] Tu (2007).
[18] Caixin Global (2023).

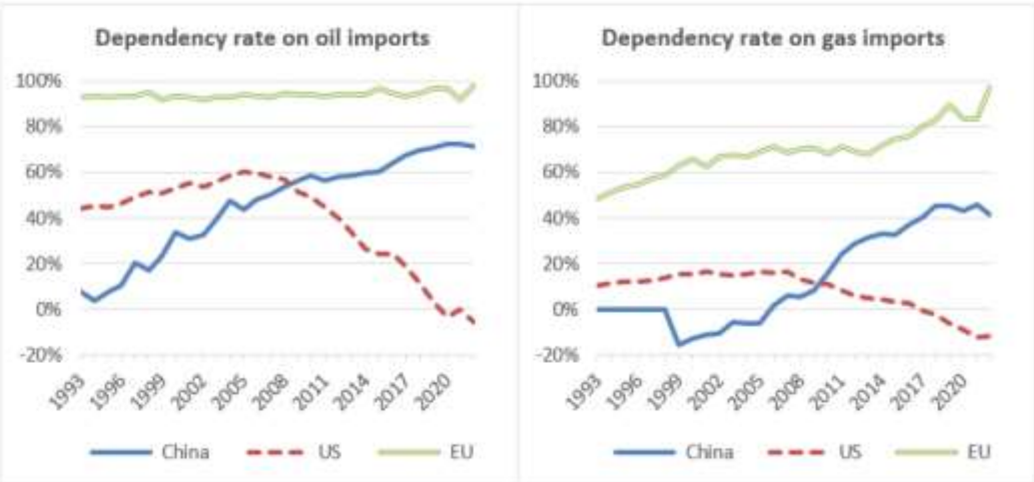
3. Drivers and limitations of coal chemical development in China

3.1 The drivers behind coal chemical development in China

To better understand the status quo and prospects of the Chinese coal chemical industry in an increasingly carbon-constrained world, it is necessary to first explore the major drivers that support coal chemical development in China.

Coal chemicals' potential to slow China's rising oil and gas imports bodes well with Chinese leadership's energy security anxiety amid rising global geopolitical tensions. Since China lost its long-cherished status of energy self-reliance in 1993, the country has imported increasingly higher amounts of oil to meet its surging demand. After China surpassed the USA as the largest oil importer in 2017, its dependency rate on oil imports reached more than 70 per cent in recent years, just when the American oil dependency rate fell to its lowest level in decades. Consequently, the tone of US–China energy relations has gradually shifted: from the looming danger of oil resource access competition-induced hostility at the beginning of the millennium, towards the bilateral energy trade's increasingly prominent role in reducing the American trade deficit with China during the Trump presidency. Nevertheless, as US–China relations under President Joe Biden remain tense, the US House of Representatives overwhelmingly passed a bill in January 2023 to ban releases of oil from the American Strategic Petroleum Reserve from being exported to China.[19] This legislative initiative, coupled with other rhetoric as well as bilateral hostility, has not only dented the potential of US–China energy trade, but also has further increased energy security anxiety among Chinese decision-makers.

Figure 5: Comparison of dependency rates on oil and gas imports among China, USA, and EU



Source: various sources.[20]

After the global financial crisis in 2008, China's national gas consumption skyrocketed. As domestic supply has been unable to meet the burgeoning demand, China's dependency rate on gas imports increased to a record 46 per cent in 2021. By comparison, the shale gas revolution made the world's largest gas consumer, the United States, a net gas exporter as early as 2017.

Since the outbreak of the Russian-Ukrainian War in February 2022, global energy markets have been in turmoil. As China is heavily exposed both to Russian commodity exports and to global markets, rising energy security anxiety, coupled with high oil and gas prices, has convinced Beijing not only to further prioritize domestic energy production, but also to double down on efforts to suppress oil and gas imports. China's dependency rates on oil and gas fell to 71.5 and 41.2 per cent, respectively, in 2022. Following the outbreak of the Israel–Hamas conflict in October 2023, a spike of geopolitical tensions in the Middle East not only put

[19] Reuters (2023a).
[20] US EIA online database, Eurostat online database, and CNPC ETRI (various years).

global energy markets at risk, but has also reinforced China's desire to reduce dependency on politically unstable oil and gas-producing regions.

Given modern coal chemicals' theoretical potential to rely on domestically abundant coal resources to substitute imports of oil, gas, and petrochemical products, during his visit to a coal chemical company in Yulin City in September 2021, Chinese president Xi Jinping made the following statement:

> The coal chemical industry possesses great potential and is very promising, [the industry should] increase comprehensive energy efficiency of utilizing coal as chemical feedstock, promote high-end, diversified and low-carbon development, regard technological innovation as the most pressing task, accelerate breakthrough of key technologies, actively develop coal-based specialty fuels as well as coal-based biodegradable materials, and etc.[21]

According to the China National Coal Association (CNCA), production capacities of CTL, CTG, CTO, and CtEG in 2025 are recommended to reach 12 Mt/annum, 15 bcm/annum, 15 Mt/annum and 8 Mt/annum, respectively.[22] In sum, the modern coal chemical industry is expected to play a more prominent role in chemical product manufacturing than petroleum substitution. By comparison, because of rapid market penetration of electric vehicles and other new energy vehicles, from 25.6 per cent in 2022 to 65 per cent in 2035, China's transport fuel consumption is projected to decline by more than 100 Mt/annum in the coming decade, contributing to national oil consumption peaking at around 2026 at about 800 Mt/annum.[23]

Even so, CTO/MTO, or coal to plastics downstream of methanol, possesses great potential to substitute petroleum imports at scale, leading to substantial growth of national coal consumption and CO_2 emissions. As zeolite[24] is proven to have excellent performance in MTO, significant progress has been made in MTO reaction mechanisms and the development of a highly efficient zeolite catalyst, with more in-depth research and development (R&D) to be carried out by the Chinese coal chemical community in the years to come.

Strong support from pro-growth local governments and a coal industry dominated by state-owned enterprises (SOEs). While the central government has been relatively cautious in permitting greenfield coal chemical facilities during the 14th FYP period, especially after the announcement of the dual carbon goals in September 2020, the attitude of the coal industry is more supportive. In June 2021, CNCA recommended further capacity expansion of the Chinese modern coal chemical industry; demonstration of CTA, CtEG, and coal tar deep-processing projects with Mt/annum capacity and 10 Mt/annum of cascade utilization of coal plants in accordance with grade and quality; completion of 30 Mt/annum of long flame coal pyrolysis capacity; and the aim to covert 160 Mt of coal equivalent (Mtce) of coal by 2025.[25] In July 2020, the China National Petroleum & Chemical Planning Institute recommended similar 14th FYP targets for the modern coal chemical industry, with an even more ambitious goal to convert 200 Mtce of coal by 2025.[26]

Moreover, the industrial structure of China's energy sector benefits coal chemical development. State-owned enterprises dominate the Chinese fossil fuel industry, and account for almost all national oil and gas output as well as three quarters of revenue of the coal industry.[27] Not surprisingly, the majority of coal chemical capacity in China is also owned by SOEs, as described below.[28]

- CTL: Except for a 0.45 Mt/annum pilot coal-petroleum co-processing oil facility operated by Shaanxi Yancheng Petroleum Group, China's other eight operational CTL plants are all owned by coal companies, with 56, 25, and 19 per cent of aggregate production capacity owned by central SOEs, local SOEs, and private enterprises, respectively.
- CTG: There are four operational CTG plants in China, with about two thirds of production capacity owned by SOEs, and the remaining by private enterprises. It is worthwhile to note that China's first

[21] Yan Jing and Ma Teng (2022).
[22] CNCA (2021).
[23] Sinopec (2024).
[24] Zeolite is a family of crystalline aluminosilicate materials commonly used as adsorbents or catalysts.
[25] CNCA (2021).
[26] NPCPI (2020).
[27] Sina (2023a).
[28] Xu Zhenggang (2020).

CTG plant was commissioned by a central SOE of the power industry in 2013, accounting for about one quarter of national production capacity.

- CTO: About three quarters of China's CTO capacity are owned by SOEs, with the remainder belonging to private companies. Central SOEs with their main business in coal (e.g., Shenhua), oil (i.e., Sinopec), and power (e.g., Datang) are all active players in this sub-sector.
- CtEG: Local SOEs dominate China's national CtEG production capacity, with central SOEs such as Sinopec only playing a marginal role in this sub-sector.

From a theoretical perspective, direct government control of SOEs can either accelerate or hinder their corporate low-carbon transition. On one hand, SOEs have a strong incentive to respond quickly to the dual carbon goals imposed by the central government, and their market dominance and deep pockets can enable them to rapidly adopt and scale up immature clean energy technologies. On the other hand, political contestation among governments and conflicting policy goals are prone to be taken advantage of by SOEs in accordance with their own interests.

Though Chinese SOEs are more likely than their competitors in the private sector to pilot advanced low-carbon technologies, China's SOE-dominated industrial structure is likely to give unabated operational coal chemical facilities more staying power than otherwise would be the case, especially after 2030.

While national oil companies dominate the Chinese oil and gas industry, so far they have shown no interest in CTL and CTG, and played only a marginal role in CTO and CtEG development. However, due to the deterioration of crude oil grades and upgrading of fuel oil quality, hydrogen demand by the petroleum refining industry is on the rise, accounting for 0.8 to 2.7 per cent of refinery throughput on a weight basis.[29]

Lured by the significant cost advantage of coal-derived hydrogen against both steam methane reforming and partial oxidation of fuel oil, Chinese national oil companies, as well as 'teapot' refineries, [30] are becoming increasingly reliant on coal gasification to meet the hydrogen demand of their petroleum refining and petrochemical operations. Given the emissions-intensive nature of coal-based hydrogen production, the National Development and Reform Commission (NDRC) and several other authorities recently urged the Chinese petroleum refining industry to switch to renewable hydrogen, to lower the carbon footprint of its hydrogen supply.[31]

The most important driving force in permitting greenfield coal chemical facilities in China is the sustained enthusiasm of local governments of coal regions. When coal resources are awarded to an enterprise, it is a common practice for local government in a coal region to impose requirements of coal conversion and utilization within its administrative boundary, the equivalent of endorsement of coal power, coal chemical, or other coal-intensive heavy industry development at the local level.[32]

As the majority of coal chemical projects in China are located in the top four coal-producing provinces, with 24 per cent in Inner Mongolia, 18 per cent in Shaanxi, 15 per cent in Xinjiang, and 7 per cent in Shanxi,[33] a phase-down of coal chemical manufacturing needs to proactively consider how alternative economic momentum may be nurtured to ensure a just transition at the provincial level.

Not surprisingly, China's top coal-producing regions have all released quite supportive coal chemical plans during the 14th FYP period.[34]

- **Shanxi**, the largest coal producer in China, with aggregate output by enterprises above a designated size at 1,357 Mt in 2023:[35] Rationally develop the modern coal chemical industry; significantly improve technological sophistication and energy efficiency of the modern coal chemical

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[29] Wang Yuqian (2014).
[30] 'Teapot' refineries refer to privately owned unaffiliated refineries in China, they are known as 'teapots' because of the shape of early designs. They grew from small clay kilns that began processing oil mainly from fields in Shandong where oil output was more than state-owned refiners could absorb.
[31] NDRC *et al.* (2023a).
[32] Song Ge (2018).
[33] Anon. (2021).
[34] Qianzhan Analyst (2022).
[35] CNCA (2024).

industry; actively promote large-scale coal chemical development at industrial parks or energy bases; and promote orderly establishment of large-scale modern coal chemical bases.

- **Inner Mongolia**, the second largest coal producer with output at 1,211 Mt in 2023: Rely on Ordos city to rationally develop CTL, CTG, CTO, CtEG, etc.; and establish a high-standard modern coal chemical demonstration park in Ordos.
- **Shaanxi**, the third largest coal producer with output of 761 Mt in 2023: Promote clean, highly efficient coal conversion; expand a circular economy of integrated utilization of coal, oil, gas, and salt; extend supply chain and increase value-added; comprehensively increase technological sophistication of energy and chemical supply chain; promote orderly cascade utilization of coal in accordance with grade and quality; develop high-end specialty olefin products; rationally control CtEG capacity; make CTA-related technological breakthroughs; and promote downstream development towards high value-added manufacturing.
- **Xinjiang**, the fourth largest coal producer with output of 457 Mt in 2023: Establish large-scale national bases for coal mining, coal power, and coal chemicals; promote large-scale development of coal bases with focus on four regions; implement large-scale coal chemical projects; promote reliable construction of strategic CTL and CTG bases; promote orderly development of the modern coal chemical industry; achieve technological breakthroughs related to seasonal conversion between CTG and other chemical products; implement clean, highly-efficient, and comprehensive utilization of coal in accordance with grade and quality; and promote switching of highly efficient and clean utilization of coal from fuel to feedstock.

Renewable hydrogen economy offers the industry a rare opportunity of redemption: Hydrogen has the potential to help decarbonize emissions-intensive industrial sectors where fossil fuel is utilized both as an energy carrier and as a feedstock. Renewable hydrogen is a promising energy vector in coal chemical manufacturing, and thus has potential to eliminate its otherwise hard-to-abate CO_2 emissions. A number of China's leading coal chemical companies, such as Baofeng and China Energy Investment Corporation (China Energy), are experimenting to explore potential low-carbon and net-zero coal chemical manufacturing solutions with renewable hydrogen.

China is the largest hydrogen producer and consumer in the world, with national hydrogen production reaching 34.1 Mt in 2020. However, hydrogen manufacturing in China is dominated by coal, which accounted for 72 per cent of national output in 2020, followed by 14 per cent natural gas, 10 per cent oil, and about 4 per cent electrolysis including chlor-alkali by-production and water electrolysis.[36]

Due to China's abundant coal resources and low production cost of coal-derived black hydrogen (that could be lower than 10 yuan/kg of hydrogen, with an average unit production cost around 14 yuan/kg), the coal-based production route is expected to continuously dominate China's national hydrogen output in the short to medium term. By comparison, depending on the price level of electricity (e.g., valley, shoulder, or peak) and types of electrolysers (e.g., alkaline or proton-exchange membrane), the unit production cost of renewable hydrogen is estimated to range from 24.04 to 70.47 yuan/kg.[37] A similar indicator of the steam methane reforming process ranges from 22.07 to 41.71 yuan/kg.[38] Given the significant cost disadvantage of renewable hydrogen, and a lack of political willingness for generous subsidies at the central government level, China's national renewable hydrogen production target is set at only 100–200 kt/annum by 2025, a rather modest level in the Chinese context.

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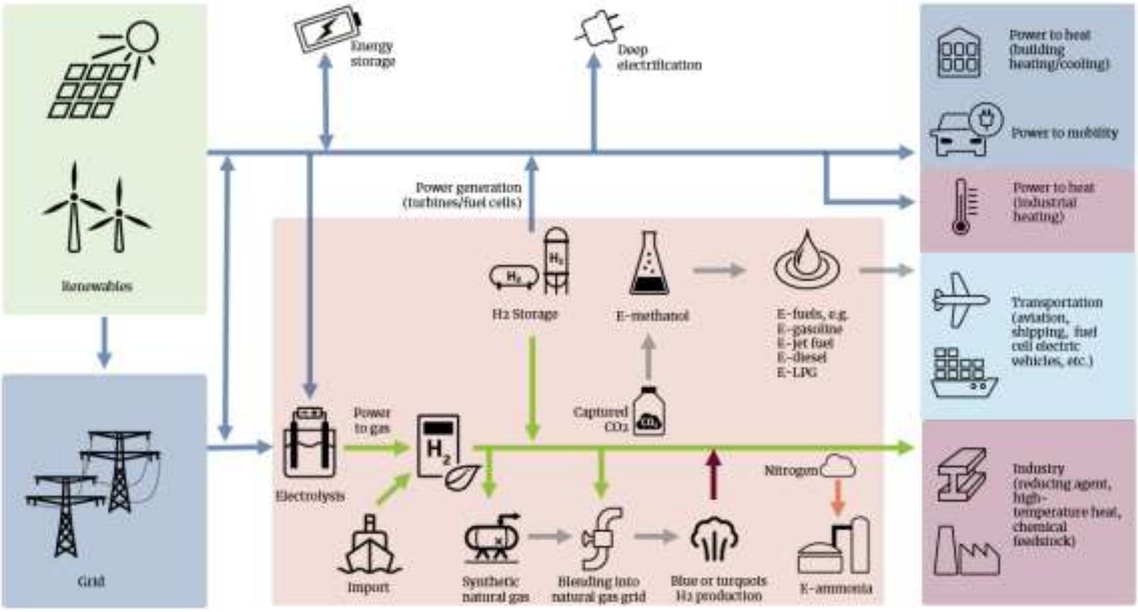
[36] Tu and Wang (2022).
[37] Sun Xudong *et al.* (2023).
[38] Coalchem.org (2022).

Figure 6: Hydrogen's role in sector coupling and power-to-X



Source: Tu and Wang (2022).

Though renewable hydrogen currently represents only a negligible share of national hydrogen production in China, it could promote sector coupling[39] between the chemical industry and renewable power, leading to low-carbon substitution of fossil fuel-based hydrogen in ammonia, methanol, and other chemical manufacturing. Some advantages of sector coupling include increased flexibility, enhanced storage, and distribution opportunities to use renewable energy, as well as reliability. In energy transition-related discourse, sector coupling implies making renewable power the default form of energy in energy-consuming sectors wherever possible. Meanwhile, energy conversion pathways that utilize electricity, especially renewables, as the primary input to produce various electro-fuels, energy services, and chemicals are often categorized as Power-to-X (PtX), especially in the European context.

In 2022, renewables accounted for 31.6 per cent of China's power generation, and China plans to increase it to 33 per cent by 2025. Though China's 14th FYP targets for renewables are widely considered conservative, the growing share of renewables in China's power mix enables renewable hydrogen to serve as an energy carrier to supplement electricity in sector coupling and net-zero decarbonization, especially in transport and energy-intensive heavy industry such as coal chemical manufacturing.

During the first 11 months of 2023, 64 renewable hydrogen projects were announced across China, with 58 per cent in Inner Mongolia alone.[40] Looking to the future, SOEs, private new energy firms, as well as coal chemical companies with deep pockets are expected to continuously dominate renewable hydrogen investment in China, with production sites increasingly concentrating in regions with promising resource endowment (e.g., Inner Mongolia, Ningxia, Xinjiang, Qinghai) or where local governments are willing to offer generous supportive measures (e.g., Inner Mongolia). As the above geographic overlay is similar to the distribution pattern of renewable and coal chemical projects in China, it could largely explain why Inner Mongolia and Ningxia have been identified as the most promising production bases in China for renewable hydrogen and green chemical manufacturing.[41]

By comparison, hydrogen may be labelled blue whenever CO_2 emissions generated from coal gasification or steam methane reforming are captured and stored underground through carbon capture and storage (CCS). Given China's rising energy security anxiety, as well as the relatively high cost of natural gas, blue hydrogen in the Chinese context is mostly likely to be produced via the coal-based manufacturing route.

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[39] Sector coupling is defined as the connection of at least two different sectors via substitution of non-renewable activities with renewable alternatives to establish fully renewable energy systems.
[40] Sina (2023b).
[41] RMI and China Hydrogen Alliance (2022).

Compared with black hydrogen, addition of a CCS facility is estimated to increase the cost of blue hydrogen by 51.5 per cent, which nevertheless still possesses a cost advantage against other hydrogen production routes, especially renewable hydrogen. Configuration of CCS is expected to reduce life-cycle CO_2 emissions intensity of black hydrogen by only 53.3 per cent,[42] while blue hydrogen may offer existing coal chemical facilities a transitional option to lower CO_2 emissions intensity with reasonable costs. However, it should not be used to justify the permitting of any greenfield coal chemical facilities.

Some coal chemical facilities are suitable for piloting carbon capture, utilization, and storage (CCUS) projects: CCUS is a climate mitigation process that captures CO_2 emissions from large point sources such as coal chemical plants, then either reuses it or transports it to a storage location for the purpose of long-term isolation from the atmosphere. As in the rest of the world, the potential of CCUS development in China has been largely untapped: its effectiveness to reduce emissions is well recognized by key stakeholders, but deployment beyond small-scale pilot projects has been slow. By the end of 2022, aggregate capture and storage capacity of operational CCUS projects in China had reached only 4 and 2 Mt/annum,[43] respectively, leading to limited impacts on national CO_2 emissions of more than 10,000 Mt/annum. As a commercially immature, relatively expensive but effective climate mitigation technology, CCUS could, in theory, serve as the last-resort solution once other net-zero options are exhausted.

According to Tao Yi *et al.*,[44] CO_2 emissions of the Chinese modern coal chemical industry (including CTM) represent more than 3 per cent of national total emissions, and they primarily consist of process emissions as well as fuel combustion emissions, with the former normally accounting for 56 to 67 per cent of total emissions. There are large streams of high-purity CO_2 (>80 per cent concentration) or pure CO_2 (>98.5 per cent concentration) available as a result of coal chemicals production and industry separation processes,[45] so coal chemical facilities are ideal high-concentration emission sources that are suitable for carbon capture. In some cases, they can avoid carbon capture processes altogether, thus coal chemical manufacturing is widely regarded as the most preferred industry for piloting CCUS projects in China.

Table 2: Comparison of CO_2 emissions parameters between typical coal chemicals and thermal power

Technology	Process emissions' share of total (%)	Combustion's share of total (%)	CO_2 concentration of process emissions (%)	CO_2 concentration of combustion emissions (%)
CTL (direct)	56	44	87	12
CTL (indirect)	67	33	91	13
CTO	63	37	90	13
CTM	61	39	85	13
Thermal power	N/A	100	N/A	13–14

Source: Tao Yi *et al*. (2023).

Compared with low-concentration CO_2 emissions sources such as thermal power plants, the capital cost of the capture process in a modern coal chemical plant could be significantly reduced, and the operating energy consumption is also lower.[46] Carbon capture of high-concentration CO_2 emissions from coal chemical facilities could have at least three end use options:

- CCS: To be transported, ideally via long-distance pipeline, and then stored underground. It is worthwhile to note that CCS retrofitting to existing coal chemical facilities is sometimes deemed as

[42] Wei Yiming *et al.* (2021).
[43] ACCA 21 *et al*. (2023).
[44] Tao Yi *et al.* (2023).
[45] Ning Wei *et al.* (2014).
[46] Jingjing Xie *et al.* (2022).

a relatively low-risk path towards reducing life-cycle CO_2 emissions intensity from an economic and technical perspective.

- CCUS: To be utilized for enhanced oil or gas recovery. In August 2023, Sinopec commissioned China's first ever 1 Mt/annum CCUS project, consisting of a carbon capture section operated by Sinopec Qilu Petrochemical Company and a utilization and storage section at Sinopec Shengli Oilfield. The project is expected to help produce more than 200 kt/annum of extra crude output. Construction of China's first-of-its-kind 100-km CO_2 transmission pipeline is also under way.[47]
- CCU or sector coupling or PtX: During periods of peak renewable power output, excess electricity could be utilized to produce hydrogen or synthetic gases via power-to-gas (PtG). Coupled with CO_2 captured from coal chemical facilities, the above gases can be further processed to various types of e-fuels for aviation, maritime shipping, and long-haul heavy-duty trucking.

With CO_2 injection operation starting in January 2011 and the full operation beginning in May 2011, the Shenhua Ordos CCS project is the first Chinese pilot-scale demonstration for CO_2 deep saline aquifer storage in combination with direct CTL production. Once CO_2 injection ceased in April 2015, the project's operations are considered to be safe from a storage point of view, and successfully demonstrate the feasibility of large-scale commercialization of CCUS in the Ordos Basin.[48]

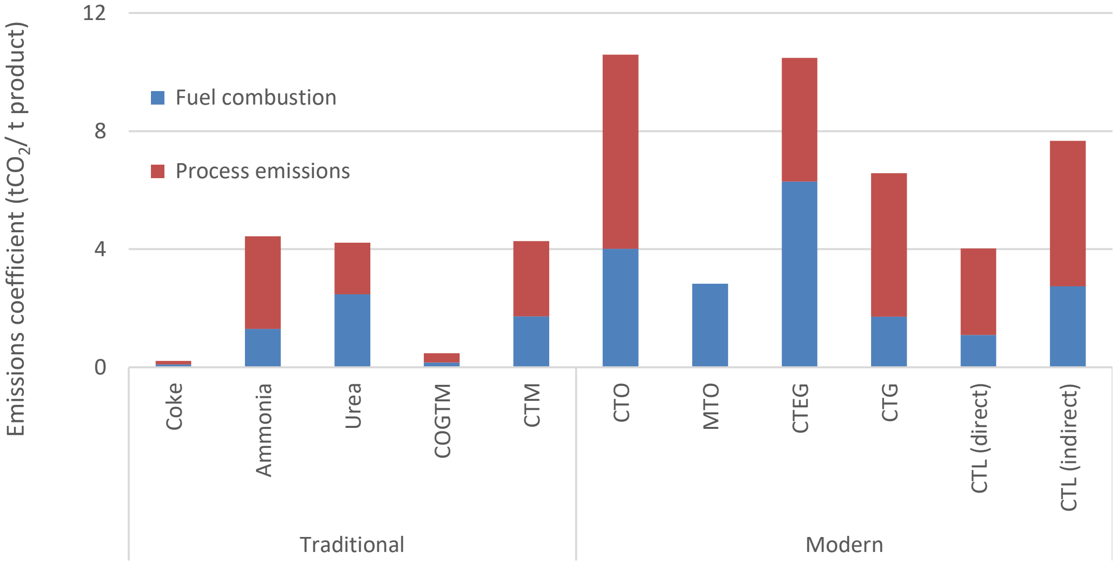
Since China's largest coal company, Shenhua, merged with China Guodian as China Energy in 2017, China Energy remains the largest coal chemical company in China, with hydrogen production capacity of its coal chemical plants exceeding 4 Mt/annum. By comparison, Sinopec, China's largest petroleum refiner, produced about 3.9 Mt of hydrogen in 2021.[49] As central SOEs with heavy fossil fuel assets and deep pockets, such companies have strong incentive to showcase their political willingness to support the climate targets mandated by the central government, and thus are actively piloting renewable hydrogen and CCUS projects, aiming to reduce the emissions intensity of their chemical manufacturing operations.

3.2 Limitations constraining coal chemical development in China

Climate change-related uncertainty is the biggest risk faced by the Chinese coal chemical industry: Given the highly emissions-intensive nature of coal chemical manufacturing, further capacity expansion will contradict China's dual carbon goals. As one of the most important sectors for coal use, the coal chemical industry is also a leading contributor to national CO_2 emissions. The processes of coal gasification and coal liquefaction, which are the main routes from coal to chemicals, are also major sources of CO_2 emissions in China. Coal use as a raw material to produce chemicals is more CO_2 emissions intensive than petroleum or natural gas due to the higher carbon/hydrogen ratio. The emission factor of coal-based ammonia in China is around 4.6 tCO_2/t of NH_3, which is about 2.2 times that of natural gas-based manufacturing route, and 40 per cent higher than the coefficient of oil-based product (see Figure 7).[50]

[47] SASAC (2022).
[48] Keni Zhang *et al.* (2016).
[49] Anon. (2022).
[50] Wenji Zhou *et al.* (2010).

Figure 7: CO_2 emission factors of different coal chemical products in China



Source: You Zhang *et al*. (2019).

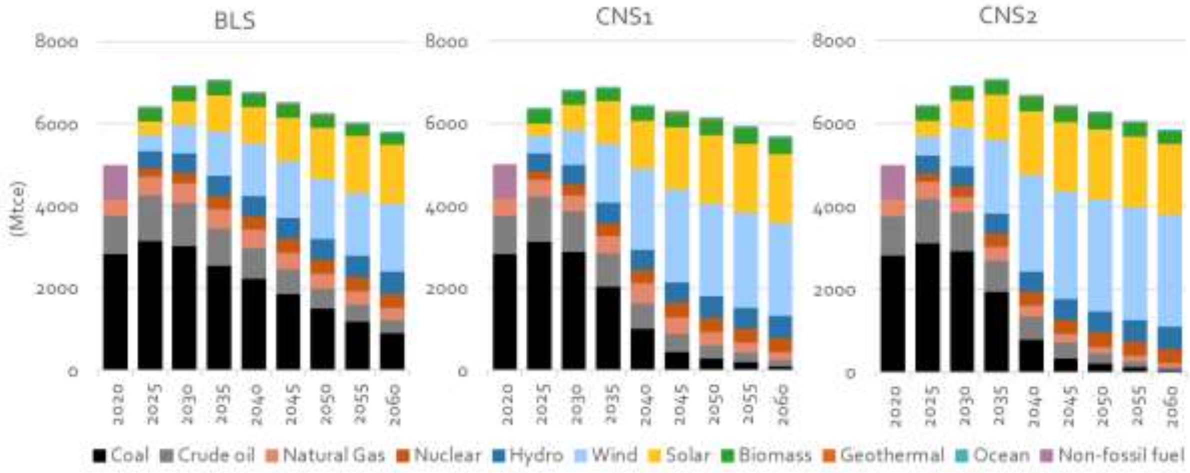
Note: COGTM, coke oven gas-to-methanol.

Compared with the traditional coal chemical industry, modern coal chemical products have much higher CO_2 emissions coefficients due to the energy-intensive nature of its operations as a result of complicated chemical processing. According to Figure 7, emissions coefficients of typical modern coal chemical products range from 2.83 to 10.6 tCO_2/t product. While the Chinese coal chemical industry is estimated to account for about 5.4 per cent of national CO_2 emissions in 2020, further expansion of the industry without a legally binding decarbonization roadmap is expected to contradict China's dual carbon goals.

Not surprisingly, China's carbon neutrality goal is likely to make the country's existing coal chemical facilities stranded assets:[51] This is often associated with the concept of 'creative destruction' in modern capitalism.[52] In the case of stranded fossil fuel assets, creative destruction would primarily be driven by climate policy: from country-level targets and how they are interpreted by economic actors, to sectoral policies meant to drive the transition to low-carbon, or trade policies aiming to discourage international flow of emissions-intensive commodities. Given the emissions-intensive nature of coal chemical manufacturing, China's sizable operational coal chemical facilities are likely to become stranded assets in an increasingly carbon-constrained world.

[51] Stranded assets may be defined as assets that have suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities.
[52] OECD (2015).

Figure 8: China's primary energy mix in different scenarios by 2060



Source: ERI (2023).

Note: The scenarios in the China Energy Transformation Outlook (CETO) comprise three development pathways for the Chinese energy system. The Baseline scenario (BLS) is developed by projecting current trends in the energy system, and incorporates considerations of prevailing political and economic tensions across the globe, aiming to serve as a benchmark for quantitative comparison with two scenarios that both envisage carbon neutrality. Both the Carbon Neutrality Scenarios 1 (CNS1) and 2 (CNS2) accept the dual carbon goals, with different choices of pathways and timing for the energy system to achieve net-zero emissions. While CNS1 targets net-zero emissions around 2055, CNS2 aims for net-zero emissions before 2055.

Note: 2020 is historical data, the data of other years are modelling results

As coal alone accounted for 56.2 per cent of China's primary energy consumption, non-fossil fuel only represented 17.4 per cent of the national energy consumption mix in 2022. According to the overarching working guidance of China's dual carbon goals, the share of non-fossil energy consumption is planned to reach around 25 per cent by 2030, and to exceed 80 per cent by 2060. So the role of coal in China's energy mix is not promising in the long run, with the caveat that setbacks in coal phase-down may occur in the short term.

To steer China's emissions trajectory away from the baseline scenario (BLS), two carbon neutrality scenarios (CNS1 and CNS2) are designed by the China Energy Transformation Outlook (CETO) 2023 project team to simulate how China may achieve the dual carbon goals. The above modeling exercise concludes that non-fossil fuels and natural gas are expected to substitute coal over time. Though coal still accounts for about one quarter of national energy consumption by 2060 in BLS, its share of the national energy mix is projected to decline to almost nil if China does achieve the dual carbon goals in time, and more specifically, 3.3 per cent in CNS1 or 1.9 per cent in CNS2 (see Figure 8).

In particular, a sudden and unexpected tightening of the carbon emission goal, or sudden changes in expectations in the presence of tipping points, can lead to abrupt repricing of fossil fuel assets.[53] With regard to tackling environmental problems, the Chinese government applied campaign-style governance as early as the end of the last century, even though the historical pedigree of these campaigns goes back to the early days of the PRC. Beyond the field of environmental protection, this phenomenon of Chinese administrative management has appeared in areas such as social stability management, resource conservation, and food safety.[54]

Since the announcement of the dual carbon goals, China has promulgated a number of regulations related to coal development, primarily consisting of enforcement of capacity swap policy, closure of backward capacity, more stringent environment regulation and enforcement, and low-carbon development of the industry, with selected examples as below.

[53] Sen and von Schickfus (2020).
[54] Feng Jia (2019).

- In September 2021, the Central Party Committee (CPC) and the State Council of China released a Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy, which is the ‘1’ of China’s ‘1+N’ dual carbon policy framework, and calls for firmly curbing irrational expansion of energy-intensive and high-emission projects including coal chemicals.[55]
- In October 2021, the State Council of China released an Action Plan for Carbon Dioxide Peaking before 2030, which aims to strictly control additional production capacity in oil refining and traditional coal chemical industry, and pursue development of a modern coal chemical industry in a steady and orderly manner.[56]
- In November 2021, the CPC and the State Council of China released the Circular regarding In-depth Efforts in the Nationwide Battle to Prevent and Control Pollution, which mandates that greenfield coal chemical capacity addition is prohibited in key regions, and calls for appropriately controlling the aggregate capacity of the CTL and CTG industries.[57]
- In February 2022, NDRC et al. jointly issued the Implementation Guidelines on Energy Conservation and Carbon Dioxide Emissions Reduction Retrofits and Upgrades in the Modern Coal Chemical Industry, which aims to pressurize coal chemical facilities with inferior energy intensity levels to improve performance through retrofitting and upgrading.[58]
- In March 2022, the Ministry of Industry and Information Technology (MIIT) et al. jointly released the Guidance for Promotion of High-quality Development of Petrochemical and Chemical Industries, which calls for safe, clean, high-end production, diversification, and low-carbon development in the coal chemical industry.[59]
- In April 2022, the Ministry of Ecology and Environment (MEE) released the 14th FYP Action Plan for Environmental Impact Assessment and Waste Discharge Permits, which calls for strict implementation of capacity swap and capacity reduction policies during environmental impact assessment of coal chemical projects in key regions.[60]
- In June 2023, NDRC et al. jointly released a Notice to Promote Healthy Development of the Modern Coal Chemical Industry. In light of several high-profile power crunches in the past several years, the notice aims to strictly control the approval, siting, and capacity of greenfield coal-to-chemical projects, and to prioritise supply of coal to power and heat plants.[61]

In the past, some regions have set overly ambitious and unrealistic goals, or simply chanted slogans without taking actions, while some industries failed to make solid energy-saving efforts in the hope that certain technology would solve the problem once and for all. To make matters worse, some regions adopt a ‘one-size-fits-all’ approach in shutting down energy-intensive projects and a sudden cut-off in loans to coal-fired power projects. Though the central government tried to rectify the above ‘campaign-style’ emissions reduction actions in August 2021,[62] the resurgence of the above governance practice at the local level is a looming danger that makes assets in the Chinese coal chemical industry much more likely to be stranded in the years to come.

The coal chemical industry has worsened China’s water shortage- and water pollution-related challenges: Coal chemical manufacturing often consists of water-intensive processes with substantial wastewater discharge. Average water demand intensities of unit coal chemical product stand at 22 t/t for CTO, 12–16 t/t for ammonia, and 13 t/t for CTM in 2020, and are only expected to improve marginally by 5 per cent by 2025.[63] Not surprisingly, water availability is one of the most important constraints of coal

[55] CPC and State Council (2021a).
[56] State Council (2021).
[57] CPC and State Council (2021b).
[58] NDRC (2022).
[59] MIIT *et al.* (2022a).
[60] MEE (2022).
[61] NDRC (2023b).
[62] Xinhua (2021).
[63] MIIT *et al.* (2022b).

chemical development, with substantial impacts on the viability of individual projects. Meanwhile, coal chemical projects are mainly located in water-stressed western regions. In particular, while Yulin in Shaanxi and Ordos in Inner Mongolia are two of China's most important coal chemical bases, both cities fall under the category of regions with heavy water stress. So further capacity expansion of China's sizable coal chemical industry is expected to result in excessive consumption of water resources, with severe impacts on water flow, water quality, and water levels of rivers and groundwater.

The production processes of the coal chemical industry are complicated, and various pollutants may be produced by each process. The resulting wastewater typically contains phenols, ammonia, nitrogen heterocyclic substances (NHCs), polycyclic aromatic hydrocarbons (PAHs), long-chain hydrocarbons, and cyanide. The wastewater generated by coal chemical manufacturing can be differentiated as gasification wastewater, purification wastewater, domestic and laboratory wastewater, circulating sewage, chemical water station drainage, initial rainwater, and concentrated saline wastewater generated during sewage treatment and reuse.[64]

Since new coal chemical projects often sited in areas without sufficient environmental capacity or appropriate discharge destination, most of the new coal chemical projects that are currently being built or that are under construction in China adopt a scheme of zero wastewater discharge. At present, most projects that have been put into operation cause different degrees of environmental problems. So far, none of these projects could achieve a long-term stable zero wastewater discharge, with water contamination-related scandals periodically reported by the media.

The financial viability of coal chemical projects is becoming increasingly uncertain in a volatile world energy market: As fuel expenditure is an important part of the production cost of modern coal chemical products, which often need to compete with their petrochemical counterparts, the economics of modern coal chemical projects are sensitive to both domestic coal prices and international oil prices. According to Table 3, the break-even Brent crude oil price for CTL projects ranges from 55 to 65$/bbl. When the international oil price is above 50, 55, and 60 $/bbl, respectively, CTO, CtEG, and CTA projects become cost competitive. When the mine-mouth coal price is less than 200 yuan/t, the production cost of CTG projects is comparable with pipeline gas imports from Central Asia. When the mine-mouth coal price is below 370 yuan/t, CTG projects in inland China could compete with LNG imports in coastal provinces in east and south China.[65]

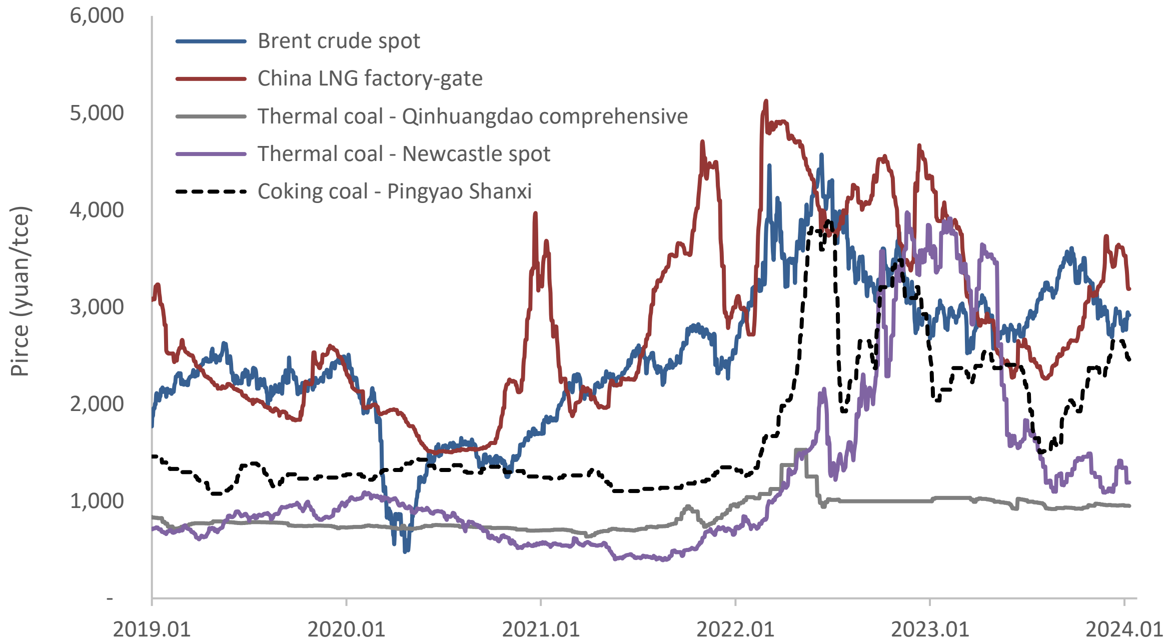
Table 3: Cost competitiveness of coal chemicals under different international oil price assumptions

Coal chemical projects		Break-even Brent oil price ($/bbl)	Brent oil price to ensure baseline investment return ($/bbl)
CTL	Direct	55–60	75–80
	Indirect	60–65	80–85
	Coal tar hydrogeneration	60–65	75–80
Coal to chemicals	CTO	45–50	70–75
	CtEG	50–55	75–80
	CTA	55–60	80–85

Source: Ping'an Securities (2021).

[64] Jingxin Shi *et al.* (2021).
[65] Ping'an Securities (2021).

Figure 9: Volatile fossil fuel prices since 1 January 2019



Source: various sources.[66]

Nevertheless, the above research findings have been concluded with several caveats. First, environmental externalities, especially carbon price, have not been fully incorporated. Though China's National Carbon Emissions Trading System (ETS) made its debut as late as July 2021 and only covers the power sector in the beginning, Beijing plans to further expand coverage of the National ETS during the 14th FYP period. As a result, a carbon pricing signal is likely to be introduced to cover the coal chemical industry in the future. Second, to justify the financial viability of modern coal chemical projects, it is a common practice for developers to use arbitrarily low mine-mouth coal price (e.g., 200–300 yuan/t) as a cost assumption. By comparison, the spot market coal price in China has increased significantly in the past several years, with thermal coal price sometimes exceeding 2,000 yuan/t in certain end-use markets. Last but not least, spot market crude oil and LNG prices as well as prices of downstream products have fluctuated widely in the past few years, which could be easily translated into a boom-and-bust cycle of coal chemical development (see Figure 9).

Over-capacity of the Chinese oil refining industry is expected to result in more fierce competition in downstream chemical markets: Oil refining capacity in China reached 920 Mt/annum in 2022, and surpassed the United States for the first time as the world's largest.[67] Constrained by the dual carbon goals as well as oil supply and demand dynamics, China's oil refining capacity is over-built by at least 200 Mt/annum.[68] However, China's national output of refined petroleum products still lagged behind the United States due to low utilization rates at Chinese refineries.

In the past, the relationship between oil refining and petrochemicals was once largely an arm's-length one. Refineries focused on fuels, and those that produced naphtha would sell it to operators of ethylene steam crackers. These plants crack naphtha at high temperatures into ethylene, propylene, and other basic chemical building blocks.[69] Amid serious over-supply of refining capacity, the Chinese oil refining industry is pressurized to accelerate extension and sophistication of the manufacturing value chain, increasingly betting its future on chemicals instead of fuels.

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[66] Wind Economic Database, CCTD Coal Database, and SHPGX online database.
[67] Reuters (2023b).
[68] Sina (2022b).
[69] Tullo (2019).

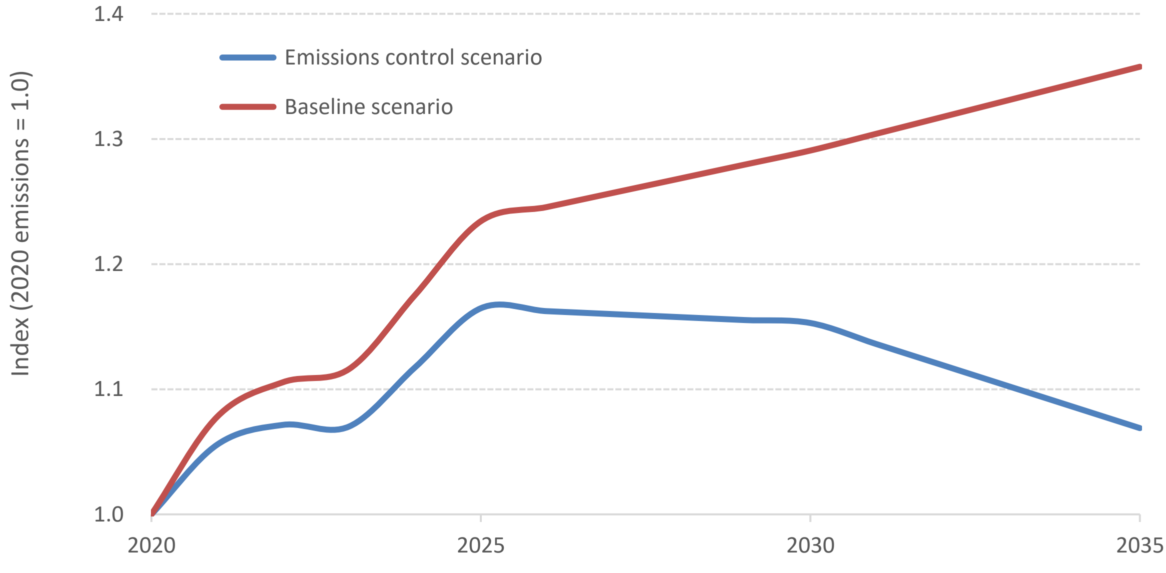
China's chemicals sector is unique globally, and the development of the industry over the past several decades has relied to a significant degree on coal technologies. This proved relatively straightforward, as such technologies have been widely available for nearly a century and have been used—albeit on a much smaller scale—elsewhere.[70] In an increasingly carbon-constrained world, the share of non-fossil fuels is expected to keep rising, which will make China's limited availability of conventional oil and gas resources a less and less important policy concern. Coupled with significant potential of greenfield petrochemical capacity expansion, resource constraint-related justification in support of coal chemical development in China is likely to gradually lose traction, and decision-makers will pay more and more attention to coal chemical manufacturing's much higher environmental externalities compared with petrochemical processes.

4. Prospects of the Chinese coal chemical industry

Though the coal chemical industry ranks as the second largest coal processing sector in China, accounting for near one quarter of national coal throughput, it only represents about 5.4 per cent of national CO_2 emissions, as most coal processed by the industry is passed to other sectors as either chemical feedstock or fuel products. Despite the dual carbon goals, the coal chemical industry remains the only major coal-consuming sector in China that still possesses great potential for substantial capacity expansion as well as emissions spikes in the coming decades.

To assess how the coal chemical industry can meet China's carbon peaking goal before 2030, Jin Ling and eight other senior experts from three of China's top environment and coal research institutes published research findings of a bottom-up modelling exercise in 2022,[71] with consideration of the status quo of the coal chemical industry, macroeconomic assumptions, energy conservation and emissions abatement technologies, and feedstock and fuel structure adjustment, among other factors. Figure 10 summarizes emissions trajectories of two scenarios in the above study, which not only sheds light on the prospects of the Chinese coal chemical industry in an increasingly carbon-constrained world, but can also be well explained using the SECTOR framework presented in section 2.

Figure 10: CO_2 emissions trajectories of the Chinese coal chemical industry



Source: adapted from Jin Ling *et al*. (2022), with sectoral CO_2 emissions in 2020 indexed as 1.0.

Under the baseline scenario: In the short term, the Chinese coal chemical industry is expected to continuously grow relatively strongly, with sectoral CO_2 emissions rising by about one quarter during the 14th FYP period, which could largely be explained by the state of play of key criteria in the SECTOR framework.

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[70] IEA (2021) Op. cit.
[71] Jin Ling *et al.* (2022).

- Rising anxiety over energy security amid geopolitical tension is the most important driver underlining coal chemical development during the 14th FYP period. As coal remains the 'ballast stone' for China's energy security, announcement of major coal chemical projects continuously unfolds in both traditional and modern coal chemical sectors.
- A sluggish post-pandemic economic recovery has led to increasingly stronger desire for investment-driven growth, especially at local level, which gives coal chemical development additional momentum.
- Though climate change, technological maturity, regulatory burden, and other pressing issues (especially water scarcity and contamination) continue to serve as major constraints of coal chemical development, for now they are outweighed by much higher political priority of energy security and economic development.

In the medium term, around 2030, the Chinese coal chemical industry is expected to undergo moderate growth, primarily driven by further capacity expansion in the modern coal chemical industry. By comparison, output of traditional coal chemicals is projected to either decline over time (e.g., coke) or fluctuate around the current level (e.g., ammonia).

- After the 14th FYP period, in the absence of any disruptive geopolitical conflicts, energy security-related anxiety among Chinese decision-makers is expected to ease over time, primarily due to peaking of national oil consumption during the 15th FYP period.
- While China further distances itself from relentless pursuit of economic growth, the priority of climate change will be significantly upgraded as 2030 is the critical juncture for China to peak national carbon emissions beforehand, while entering the era of carbon neutrality goal thereafter.
- Though technological maturity may improve over time, as other criteria of the SECTOR framework remain largely intact, progress achieved via technology innovation alone cannot entirely outweigh the damping effects related to energy security and economic development, leading to lower overall sectoral emissions growth around 2030.

In the long run, the future of the Chinese coal chemical industry looks rather uncertain. In theory, the rollout of the carbon neutrality goal after 2030 is expected to eventually plateau sectoral CO_2 emissions. However, the extent to which the Chinese coal chemical industry may be able to actually decouple its energy-intensive operations away from CO_2 emissions will largely depend on technology maturity-related progress in the baseline scenario.

Looking ahead, in the case where any key drivers in support of coal chemical development under the SECTOR framework are drastically prioritized (e.g., worsening energy security anxiety amid a disruptive geopolitical conflict), more active coal chemical development across China, as well as a much higher sectoral CO_2 emissions trajectory, would ensue.

Under the emissions control scenario: In order to peak sectoral CO_2 emissions by 2025, it is necessary to restrict permitting of greenfield coal chemical plants, optimize feedstock and fuel structure, and improve energy efficiency, among other abatement measures. Even so, sectoral CO_2 emissions in 2035 are only lower than those in the baseline scenario by about one fifth, which explains why the coal chemical industry is considered as a hard-to-abate sector.

In the case where much more stringent climate targets than that of the emissions control scenario are imposed on the Chinese coal chemical industry, both economic viability and growth potential of the industry would become questionable. Not surprisingly, resilience of the Chinese coal chemical industry will ultimately depend on whether an appropriate balance among key criteria of the SECTOR framework could be maintained in an increasingly carbon-constrained world. In particular, disruptive policy adjustments in the areas of climate change, regulatory burden, and other pressing issues (especially air pollution and water availability) possess significant risks to coal chemical development.

In sum, despite its large industrial scale, the Chinese traditional coal chemical industry has long suffered from overcapacity, legacy assets, single product structure, and heavy pollution among other chronic weaknesses, and thus is continuously subject to increasingly stringent and sometimes disruptive energy and environmental regulations. In the above context, the modern coal chemical industry is prioritized by key stakeholders, especially local government and the coal industry, to supplement petrochemical manufacturing and climb up the value chain. Nevertheless, unless the modern coal chemical industry could outperform its petrochemical counterpart in net-zero transition once China enters the era of carbon neutrality goal after 2030, the long-term prospects of the Chinese coal chemical industry as a whole would not necessarily be promising.

5. Policy recommendations

Based on an extensive literature review, conversations with numerous industrial insiders, and several site visits to coal chemical facilities across China since 2019, this paper suggests pathways that could be adopted to better regulate the Chinese coal chemical industry, aiming to trigger interest in follow-up policy discussions as well as more in-depth studies.

Please note that all these recommendations have been prepared by the author in a personal capacity, and do not necessarily reflect the views of the Oxford Institute for Energy Studies or any of its members.

The energy decision-making framework in China should shift from the traditional 3E model to a more sophisticated paradigm.

Since the beginning of the millennium, an increasingly interconnected and digitized energy world has been testing the limitations of the traditional 3E model of energy decision-making. While energy security was once defined as the uninterrupted availability of energy sources at an affordable price, its definition should be broadened into energy system security, which may be defined as reliable, affordable access to increasingly interconnected energy sources for all key energy stakeholders, including energy importing, exporting, and transition countries. To better regulate its coal chemical industry and beyond, China may consider shifting its energy decision-making framework from the traditional 3E model to a more sophisticated paradigm, with appropriate consideration of a list of driving forces such as energy system security, economic development, climate change, technological maturity, regulatory burdens, and other pressing issues (i.e., SECTOR). If so, a more sophisticated paradigm is expected to better reflect an increasingly complicated energy decision-making landscape in China and abroad.

Comprehensive and transparent statistical reporting and accounting throughout the Chinese coal value chain should be established.

Reliable statistical reporting is the basis of sound and sensible decision-making in the energy sector and beyond. Given the potential of substantial greenfield capacity addition of coal chemical facilities across China in the decades to come, reliable statistical reporting and accounting throughout the Chinese coal value chain is a prerequisite for better regulating the industry, as well as for improving understanding of associated social, economic, environmental, and climate consequences. While digitalization of industrial asset data is well under way, access to such data remains a challenge. Overcoming access-related obstacles is key to quality improvement of statistical reporting, with the caveat that digitalization alone is insufficient to eliminate all the embedded systemic weaknesses related to statistical reporting in China.

China should consider adopting a politically feasible but increasingly emissions-constrained approach to actively reduce the carbon footprint of the coal chemical industry.

As the first ever 'hybrid superpower' in the modern era, China's phase-by-phase climate commitment reflects the so-called 'developing country mentality'. In particular, the current generation of Chinese leadership grew up in a much poorer and more backward country compared with today. This helps to explain why China did not commit to peaking national carbon emissions until 2030, giving itself a 10-year buffer. From 2030 onward, as the younger generation of Chinese in possession of a superpower mentality assume leadership positions, China's energy and climate policies are expected to close the gap with those of advanced economies.[72] Similarly to the dual carbon goals, China should consider adopting a politically feasible but phase-by-phase approach to actively lower the carbon footprint of the coal chemical industry, as below.

- In the 14th FYP period, similarly to regulatory restrictions imposed on the iron and steel industry, China should consider permitting greenfield coal chemical capacity through the so-called capacity

[72] Tu (2021).

swap policy, which allows manufacturers to swap greenfield capacity addition in return for closures elsewhere.

- In the 15th FYP period, China should consider only permitting greenfield modern coal chemical facilities with carbon emissions intensity no greater than natural gas-based production routes.
- After 2030, a net-zero roadmap featuring legally binding emissions reduction caps over time should be imposed on the Chinese coal chemical industry in support of achieving the carbon neutrality goal by 2060, ideally as early as 2050.

Renewable hydrogen's role in deep industrial decarbonization should be prioritized, especially in coal chemical, petrochemical, and iron and steel manufacturing.

Given the enormous potential of renewable hydrogen utilization in heavy industries, industrial decarbonization should become the focus of scaling up the renewable hydrogen supply chain in China. Apart from covering selected industrial sectors such as iron and steel into the national ETS, innovative policy and financial policy instruments should be considered in the Chinese context, especially green public procurement, Carbon Contracts for Difference (CCfD), and demand quota for climate-friendly raw materials. Meanwhile, though blue hydrogen's potential to reduce life-cycle CO_2 emissions intensity of coal chemical facilities should not be overlooked, prospects for this transitional decarbonization solution are expected to become much less promising once China enters the era of carbon neutrality, starting from 2030.

The potential of CCUS in lowering life-cycle CO_2 emissions intensity of existing coal chemical facilities should be tapped, but whether sector coupling of renewable hydrogen and CCU could justify permitting of greenfield coal chemical capacity still deserves more in-depth R&D.

As the CO_2 concentration of process emissions of modern coal chemical plants is often above 85 per cent, coal chemical manufacturing is widely regarded as the most preferred industry for piloting CCUS projects in China. As the share of process emissions normally accounts for less than 70 per cent of total emissions of a modern coal chemical plant, assuming a 90 per cent CO_2 capture rate, less than 60 per cent of total emissions in a modern coal chemical facility may be captured with relatively low costs. Even so, the potential of CCUS in lowering life-cycle CO_2 emissions intensity bodes well for China's national carbon emissions peaking goal before 2030, and thus should be tapped by both the Chinese government and the coal chemical industry.

Once high-concentration CO_2 emissions from coal chemical facilities are captured, they may be coupled with renewable hydrogen to produce various types of e-fuels or chemicals. Theoretically speaking, prospects of CCU, sector coupling, or PtX are rather promising, thus offering emissions-intensive coal chemical industry a rare opportunity of redemption. Nevertheless, given all the unresolved technological, economic, environmental, as well as social acceptance-related obstacles, more in-depth R&D should be conducted to thoroughly evaluate whether permitting of greenfield coal chemical facilities could be justified by the above-mentioned technological routes.

Performance evaluation and promotion mechanisms of provincial governors and senior executives of SOEs should be revamped, aiming to incentivize decision-making with longer-term orientations.

China runs the world's largest state asset system. State-owned enterprises are the economic and political bases of the ruling party and the Chinese state. Similarly to high-ranking officials such as provincial governors, senior executives of SOEs are governed by the ruling party's cadre management system, under which senior officials and SOE executives are recruited, evaluated, promoted, trained, and supervised by the ruling party's Organisational Department.[73] Since implementation of the reform and opening-up policies in 1978, the above system has worked well and contributed to China's spectacular economic growth until recently. Due to the limited duration of each political appointment and over-emphasis on economic performance, both provincial governors and senior executives of SEOs have strong incentives to favor large-scale investment delivering short-term political return, without adequate consideration of the longer-term economic, environmental, and climate consequences. Unless serious reform could be initiated by the ruling

[73] Xiankun Jin *et al.* (2022).

party to tackle the above systemic weakness, rising risks of manufacturing over-capacity and stranded climate assets in the Chinese coal chemical industry cannot be easily alleviated.

In cases where a carbon pricing signal needs to be introduced, carbon tax is recommended as the preferred option to price CO_2 emissions in the Chinese coal chemical industry.

Almost one decade after the first pilot ETS launched in Shenzhen city in 2013, the eight pilot regional markets continue to operate in parallel with the national ETS. However, the coverage expansion of national ETS is slow to come. One of the key barriers is that China presently has insufficient greenhouse gas emissions monitoring capacity, and there have been reports of data fraud in reporting and verification. Given the fact that the power industry is widely deemed the easiest sector in terms of data reporting and verification, and considering the complicated manufacturing processes of the coal chemical industry, carbon tax is recommended as a better option than national ETS to price CO_2 emissions in the Chinese coal chemical industry. Above all, carbon tax is much more effective than ETS to motivate government to improve statistical reporting and penalize fraud.

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