ICSC/335 JANUARY 2025

COAL AS A RESOURCE: GASIFICATION AND CHEMICALS

DR IAN REID

50 YEARS | 1975–2025
INTERNATIONAL CENTRE FOR
SUSTAINABLE CARBON

COAL AS A RESOURCE – GASIFICATION AND CHEMICALS

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Technology Collaboration Programme
by IEA

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ICSC REPORT NUMBER **ICSC/335**

ISBN **978–92–9029–658–4**

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PUBLICATION DATE **JANUARY 2025**

Front cover image: Baofeng Ningxia Coal Gasification and Methanol-to-Olefins plant (credit: Mao Ye, Peng Tian, Zhongmin Liu)
Available from: https://www.sciencedirect.com/science/article/pii/S2095809920303660?via%3Dihub#f0005

PREFACE

This report has been produced by the International Centre for Sustainable Carbon (ICSC) and is based on a survey and analysis of published literature and on information gathered in discussions with interested organisations and individuals. Their assistance is gratefully acknowledged. It should be understood that the views expressed in this report are our own and are not necessarily shared by those who supplied the information, nor by our member organisations.

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ABSTRACT

China's fuel and chemicals strategy has focused on maximising the use of its indigenous coal to protect its economy from wide variations in the price of imported oil and gas. Coal-to-chemicals is a relatively new industry that has grown fast and is the largest consumer of coal after power, steel and cement. The study reports on the status of the industry, its technologies and syngas processes. It explains how syngas can be used to make the key products generally obtained from petrochemicals, including hydrogen and ammonia, benefitting from flexibility in syngas composition. The future of the coal gasification industry in China is under pressure due to its poor utilisation of coal carbon and consequent high emissions that are incompatible with national targets.

The use of coal as a feedstock for products has been treated separately from coal power in net zero calculations, but this is no longer tenable as the sector expands. It takes about three tonnes of coal to make one tonne of chemicals. Carbon dioxide (CO_2) emissions from China's coal chemical sector now exceed 1 gigatonne (Gt)/y. Strategies are needed to lower emissions. Increased use of renewable power and carbon capture can improve the sustainability of coal chemicals.

Concern about waste plastic issues is growing, which could be a problem for the entire chemicals industry. If the difficulties of recycling plastics are resolved, demand from China may be reduced.

The closure of blast furnaces for steel production reduces the availability of by-products from coking coal to make coal tar chemicals, which remains a valuable sector. As China has a young fleet of blast furnaces, it will remain a dominant producer of these aromatic products. In the construction sector, decarbonisation of the cement industry is a critical part of greenhouse gas emission reduction strategies. Fly ash, a coal combustion by-product, has a role in construction that may be enhanced in the future, lowering its CO_2 emissions.

Steel, cement and coal gasification to chemicals are the largest non-energy uses for coal, but significant developments are taking place in coal carbon-based products such as pitch carbon fibre, nanocarbons and graphite. There is a notable project developing an abandoned coal mine as a new source of mineral ore, as concern grows over China's domination of rare earth element supply. Viewing coal as a carbon resource rather than a fuel has led to one major new industry, and the availability of new carbon allotropes is expanding coal's use beyond fuel.

ACRONYMS AND ABBREVIATIONS

AEM	anion exchange membrane
BECCS	bioenergy with carbon capture and storage
BF	blast furnace
BOF	basic oxygen furnace
CCS	carbon capture and storage
CCUS	carbon capture, utilisation and storage
CF	carbon fibre
CLCG	chemical looping coal gasification
CLHG	chemical looping hydrogen generation
CPG	coal pyrolysis gasification
DAC	direct air capture
DRI	direct reduced iron
EAF	electric arc furnace
EFC	Earth Friendly Concrete
EOR	enhanced oil recovery
EV	electric vehicle
FJH	Flash Joule Heating
FYP	Five-Year Plan
GGBFS	granulated ground blast furnace slag
MEG	mono ethylene glycol
MTO	methanol-to-olefins
NZE	net zero emissions
NIH	National Institute for Health, USA
PE	polyethylene
PEM	proton exchange membrane
REE	rare earth element
SOEC	solid oxide electrolyser cell
SWCG	supercritical water coal gasification
WTI	West Texas Intermediate crude oil

Note: all monetary values are in United States dollars ($) unless otherwise stated.

UNITS

bbl	barrel
Bt	billion tonne
GPa	gigapascal
Gt	gigatonne
GW	gigawatt
ha	hectare
kt	kilotonne
$MtCO_2$	million tonnes of carbon dioxide
Mt/y	million tonnes per year
%/y	per cent per year
W/m/K	Watts per metre-Kelvin

CHEMICALS

CO	carbon monoxide
CO_2	carbon dioxide
DME	dimethyl ether
H_2	hydrogen

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EXECUTIVE SUMMARY

A new coal chemical industry has emerged in China that combines coal gasification and liquefaction with the production of commodity chemicals for polymers, fibres, fertiliser and fuel. The strategic basis for the industry is to support China's energy and chemicals security by using indigenous resources. Coal-to-chemicals is now a global scale sector and provides China with a degree of protection from crude oil price fluctuation. The main challenge for the future is that coal-to-chemicals is more carbon intense than petrochemicals; it takes more than three tonnes of coal to make one tonne of product. This is a serious issue given China's intention to reach peak CO_2 emissions by 2030. This target appears at risk as coal-to-chemicals has added substantially to the emissions already produced from cement and steel manufacture and an enhanced coal power sector.

COAL GASIFICATION, CO_2 EMISSIONS AND DECARBONISATION

The coal gasification industry has successfully produced chemicals and polymers of comparable quality to the petrochemicals industry which remains dominant in China. Using methanol-to-olefins technology for polymer manufacture, the raw syngas product from coal gasification possesses a low H_2/CO ratio, and so the carbon monoxide is reacted with water to form hydrogen and CO_2. For polymers, this means less than one third of the original coal carbon is present in products, with the rest emitted as CO_2. For fertiliser production, involving the conversion of coal to hydrogen and ammonia, much less coal carbon is present in the final urea product. Collectively emissions from coal gasification in China exceed 1.1 $GtCO_2/y$, approaching half that emitted by China's steel and cement sectors.

Carbon capture: Coal gasification plants offer a technically advantaged, lower-cost route to carbon capture and storage (CCS) as a highly concentrated CO_2 stream is obtained prior to methanol production; this is simpler to process than the relatively dilute streams from power, cement and steel reactors. The location of coal gasification plants appears promising for permanent geological sequestration, avoiding construction of excessive infrastructure. Demonstration units are in operation, some assigned to coal-to-chemicals; the overall intent across industry is to remove up to 500 $MtCO_2/y$, ten times the current global capacity of CCS.

Hydrogen: China's renewable energy capacity is developing rapidly, and the cost of solar power is still falling, which supports the deployment of water electrolysis for hydrogen production based on renewable electricity. This raises the prospect of combining coal gasification with electrolytic hydrogen to change syngas composition, providing several benefits. As hydrogen is added, less carbon monoxide and water need to be converted to CO_2 and hydrogen, increasing the proportion of coal carbon incorporated into products. Less coal would be needed per unit of product, lowering handling costs. Ultimately three gasification reactors could be replaced by one. Currently, most of China's

hydrogen is obtained from coal and hydrogen is the highest emission product from the industry, so a switch to electrolytic hydrogen is a major industrial event. Hydrogen production using renewable electricity is intermittent, and all manufacturing units would operate beneficially with a constant supply, perhaps solvable by local hydrogen storage. The cost of electrolysis must approach that of coal-to-hydrogen which appears to be increasingly realistic. This hybrid production method would make coal a valuable resource for chemicals with a reduced impact on the climate.

PLASTIC WASTE

The carbon intensity of the industry is one challenge. Plastic waste pollution is another. It is already a highly visible problem, which is worsening with low recycling rates. This is an issue for coal and for petrochemicals, as the dominant producer of plastics. Coal-to-polymers production is unique to China and currently forms less than 20% of polymer production in the country. However, China is expected to produce half of all polymers by 2050. The issue with recycling is that it always means downgrading plastic as the huge range of additives means that fresh plastic cannot be produced. New research may change this in the future, as a low-temperature catalytic process can revert plastic back to a monomer composition making the production of fresh polymers a possibility. The regenerations of plastic is at an early phase of development. If it makes good progress, it could pose an issue for China's chemical industry.

Plastics are durable with lifetimes of centuries in the environment, but are subject to mechanical breakdown forming small particles, termed micro or nanoplastics. These particles are pervasive in the environment, in water supplies, in plants, and in all animals. The health impacts of plastic are unclear, but there are indications that plastics accelerate cardiovascular conditions. The recent finding of plastic in the brain, overcoming the blood-brain barrier, has raised concern leading to calls for extensive research on this subject. Plastics have become central to modern life, and the polymer market is set to increase by up to 50% by 2050, with more than half used in single-use packaging. The use of plastic is likely to come under increasing scrutiny, because of the waste created and the implications of the disquieting health indicators for investors, companies and governments.

RARE EARTH ELEMENTS AND GRAPHITIC CARBONS

Rare earth elements (REEs) are essential to an array of technologies utilising electric motors and batteries. The IEA predicts that demand will rise 7-fold in coming decades as the world transitions from fossil fuels. The issue for OECD countries is that resources are dominated by China. There is an urgency to develop new resources and build independent refining capacity. The connection to coal is the focus of the ICSC. The emphasis has been on extracting REEs from coal wastes and combustion residues, but the discovery of REEs at the Brook coal mine, Wyoming, USA may be groundbreaking. REE concentration is lower than for conventional ores, but they are present in a more easily extractable form. The original intent prior to discovery of REE was to produce carbon products at the

minehead, shipping products rather than raw materials. Coal for graphitic compounds has the potential to lower materials costs but the impurities in coal can make that challenging. New approaches combine coal and petrochemical products to achieve suitable properties, for example, mixing pitch and polyacrylonitrile (PAN) carbon fibres to offer strength of PAN and high electrical conductivity of pitch for new applications in energy and carbon storage. Carbon as a resource is still developing but has widespread market potential, especially for inclusion in high-tonnage production.

PROSPECTS

The coal gasification industry in China is at a global scale with the strategic aim achieved for China to possess an alternative source of chemicals using its indigenous feedstock. However, the industry is carbon intensive; expansion is in progress but the momentum has lessened. If future IEA predictions on oil prices are correct, then the economics for coal products will be challenged more by petrochemicals. Gasification is technically advantaged for carbon capture and the industry has the potential to use renewable generation to transform carbon intensity, potentially rivalling petrochemicals. Environmental performance and economics are likely to be more critical factors to future projects than feedstock security.

1 INTRODUCTION

Historically, coal gasification was associated with the production of town gas that once dominated the cooking, heating and lighting of homes, but was subsequently supplanted by natural gas and electric power. Coal was converted to transport fuels in World War II and later in South Africa at a modest scale. More recently, a new global-scale industry has emerged combining coal gasification with the production of commodity chemicals for polymers and fibres. This is part of China's strategy to enhance energy and feedstock security, to provide an indigenous feedstock to supply its chemical industry; and to be independent of imports of oil and gas from the USA and Middle East. The industry has grown rapidly since 2018 and China has a significant market share. The question is what is the future for this large carbon-intensive industry that does not fit well with climate change mitigation targets?

Coal in China, 2024

Transformational changes taking place in the energy sector are set to have a profound impact on coal markets, amid trends in the Global North to move away from fossil fuels. In its Annual Energy Outlook 2024, bp identifies coal as the most significant barrier to moving from the current state of 'energy addition' to an 'energy substitution' scenario where renewable energy replaces fossil fuels to realise climate change mitigation targets (Dale, 2024). Targets to lower greenhouse gas emissions by 43% before 2030 require profound changes to global coal use including coal-to-products (United Nations Climate Change, 2020). Despite successive statements that coal consumption is peaking, expansion of coal use in China, the predominant user, means global coal consumption is expected to reach 8.77 Gt in 2024, a record (IEA, 2024c). Even as coal power stations close across Europe and North America, new plants become operational in China to address energy security concerns (IEA, 2023a). During 2023, China produced a record 4.7 Gt of coal with over 1 Gt of new coal mining capacity in development. However, while China has increased coal use, a rapid expansion of renewable generation is underway outpacing other countries and beginning to take a significant and preferential share of energy markets. Plans for new coal stations are slowing after an intense period when two new coal stations were built a week (Nace, 2023). Given China's intentions to achieve net zero emissions (NZE) by 2060, the country will need to reassess its large-scale coal chemicals industry.

Status of coal gasification

Globally, electricity generation remains the dominant use of coal at 5.5 Gt/y. Heavy industry, including steel and cement, are also large consumers of coal, using around 2.5 Gt/y. The coal gasification industry, primarily located in China, now consumes over 400 Mt/y of coal (2023), making it a significant coal market. In coal gasification only a fraction of this coal carbon is incorporated into products; most is emitted as carbon dioxide (CO_2), making it a carbon emission-intensive sector.

Production of polyethylene and polypropylene by coal gasification initially appeared economically unattractive but sustained high oil prices since 2018 have underpinned this new industry to establish

a significant share of the polymers market. During 2024, production from coal gasification increased by 20% indicating lower utilisation in 2023 when coal was assigned for power. Thus, it is currently a profitable industry that competes with petrochemicals, while the oil price is above 70 $/bbl (barrel) (Myllyvirta, 2024).

Coal gasification and CO_2 emissions

The high-emission industrial coal sectors are coming under intense scrutiny as nations struggle to meet their Nationally Defined Contributions (NDCs) to lower emissions under the 2015 Paris Agreement. Industry estimates for coal gasification chemicals put emissions at close to 1.1 Gt/y, set to rise a further 20% by 2030 (Guo and others, 2023). A portion of the original coal carbon remains present in final products, ranging from 30% to 40% for methanol and polymers such as polyethylene and polypropylene, to 0% for hydrogen or ammonia. Europe has embarked on industrial decarbonisation to produce low emission products, and, although delayed, there is still intent to impose carbon footprint levies on imported steel, fertiliser, cement and chemicals (Pollard, 2024). China's coal chemical industry is addressing CO_2 emissions urgently through the implementation of new technology options that include carbon capture and non-fossil supplementary feedstock.

China's energy transition

President Xi has pledged that China will reach peak CO_2 emissions by 2030 and achieve NZE by 2060. This will require both using less coal and more renewable energy, a pledge that appears inconsistent with China's coal power programme to 2023 but may be supported by more recent data indicating a decline in coal station permitting (Qin and Shearer, 2024). It is also relevant to coal gasification chemicals, as although less carbon-intense than other heavy industries where all carbon is consumed, coal chemicals are now a global-scale emitter of CO_2. In seeking reduction of CO_2 emissions nationally, the coal chemicals industry is vulnerable as it is more carbon intense than petrochemicals, although it has the advantage of using a low cost, indigenous feedstock.

This study sets out the status of the coal gasification industry and explores options for retrofit to lower emissions by adding carbon capture or modifying the feedstock (Eriksen, 2024).

Basic oxygen furnace steel and tar chemicals

Globally, the steel industry uses over 1 Gt/y of coal; for every tonne of steel, blast furnaces need 0.75 t of metallurgical coal, with additional thermal coal. The preparation of coal for steel in coking plants yields coal tar, which is used as feedstock for the production of a suite of valued chemicals. As the steel industry is a large emitter of CO_2, there is a switch from basic oxygen furnace (BOF) plants to electric arc furnaces (EAF) in OECD countries, but China's BOF fleet averages only 15 years old. Carbon capture is a potential long-term option to keep blast furnace fleets operational but at a significant additional cost. The age of China's BOF fleet means it is unlikely to shut down units, adding CCS would

increase costs and that would have an impact on the strategic position of the steel industry as China seeks to reduce its emission impact (Kelsall, 2023).

Cement and coal by-products

The other chief industrial source of CO_2 emissions from coal is the manufacture of cement. Partially replacing Portland cement with fly ash obtained from coal power plants can lower emissions associated with concrete (Reid and others, 2020). Ash addition has long been practiced at low substitution rates, and China, as the largest producer of fly ash, is a leader in this field with key projects utilising high levels of fly ash in cement mixtures. The benefits of fly ash substitution are lower costs and CO_2 emissions while improving the bonding properties and moisture resistance of the cement. The other approach to reduce the carbon intensity of cement production is to deploy carbon capture technology, already underway in the USA. Unlike substituting Portland cement with fly ash, this adds to product cost; estimates indicate that adding carbon capture and storage (CCS) in the USA or Europe to cement production could increase costs by over 60% (Subraveti and others, 2023; Davila and Aagesen, 2024). As the construction industry in China is currently in recession, there may be a default reduction in national emissions from this sector.

Graphitic carbon and critical elements

Although gasification of coal for chemicals is the largest non-energy use of coal, but there are significant developments in graphitic carbons and in mineral extraction from coal seams, where mining coal is secondary. Progress in these topics is briefly described, especially developments in coal as a source of rare earth elements (REEs). REEs are key to the energy transition and the development of high-tech industry and their production and supply is largely controlled by China.

Report structure

The study focuses on coal gasification technology, technical developments and its major industrial markets. The industry's products of chemicals, plastics and fuels face a complex suite of challenges that include carbon emissions intensity and pollution. Potential solutions are discussed ranging from CCS to electrolytic hydrogen. For carbon intensity amelioration the sector competes with power, steel and cement. Coal gasification is the new global scale industry but the use of coal carbon as a resource is progressing in other sectors such as coal mines to minerals and graphitic carbon products.

2 OVERVIEW OF THE COAL GASIFICATION INDUSTRY

This chapter introduces coal gasification in China and some of the related environmental issues.

2.1 COAL GASIFICATION IN CHINA

The aim in China is to lower the energy-related global share of CO_2 emissions from one-third in 2023 to one-fifth by 2025; President Xi has stated that China's energy transition policy will be fully published in 2026 at the commencement of the next Five-Year plan (FYP). As the world's largest coal user, the implications of this policy are massive. In the longer term, emissions will have to fall by 70% to meet commitments; emissions from coal in China would need to fall from 8 $GtCO_2/y$ in 2022 to 1.8 $GtCO_2/y$ by 2050 (Eriksen, 2024). Whether this can be achieved is debatable, but China has acted swiftly in the past to create new steel, construction and chemicals industries, and currently, the intention is largely to deploy renewable energy and remove poorly performing plants to achieve these goals.

China's drive to electrification and renewable energy supports the aim of energy independence. A thriving coal-to-chemicals sector is part of that strategy as it uses domestic feedstock rather than imports. However, the contribution from the coal chemicals sector is already substantial, and provides a degree of feedstock security, weakening the argument to further increase coal chemicals. Coal chemicals dominate some products such as methanol, but a petrochemicals sector using imported oil remains the chief source of chemicals feedstock for the most profitable sector of polymers (Eriksen, 2024).

Coal gasification has become a key producer of methanol, ammonia and hydrogen. China is the sole nation producing hydrogen from coal which accounted for 22% of the global hydrogen supply in 2022, and 66% of China's hydrogen production. Coal is the feedstock for 52% of ammonia production and 80% of methanol. China produced 104 Mt of methanol in 2023, of which 79 Mt were obtained through coal gasification, with coal-to-methanol growing at more than 6%/y during the five years from 2018 (CCF Group, 2023). China recognises that this industry is carbon intensive and while coal gasification fits the strategy for using indigenous coal feedstock, it is currently incompatible with CO_2 emission reduction targets. Along with steel and cement, China's coal-to-chemicals is facing a substantial challenge to contribute to lower national emissions, and coal-to-hydrogen is the most carbon-intensive activity in the sector.

The '*Action Plan for Energy Conservation and Carbon during 2024/25*' sets out requirements for Chinese industries to reduce emissions. New build energy and chemical projects must reach an 'A level performance, with underperforming plants to close'. A switch to advanced gasification technology and

adoption of ion membrane electrolyser technology for hydrogen are among the measures supported, with 'renewable energy to form hydrogen, replacing coal-to-hydrogen'. The first aim is to reduce emissions from the combined energy and chemicals sector by 100 $MtCO_2/y$. Given that 47 GW of new coal power capacity was added during 2023 to meet concerns over energy security, it seems that coal-to-chemicals is the sector most vulnerable to demand for reduced emissions (Hu and Liu, 2024; Climate Cooperation China, 2024; Huld, 2024). This heralds changes to the existing coal chemicals gasification industry, involving the development of existing sites to reduce emissions and more stringent project criteria for new facilities that will inevitably impact their economic competitiveness with petrochemicals. It will also make development of new coal-to-chemicals plants more unlikely, although coal-to-oil and coal-to-gas are still supported, including a substantial $24 billion investment in coal-to-oil in Xinjiang, to produce 4 Mt/y of oil using coal gasification for hydrogenation (Rogers, 2024).

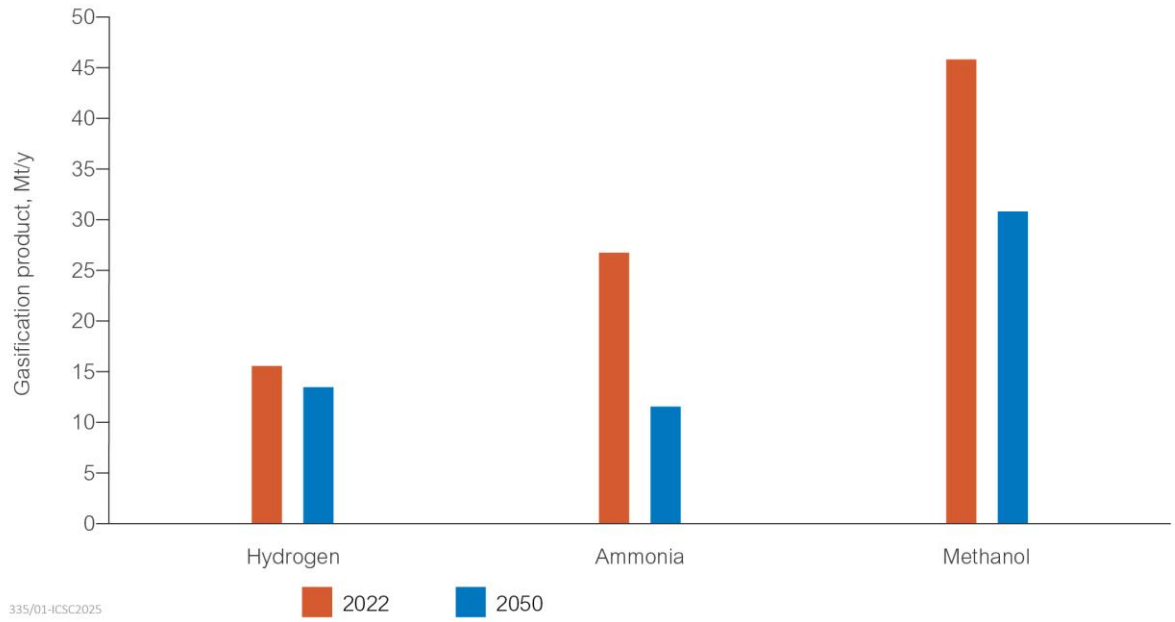

Figure 1 A scenario for coal gasification to fit with China's coal and emission reduction targets for 2050 (Eriksen, 2024)

Figure 1 depicts the change in production from coal gasification that will be needed to match China's ambition to lower emissions from coal. For hydrogen, the share of production from gasification would have to fall from the current levels of 66% towards 30%, with half the remaining production mitigated by CCS. Similarly for ammonia, a derivative of hydrogen, a reduction of 52% of market share to 25%, and for methanol, the key gasification intermediate, 80% of the nation's output down to 60% with at least a third of that mitigated by CCS. CCUS is included in China's national FYP (2021-2025) and in the '*Action Plan for Carbon Dioxide Peaking before 2030*' issued by the Chinese government (Zhang and others, 2023).

However, in 2024 new coal-to-hydrogen production came on stream and gasification increased its share of production of these key chemicals. DNV's Energy Transition Outlook China 2024 predicts an initial rise in China's coal consumption to 2026, before beginning to fall by one-third by 2040, towards a quarter of peak coal use by 2050 with coal-to-chemicals much reduced over that period (Eriksen, 2024). However, China commenced construction of 37 GW of new coal power generation in 2023, with a further 41 GW announced, and an additional 8 GW of shelved products restarted. Thus, China's coal power capacity may increase by 33% if all plants are permitted and constructed (Qin and Shearer, 2024). For chemicals, demand is expected to increase by up to 50% by 2050 making the closure of coal chemical units unattractive. Most of the coal chemical industry was commissioned within the last five years, so two-thirds of these units would need to close early in their service life. There are opposing forces at play for gasification, perhaps compounded by new plants coming into service during 2023/24. A significant question will be the degree of implementation of CCS, the impact of renewable energy and the application of an alternative hydrogen source to allow the existing industry to mitigate carbon intensity concerns.

2.2 CARBON DIOXIDE, NET ZERO AND COAL-TO-CHEMICALS

Over the last decade, the political pressure to reduce fossil fuel consumption and especially coal has intensified, with bp Energy Outlook describing the need to 'crowd out coal' (Dale, 2024). Coal possesses the lowest hydrogen/carbon (H/C) ratio of hydrocarbon fuels, making coal the prime target to reduce CO_2, emissions, followed by oil and natural gas. The current strategy to lower CO_2 emissions by introducing renewable energy has not yet been effective as renewable capacity has been added to energy production rather than substituting for fossil fuels, even as China heads towards 40% renewable energy generation (Dale, 2024). The overall strategy is to first lower coal use, followed by reductions in oil for transport and finally natural gas, transformative energy efficiency in new and existing buildings, enhanced wind and solar and deployment of CCS.

In bp Energy Outlook 24 (Dale, 2024), scenarios are established based on current fossil fuel use and those needed to meet NZE, where CO_2 emissions are balanced by the amount that is removed from the atmosphere and are compatible with IPCC scenarios consistent with the Paris Agreement, depicted in Figure 2.

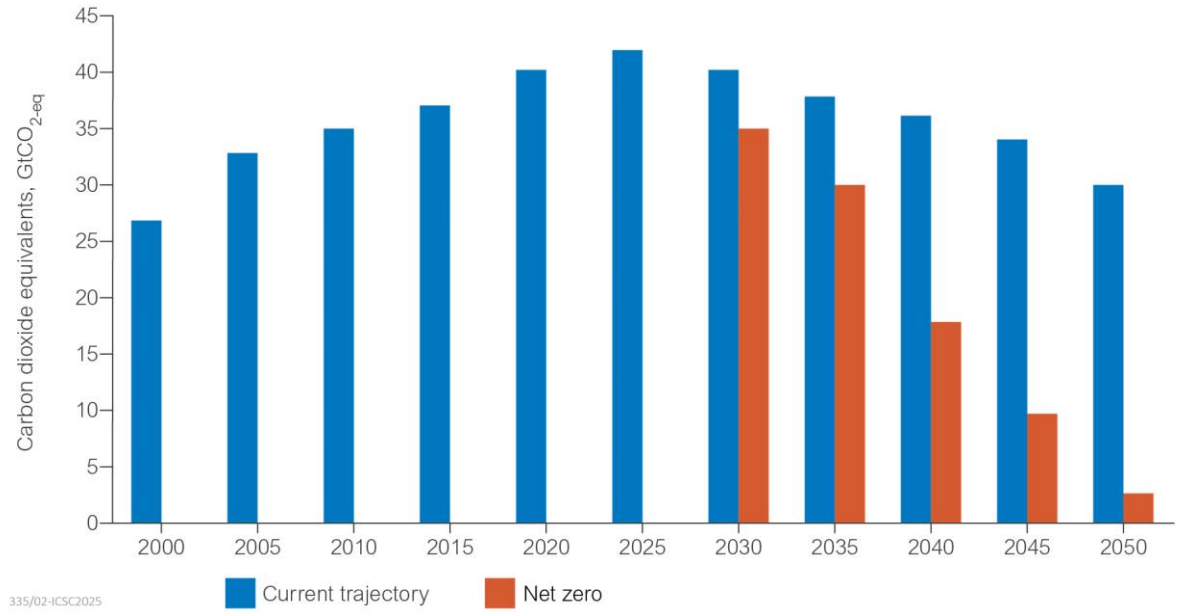

Figure 2 bp Energy Outlook scenarios to explore trends in CO_2 emissions: current trajectory versus net zero by 2050 (adapted from Dale, 2024)

Current global trends are rising CO_2 emissions, with China and India dominating coal use. Reductions in the use of coal in OECD countries are more than offset by an increase in the use of coal for power in Asia, and, emissions from key industries led by steel, cement and now coal chemicals.

The focus of this study is on coal chemicals, which have grown from just a few plants in 2018 to become a major producer of chemicals encompassing 400 chemical processors by 2023 (Asiachem, 2019). Due to the need to shift syngas to higher hydrogen content, coal chemicals are now a major emitter at over 1.1 $GtCO_2/y$. China is the dominant user of coal and according to the IEA (2024) has increased coal consumption by 200% since 2000 with emissions exceeding 8 $GtCO_2/y$.

The NZE scenario is only possible if China dramatically reduces its reliance on coal or implements mitigation measures, with implications for the existing coal-to-chemicals industry. Steel and cement are already under pressure to find ways to reduce emissions by using EAFs, fly ash and CCS. The difference is that while alternative processing options for iron ore and concrete are awkward, for chemicals, they are already produced from oil and gas with lower emissions.

2.3 PLASTICS

The prime products from the coal chemicals industry are fibres and polymers and in recent years plastic pollution has become a greater concern. The current focus is on the interaction between microplastics and human health.

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Figure 3 a) Polluted beach at the Red Sea, Egypt (Wikipedia: Vberger), b) recycled bottles for shipping (Wikipedia: Bin52)

Plastic washing up on the beach is a familiar sight (*see* Figure 3). The Great Pacific Garbage Patch (Pacific Trash Vortex) present over two locations is collectively about twice the size of Texas, USA, mostly comprising plastic marine debris (National Geographic, 2024). The picture on the right is from a plastic recycling bale; on average about 9% of plastic is recycled and 12% incinerated. The rest goes to landfill or adds to general pollution.

Many countries no longer accept plastic waste for recycling, The main issue with recycling is the large number of compounds that are added to the basic polyethylene and polypropylene which make it awkward to simply melt and remould materials. These include plasticisers, dyes, antioxidants, lubricants, antistatics, flame retardants and light absorbers. In almost every case, plastic is downgraded to more basic products for recycling as the original properties cannot be maintained. This makes the adoption of a circular economy for polymers difficult to achieve, although it is seen as an essential next phase for the chemical industry (European Environment Agency, 2024).

A major concern is the mechanical degradation of plastic to micro or nanoplastics. These tiny particles pose significant risks as they are taken up by plants and animals, entering the food chain. Recent research has detected plastics in all human organs and within the brain, placenta tissue and breastmilk (Liu and others, 2023). Penetration of the blood-brain barrier is considered especially concerning and may be associated with respiration issues. Research is at a preliminary stage, but lines of investigation on the health impact of plastic particulates now encompass:

- oxidative stress;
- inflammation;
- impaired immune function;
- alteration in cellular and energy metabolism;
- inhibition in cell proliferation;
- tissue degeneration;
- abnormal organ development and dysfunction;
- alteration in biochemical parameters; and
- genotoxicity and carcinogenicity.

The overall view of the medical community is that plastic particles are potentially harmful to human organ systems. Initial research focused on polystyrene and has been extended to other plastics (Ali and others, 2024). Research is at an early stage and many questions remain, but the presence of plastics in all organs is confirmed; whether they are at harmful levels needs further study. A call for research submissions into nanoplastics and health has been issued by the US National Institute for Health (Stetler, 2024). The environment is already loaded with plastic and industrial production of a range of materials is increasing, which has become an essential feature of life in he 21st century. Meanwhile, evidence is building that these particles are harmful, and this may pose a risk to investors, companies and the wider chemicals industry, not just coal-to-chemicals.

2.4 COMMENTS

The expansion of coal power since 2022 has undermined China's credibility in addressing climate change but there are indications that the use of coal may begin to fall. Initiatives to reduce pollution in cities are working, partly due to the closure of urban power plants and a shift to electric transport. China leads on introducing renewable energy and another expansion phase for nuclear is likely in the next FYP. The intention to reduce CO_2 emissions is in China's future strategy which has implications for coal-to-chemicals. Although it is a new industry, it may be more vulnerable than other heavy industrial sectors seeking to reduce CO_2 emissions. Further expansion of the coal-to-chemicals industry may be difficult in the face of stringent climate change mitigation targets. The chemicals industry, including coal and oil, contributes to pollution, with increasing concern over plastic waste. Cumulatively these are strong headwinds for an industry that is only a few years old.

3 COAL CHEMICALS: TRADITIONAL AND MODERN

Petrochemicals derived from oil and gas remain the dominant source of commodity chemicals and polymers in China, but a decade ago this was perceived as high risk as almost all feedstock was imported. Thus, a new coal-based sector was created to support China's booming plastic and fibre industry. The new coal chemical industry produces substitute natural gas, liquid hydrocarbon fuel, ammonia, polymers and aromatics (*see* Figure 4). The feedstock for this industry is thermal coal as opposed to the traditional coal chemical industry which is based on processing metallurgical. The modern coal chemicals plant uses oxidative gasification of coal forming synthesis gas (syngas) and subsequently, a methanol intermediate to make polymer precursors and other chemicals. At the heart of the process is methanol-to-olefins technology (MTO). The modern coal-to-chemicals industry comprised only a few plants before 2018 but has expanded rapidly over just five years and in 2024 consumed 400 Mt/y of coal, making it a significant user of coal in China. Often the coal is of lower quality and cost than that used by power plants, reducing feed costs, with the technology adapted to handle coal with a higher ash content.

Traditional coal chemicals use coke oven gas to make ammonia and convert a coal tar by-product into chemicals, with the main product, coke, used in steel manufacture. The manufacture of coke remains the dominant pathway for 'coal-to-products' with traditional coal chemical products obtained as a by-product outlined in Figure 4; for more information on traditional coal chemicals which provide a wide range of familiar products from nylon to baking powder, medicated shampoo to ammonia *see* earlier ICSC reports (Reid 2018, 2021).

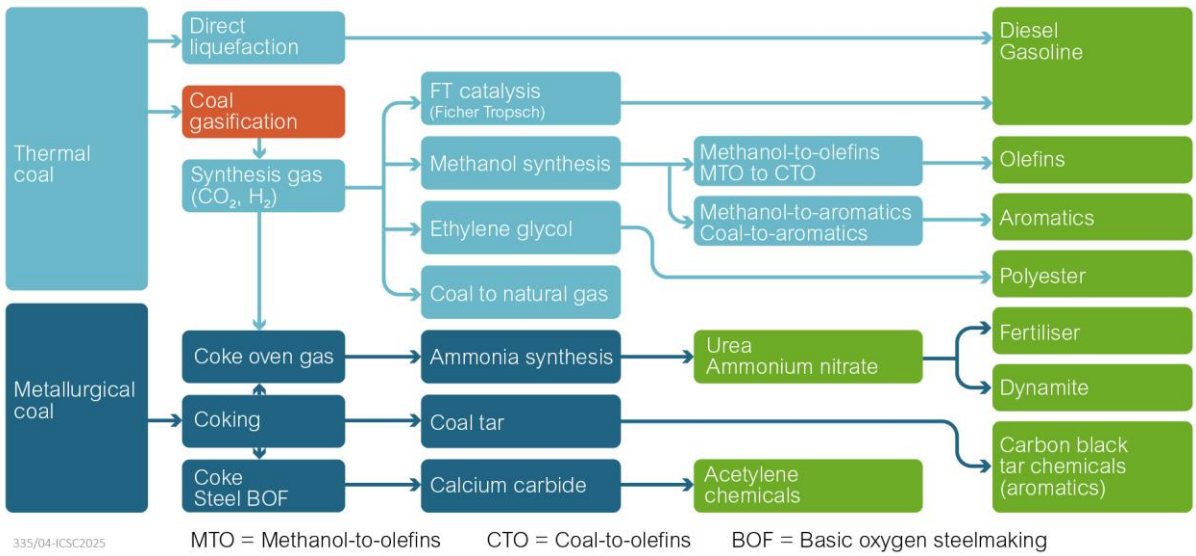

Figure 4 Coal-to-chemicals processes: modern and traditional coal-chemical industry (adapted from Tu, 2024)

Referring to Figure 4, gasification yields a syngas initially rich in carbon monoxide due to the lack of hydrogen in coal, this is adjusted using water-gas-shift chemistry making hydrogen and CO_2 which is mostly discarded. The syngas can simply be a hydrogen source, often exported to refineries for hydrogenation processes, used for direct coal liquefaction or converted to ammonia for urea manufacture for fertiliser production. It is the production of methanol as an intermediate for dimethyl ether (DME), ethylene and propylene that is the most significant technology and leads to the profitable sector of polymer manufacture (IEA, 2023). In Figure 4 the olefins product would then be polymerised into a range of plastics including high, low and linear density polyethylene and polypropylene. Ethylene is used for many chemicals, but polyethylene's (PE) main use is packaging (60%) while monoethylene glycol (MEG) is used as antifreeze and as a precursor for polyester fibre manufacture.

The industry is approaching the end of a period of high growth. Initially reliant on Western technology for coal gasification and MTO, the development of the industry is supported by research in China that has resolved operational problems and issues of product quality. Coal now has a significant share of China's chemicals industry, especially in methanol at 80%, which can be processed to support a complete range of chemicals. The industry competes directly with petrochemicals from oil and gas feedstocks and encompasses over four hundred gasification and derivatives facilities.

The development of polyethylene and polypropylene in coal chemicals has followed parallel pathways so consideration of polyethylene can give a view on the prospects of coal-to-plastics today.

China is a major and growing manufacturer of polyethylene but not dominant, as there are major production sites in North America and the Middle East which benefit from low-cost gas feedstock. Globally, ethylene production was 228 Mt in 2023, of which 40 Mt was produced in China and of that, 8 Mt was derived from coal. The plan in China is for ethylene production to exceed 73 Mt by 2025 as more plants come on stream with production rising faster than elsewhere. Of these new plants, only a fraction of the ethylene will be produced using coal gasification technology (*see* Table 1).

The coal industry makes a significant contribution to other products including polyvinylchloride (PVC) and hydrogen. However, coal chemicals remain a minority sector; the majority of polymers are still produced using naphtha cracking technology and rely on oil imports and refining, as is the case for many European plants.

TABLE 1 NEW WORLDWIDE POLYETHYLENE PLANT CAPACITY ANNOUNCED FOR 2023 (ICIS, 2023)

Country	Site	Company	Capacity t/y	Date
Canada	Longview	Flint Hill Resources	50,000	Q2, 2023
USA	Baytown, Texas	Exxon Mobil	400,000	Q1, 2023
USA	Cartagena	Essentia	50,000	Q1, 2023
USA	Police	Grupa Azoty Polyolefins	437,000	Q1, 2023
USA	Bratislava	Slovnaft Petrochemicals	45,000	Q3, 2023
USA	Dongguan, Guangdong	Dongguan Grand Resource Science & Technology	300,000	Q1 2023
China	Dongguan Guangdong	Dongguan Grand Resource Science & Technology	300,000	Q1 2023
China	Taixing, Jiangsu	Jiangsu Yanchang China Gas	300,000	Q1, 2023
China	Ningbo, Zhejiang	Ningbo Kingfa Advanced Materials	400,000	Q4,2023
China	Ningdong, Ningxia	Ningxia Baofeng Energy Group	300,000	Q4, 2023
China	Maoming, Guangdong	Oriental Energy Resources	400,000	Q1, 2023
China	Xining, Qinghai	Qinghai Damei Coal Industry	400,000	Q3, 2023
China	Binzhou, Shandong	Shandong Chambroad Sinopoly New Materials	200,000	Q1 2023
China	Shouguang, Shandong	Shandong Shouguang Luqing Petrochemical	350,000	Q1 2023
China	Weifang, Shandong	Sinochem Hongrun Petrochemical	450,000	Q1 2023
China	Yangpu, Hainan	Sinopec Hainan Petrochemical	200,000	Q1, 2023
China	Yangpu, Hainan	Sinopec Hainan Petrochemical	250,000	Q1, 2023
India	Anqing, Anhui	Sinopec Anqing Petrochemical	300,000	Q4, 2023
India	Rasayani, Maharashtra	Bharat Petroleum	450,000	Q2, 2023
India	Pachpadra-Barmer, Rajasthan	HPLC Rajasthan	490,000	Q2, 2023
Malaysia	Barauni	Indian Oil Corporation	200,000	Q3, 2023
Philippines	Map Ta Phut	HMC Polymers	250,000	Q1 2023
Philippines	Long Son	Long Son Petrochemicals	400,000	Q1 2023

Table 1 lists the new polyethylene plants announced in 2023 and covers gas-fed reactors using ethane and propane, naphtha crackers and coal gasification. Of the 23 new plants listed, 11 are in China and of those, two are coal-based: Ningxia Baofeng Energy Group and Qinghai Damei Coal Industry.

The current 13 coal-to-olefin (CTO) manufacturing sites are shown on the map (*see* Figure 5). These are sites where methanol is used directly as an intermediate. There are an additional 19 MTO manufacturing sites mostly located in southeastern China and concentrated in Shandong province. Most methanol in China is derived from coal gasification and transferred to manufacturing sites in Eastern China. The new polyethylene plants will join the existing facilities shown on the map in western (A) and northern China (B).

Figure 5 China provinces, showing the location of 13 CTO sites across northern China as of 2024, associated with 19 MTO facilities; Ningxia Baofeng marked as A and Qinghai as B (extracted from Asiachem, 2024)

Thus from 2023, there will be a total of 700,000 t new polyethylene capacity that will be coal derived, out of a total of 4.1 Mt in China, and 5.9 Mt worldwide, with the prospect for more polyethylene production in coming years. Table 1 shows that China dominates the expansion in polyethylene production, but the share of the coal gasification industry in new plants will be only 17%. This is still a significant rise in production for the coal-to-chemicals sector, but a reduction compared to the current 20% capacity share, indicating a shift in China's drive to establish a coal gasification industry. Most new polyethylene projects are in coastal sites including Guangdong, Shandong and Zhejiang, aligned with oil import terminals, whereas new coal-based units are located in the interior in Qinghai and

Ningxia to exploit domestic coal resources where local governments are invested in the technology (Figure 5).

Coal gasification is a significant minority source of polyethylene, expected to approach 13 Mt/y by 2025 if all planned projects become operational. Similar to Europe, China remains largely dependent on oil imports for its naphtha to ethylene production. Coal retains the advantage of an indigenous feedstock for China over imported oil and gas fitting with the desire for a domestic feedstock supply, and yet the dominant chemicals expansion will be based on petrochemicals rather than coal. This may reflect that, despite relatively high oil prices exceeding 70 $/bbl, the economic benefit from using coal is marginal compared to petrochemicals (Xiang and others, 2023).

3.1 POLYETHYLENE MARKETS AND GASIFICATION

The new polyethylene plants announced for 2023 are expected to create a temporarily oversupplied market, dampening global demand for polymers and depressing prices in early 2024. Polymer prices are near their lowest in five years, for instance, polypropylene was under 1120 $/t (November 2024) compared to a peak of 1200 $/t and polyethylene is higher at 1190 $/t (Trading Economics, 2024). The majority of new capacity is in Asia, with two Chinese plants using coal gasification (ICIS, 2023). Asian polyethylene capacity reached 62 Mt/y in 2023, with the majority of plants in China, others include Vietnam Long Son Petrochemicals complex and Malaysia's PREFChem (*see* Table 1).

Major producers including Dow Chemical have an advantage in feedstock position; for North America and the Middle East low-cost shale oil supplies of ethane and liquid petroleum gas (LPG) underpin competitive industries. The North American shale gas feedstock has led to US self-sufficiency in both oil and gas giving a competitive advantage with new 0.4 Mt polyethylene plants at Exxon's Baton Rouge, and a further 3.5 Mt in the pipeline.

In Europe, the situation is less robust. Polymer feedstock is dominated by naphtha imports, although Ineos has created a virtual (8-ship) pipeline to use USA shale gas liquefied ethane. Overall, Europe is experiencing intense competition in both polyethylene and polypropylene which worsened in early 2023 with lower Asian prices; there are no plans for new plants. There is an expectation that plant operating rates will fall and there will be a rationalisation of ageing facilities. Capacity expansion in Asia and North America is expected to put European plants under more pressure as imports head to Europe at a time when the EU seeks industry to invest in sustainable production to make more environmentally benign products protected by tariffs (ICIS, 2023).

Of particular concern in Europe is that, whereas in 2019 feedstock dominated variable costs, it has changed to near parity with energy charges for European producers. The conflict in Ukraine led to both energy shocks and supply issues in Europe, as Russian gas supplies were terminated, and even chemical products and metallurgical coal feedstocks were consumed to provide power at one stage (Williams, 2023).

Polypropylene is experiencing similar circumstances to polyethylene. Twenty-three new plants were announced for 2023, 13 of which are in China amounting to 4.4 Mt of new production capacity, a further 1.8 Mt in Asia and 0.5 Mt in North America means an almost 7 Mt increase overall. Thus, new production of polypropylene is dominated by Asia, with most new facilities in China including a small proportion based on coal gasification as for polyethylene (ICIS, 2023).

3.2 COAL VERSUS OIL AND GAS

The main logic behind a coal-to-chemicals industry is for feedstock security, but in addition, there is the potential to gain economic advantage during periods of high oil prices. Political events including the energy crisis of 2022 increased the price of oil relative to coal; oil prices in June 2024 were 82 $/bbl or 590 $/t compared with 110 $/t for export quality thermal coal. The coal gasification industry generally consumes lower quality, cheaper domestic coal supplies with imported coal delivered to power plants (Oilprice, 2024; Markets Insider, 2024).

The 2024 oil price is double that which prevailed during the initial rapid expansion of the industry in 2018 suggesting improving profitability for coal chemicals. The lower feedstock price coupled with state subsidies that exceeded $2 billion per year to the coal sector in 2019 counterbalanced more complex manufacturing and a high coal feed/product ratio (Li and Li, 2019). A coal-based chemical industry complied with a directive to reduce reliance on imported feedstock where China was at an economic disadvantage to the USA and the Middle East (Energy Institute, 2024).

In considering alternative feedstocks, domestic coal provides the lowest cost per tonne, but more feedstock is needed for every tonne of product. Figure 6 has the relative costs for feedstocks on a per tonne basis:

- USA ethane prices are similar to natural gas Henry Hub charges; this is a reasonable measure of local ethane price that compares well with Middle East ethane prices;
- LNG is a measure of remote ethane rates;
- oil prices in Asia are a good indicator for naphtha, the main cracker feed in China; and
- export coal pricing is an upper cost for coal gasification feedstock that can be as little as 15 $/t.

Ethane separated from natural gas (including shale gas) offers the lowest cost and simplest manufacturing route to ethylene and is preferred in the Middle East and North America. Liquefied ethane shipped to Europe in a virtual pipeline costs less than naphtha cracking. There is an expectation that China will have more access to natural gas in the future from a second Power of Siberia pipeline proposed for 2030, but the shortage of gas for domestic supply means that this will likely be reserved for residential heating and that imported oil and domestic coal in a supporting role will continue to dominate feedstock choice.

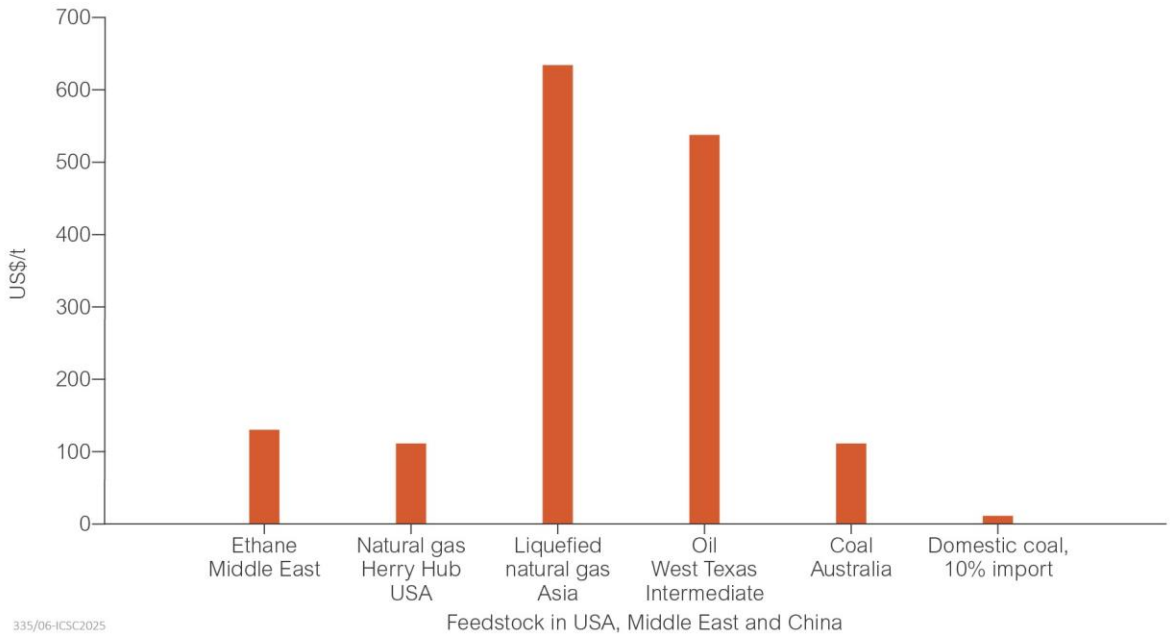

Figure 6 Comparison of feedstock prices for gas, oil and coal (Rajendra, 2024; Markets Insider, 2024; Oilprice, 2024; YCharts, 2024)

The costs are shown on a $/t basis in Figure 6 to allow a clearer assessment of feed charges. It indicates that imported coal is cheaper than US/Middle East ethane feed. The coal price in this case is export-quality thermal coal, which is higher quality than that supplied to the coal gasification industry. The high oil import charges make coal appear attractive, even if imported, but for every tonne of ethylene, more than one tonne of feedstock is needed. Typically, approximately three tonnes of coal is needed per tonne of ethylene, rising as quality falls. Subbituminous coal is suitable for gasification and indeed the reactor development in China is aimed at processing lower quality and cheaper feedstock that would lower efficiency if used in power plants. In project proposals, the cost of coal is often quoted at far below international thermal coal pricing, as low as 10% of import prices, and that would make coal about half the price of US gas feed (Tu, 2024; Asiachem, 2024).

Natural gas, LNG (Asia) that equates to ethane LNG import and oil that equates to naphtha is heavily disadvantaged compared to domestic ethane in Saudi Arabia or the USA, but China competes on its lower plant and operability costs.

At the time of the major expansion of coal gasification in 2018, an economic assessment indicated that an oil price of about 40 $/bbl would be needed for a competitive coal gasification industry. The industry initially expanded at lower oil prices with state assistance, while today West Texas Intermediate (WTI) oil is trading above 70 $/bbl, first falling back somewhat due to oversupply in the first half of 2024 and then rising due to conflict in the Middle East, perhaps heralding another period of oil price volatility (Oilprice, 2024). For the current industry, coal gives a perceived feedstock advantage, but it is noteworthy that coal gasification does not dominate new polymer plants in China. The advantage of low-cost local coal supplies, even at 10% of imported coal prices, does not balance

out the additional plant cost and complexity even at the increased plant scale adopted in China. In the future, measures to lower carbon intensity of coal-to-chemicals are likely to increase costs in the gasification industry making coal gasification projects less attractive.

3.3 COMMENTS

The key driver for the coal-to-chemicals sector is energy and resource security, with the industry benefiting from low domestic coal feed prices to compensate for higher processing costs involved in gasification, intermediate conversion and purification.

The coal industry is water-intensive with the need to 'shift' water and carbon monoxide to carbon dioxide and hydrogen, and this need has exacerbated water supply shortages in China. Projects are now directed to produce zero wastewater which is challenging.

Coal gasification is carbon intensive in comparison to alternative routes. Given the paucity of natural gas supplies, coal gasification is currently the preferred route to hydrogen in China which is supplied mainly to refineries despite this route possessing the highest CO_2 intensity of all coal-to-chemicals processes.

The future of the industry depends on its potential to reduce carbon intensity which is likely to add to processing costs. Current feedstock prices and views on key oil price profitability thresholds suggest the industry can operate profitably, but in the list of new-build polymer plants, China has decided the majority will be based on oil imports rather than use indigenous coal.

4 COAL GASIFICATION TECHNOLOGIES

Coal gasification is based on technology developed in Europe and the USA. The early history of coal gasification is rooted in the gas lighting industry of the 19th century when many towns possessed their own gasifier. Town gas was originally obtained as a by-product of the coking industry with reactors developed to maximise gas production.

Early gasification reactor designs were updraught reactors with an air intake at the base, arranged for combustion at the grate, with reduction reactions taking place higher in the gasifier; gas mixtures are primarily hydrogen and carbon monoxide. The gasification industry has since experienced a series of developments including coal-to-diesel using Fischer Tropsch catalysis in the mid-20th century, an activity that has continued with the coal-to-fuel programme in South Africa. Before the deployment of natural gas and later LNG, there was a synthetic natural gas programme using coal feedstocks.

Modern reactor designs are oxygen blown to avoid dilution and two are shown schematically in Figure 7. The Texaco gasifier (GE gasifier) was deployed extensively in China during the initial phase of the new coal gasification industry while the Shell gasifier is offered by Air Products. GE's gasification business was acquired by Air Products in 2020, but the GE gasifier remains a key design for gasification and Wuxi Powermax in China offers their own bespoke gasification technology specifically aimed at lower-rank coal feedstocks and, more recently, bio feedstocks.

In the latest developments in the Chinese steel industry, coker gas is under trial as a hydrogen source in the development of coke-free BOFs; coker gas mixture is composed of roughly equal measures of hydrogen and carbon monoxide.

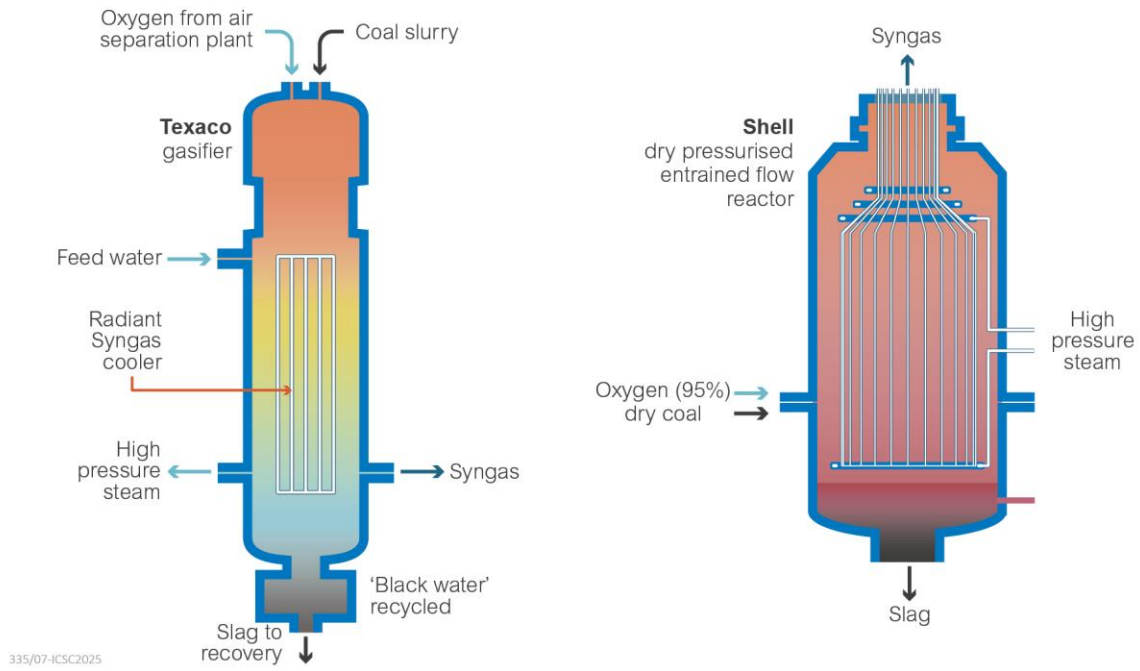

Figure 7 GE Energy's coal slurry gasifier (left) and Shell's dry pressurised entrained flow reactor (right) (adapted by the author)

The GE (Texaco) single burner slurry reactor was first deployed to demonstrate the technology in 2012 for an anthracite gasification project with China Coal Shaanxi Yulin Energy & Chemical Company and Guizhou Jinchi Chemical Company Ltd, in Yulin, Shaanxi province (GE, 2012). This was one of the early plants in a new wave of gasification projects producing methanol and ammonia. The plant required a significant scale-up of the pre-existing gasifier technology to supply syngas to produce 3.6 Mt/y methanol, beginning in 2015. Four main processes take place as coal descends in the reactor to form a syngas: drying, pyrolysis, oxidation and reduction. Current gasification technologies include fixed bed gasification and fluidised bed gasification, in addition to entrained flow and coal slurry gasification. These technologies are mature and reliable with many units in operation, using a broad range of coal feedstocks from lignite, Indian coal, bituminous coal, and even anthracite. The GE design is used for 75 slurry-fed gasifiers in China's coal gasification industry.

The Shell dry feed pressurised entrained flow reactor is deployed by Air Products in various key projects. The Shell Gasifier design delivers syngas to several projects in China, for example providing gas for 1 Mt coal-to-liquids in Shaanxi, 1 Mt lignite to MEG for Jutai New Material Co, and 0.35 Mt for Debankg Group in Jiangsu (Air Products, 2023).

The main issues to be addressed in coal gasification process design are the high emissions of CO_2, sulphur dioxide (SO_2), nitrogen oxides (NOx) and mercury. While CO_2 is of primary concern as a greenhouse gas, the others are serious air pollutants. The GE and Shell reactor designs are the workhorse gasifiers for the industry with modified designs to cope with lower quality feeds. Although

well-established technology, Pakistan recently announced it would not adopt coal gasification partly due to the cost but also because the technology is considered too complex (Yousafzai, 2024).

4.1 EVOLVING GASIFICATION TECHNOLOGY

The main aim of improving gasification methods is to reduce CO_2 emissions. This section provides a brief description of alternative reactor designs that use supercritical water gasification, plasma gasification, chemical looping coal gasification (CLCG) and decoupling gasification (Dai and others, 2023). The electrolytic production of hydrogen combined with current gasification designs is of particular interest and is discussed in Chapter 5.

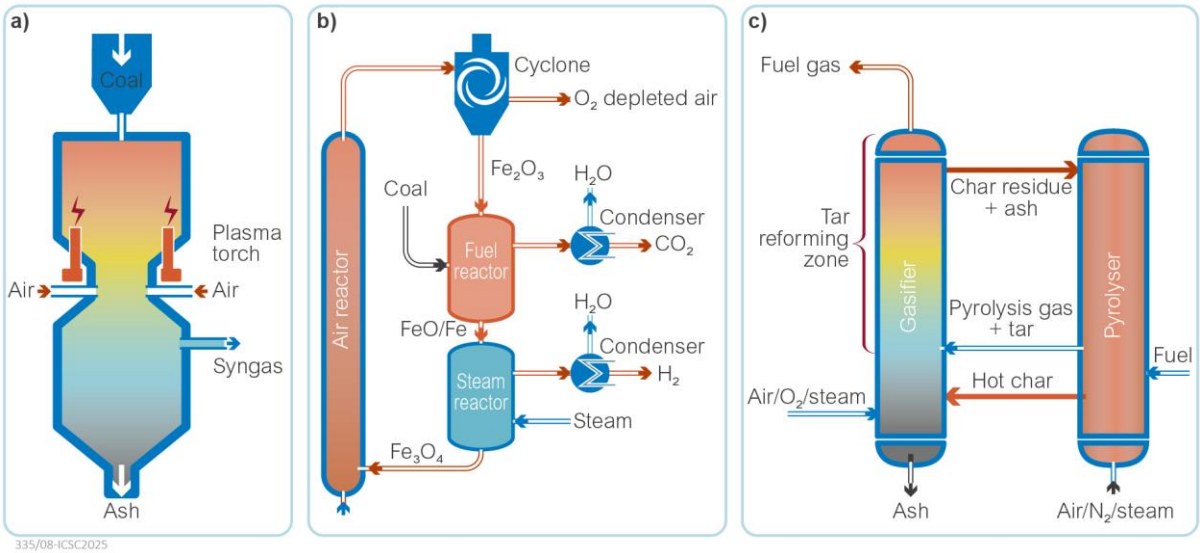

Figure 8 Advanced gasification technologies: plasma torch; CLCG and coal pyrolysis gasification (adapted from Dai and others, 2023)

4.1.1 Supercritical water gasification

Supercritical water gasification (SCWG) of coal takes place at high pressures, approaching 30 MPa, but modest temperature, in the range of 500-850ºC. For comparison, oxygen-fed reactors operate at lower pressure but a peak temperature of 1600ºC. The products from SCWG are skewed more towards hydrogen, with higher coal conversion due to less formation of tar and coke. Impurities such as sulphur, phosphorus, nitrogen and alkali metals form inorganic salts in the aqueous atmosphere assisting gas purification and near elimination of NOx and SOx.

Development of SCWG designs focuses on catalysts that promote gasification through enhanced pyrolysis and steam reforming of carbon into carbon monoxide. Catalysts lower the reaction temperature which needs to be higher, at 900ºC, in the absence of a catalyst, which is high for supercritical conditions. Potassium carbonate is a suitable catalyst candidate (Chen and others, 2021). Optimised gasification conditions require fine control over the rate of coal addition and resultant

carbon concentration which changes the reactant ratios and physical conditions in the reactor, combining to influence hydrogen production (Dai and others, 2023).

SCWG promises to be a low pollution method to produce a high hydrogen content syngas from coal. There are reactor design issues, including relatively high reactor costs related to the risk of corrosion due to the presence of salts, while precipitates can also be linked to flow problems in research units (Chen and others, 2021; Pinkard and others, 2019). An option for the future of SCWG technology is the co-gasification of coal with biomass and plastic waste to reduce carbon intensity.

4.1.2 Plasma gasification

A plasma torch reactor provides an additional heat source in the endothermic zone of the reactor. Figure 8 (a) is a representation of a reactor with air, or preferably oxygen, injection fed into the reactor centre. Coal is supplied through a hopper at the top such as for the Lurgi gasifier, and plasma torches precede the oxidant injection. Coal plasma gasification takes place at similar reaction conditions to conventional oxygen-fed reactors, but a proportion of the oxygen is provided independently in the form of a plasma, an electrically charged gas comprised of reactive radicals, ions, and energetic electrons, with gasification taking place at more severe conditions than in a typical gasifier.

The plasma reactor, as for the SWCG, produces less tar and a more hydrogen-enriched gas than conventional systems. The plasma reactor is an adaptation of existing reactor designs but has its own design issues to be overcome. Economic challenges include the energy demand for the thermal plasma and there are also practical difficulties due to electrode oxidation (Dai and others, 2023). Commercial designs have operated on processing municipal waste rather than coal gasification. What has changed, is the advent of renewable energy, the plasma injection lowers the degree of combustion within the reactor and there is a consequent reduction in overall CO_2 emissions. As for SWCG technology, the plasma design is compatible with alternative feedstocks such as plastic waste, one option to lower carbon intensity. As the temperature is maintained above 1000°C the formation of tar is prevented, maximising syngas production and simplifying downstream processing (Galaly and others, 2024).

4.1.3 Chemical looping coal gasification

Chemical looping coal gasification (CLCG) uses the indirect transfer of oxygen from the air as a feedstock rather than oxygen from air separation. Oxygen is carried by solid particles which are reduced on contact with coal. Figure 8 (b) shows a variant of the CLCG process aimed at hydrogen production that incorporates a steam reactor as part of the metal oxide circuit. The main gasifier section acquires oxygen from the carrier, in this case, oxidised iron with an inert medium that oxidises coal to carbon monoxide. In a variation from conventional gas conversion and water-gas-shift as separate processes, the CLCG incorporates a steam section that partially re-oxidises reduced iron (Fe_2O) from the first stage and converts it to carbon monoxide and hydrogen by water-gas-shift

chemistry. Finally the carrier reoxidation reactor returns fully oxidised iron (Fe_2O_3) to react with fresh coal supplies (Jafarian and others, 2023; Dai and others, 2023).

The main challenge in chemical looping oxidation is to use a high-activity carrier that can maintain coal conversion while exhibiting a long operating life, resisting carbon deposition and maintaining particle stability. The impact of coal mineral accumulation on the carrier is a concern. Research on carriers has focused on iron oxide where the oxidation state of iron changes rapidly. A second attribute is that iron acts as a useful heat carrier. Alternative carriers involve mixed metal systems generally based on iron that include nickel, iron oxide, ferrite and calcium, cobalt and cerium analogues ($NiFe_2O_4$, $CaFe_2O_5$, $COFe_2O_4$, and $CeFeO_3$). These hybrid carriers are reported to show improved oxygen transfer and higher coal conversion (Dai and others, 2023). The technology has only been trialled at small scale. Thus, it will be a major step to operate a novel large-scale CLCG reactor based on data collected from small-scale pilot tests.

4.1.4 Coal pyrolysis gasification

Sometimes termed polygeneration from coal, the concept of coal pyrolysis gasification (CPG) is to first separate coal using pyrolysis into three streams of gas, tar and char, so there are similarities with coking plants for the steel industry. Sometimes pyrolysis is termed devolatilisation, taking off-gases and distillates, with heavier char falling to the base of the reactor. Pyrolysis gas can be used to produce hydrogen or synthesised into methanol or DME. Tar provides aromatic coal chemicals such as phenol as a separate product stream, of especial interest as an alternative to coker plants in the steel industry. Finally, the char forms a gasification feedstock to form carbon monoxide and hydrogen, with hydrogen-enriched when the product stream is processed by steam reforming (Dai and others, 2023).

Figure 8 (c) shows a gasifier reactor linked to a pyrolyser. In this variation hot char is transferred into the oxidation zone of the gasifier and tars and pyrolysis gas are added back into the reactor avoiding the oxygen-rich zone. This enhances the hydrogen concentration in the synthesis gas. In Figure 8c, the pyrolyser requires its own fuel/air supply and would create a separate combusted gas exhaust stream. For coal rather than char, pyrolysis occurs within gasifiers following a drying step, but separating a hot char would reduce overall oxygen demand and resultant CO_2 formation within the gasifier.

Another variation of this design is to supply char to the gasifier from the pyrolysis reactor but to then use the hot coal gas that is produced as the heat source to pyrolyse the fresh feed, reducing the need for external heating. Instead of just cooling the gasifier output, it is used to heat the pyrolyser to 600°C, the optimum temperature to maximise tar formation (Li and others, 2021). The hydrogen-rich gas from char gasification was found to enhance the coal pyrolysis stage, reducing formation of oxygenated and heterocyclic compounds. Avoiding the need for external heating means that in this design all CO_2 produced by the process could be fed to a capture unit, as for current gasification methods.

There are issues for the development of pyrolysis/gasification technologies: the reactivity of char is less than the original coal potentially requiring further activation, for example by addition of a catalyst; and an extra process step to the gasifier increases complexity in reactor operation (Dai and others, 2023).

4.2 COMMENTS

The established gasification methods have been implemented successfully in China, but others are wary of setting up new industries based on complex reactors and technology; it took many years to achieve the necessary product quality and performance for the plastic industry before the rapid industrial expansion from 2018. A suite of alternative technologies has the general aim of improving the hydrogen content of the gas product stream as it is directly related to final CO_2 emissions. In addition, there is growing interest in designs that can process coal with biomass or plastic waste to improve the sustainability of the overall process; all important options in industrial decarbonisation.

5 DECARBONISATION OF COAL-TO-CHEMICALS

Global demand for chemicals, especially polymers, is predicted to increase to 2050 (*see* Figure 9) while producers face demands to use more sustainable manufacturing methods without raising prices, which is a challenge (Gabrielli and others, 2023). China, as a leading producer making around 78 Mt/y, more than one-third of the world's plastics, recognises that chemicals production will grow substantially, especially polymers. 2023 was the first year Europe imported more chemicals from China, than it exported, indicating a future manufacturing trend, with a projection that China will account for 50% of the chemicals market by 2030 (Arp and others, 2023).

The high carbon emission intensity of coal chemicals compared to petrochemicals is a hurdle for the coal chemicals industry, especially now the industry is a significant size (Li and others, 2022). For instance, anticipated demand for ethylene in China is set to increase by 30% by 2050, a slower rate of increase than 2018-23, but still, an additional 20 Mt. Emissions from the coal chemical industry already exceed 1 $GtCO_2/y$ and are approximately three times those of oil and gas chemicals on a tCO_2 per tonne of product basis (Amghizar and others, 2017).

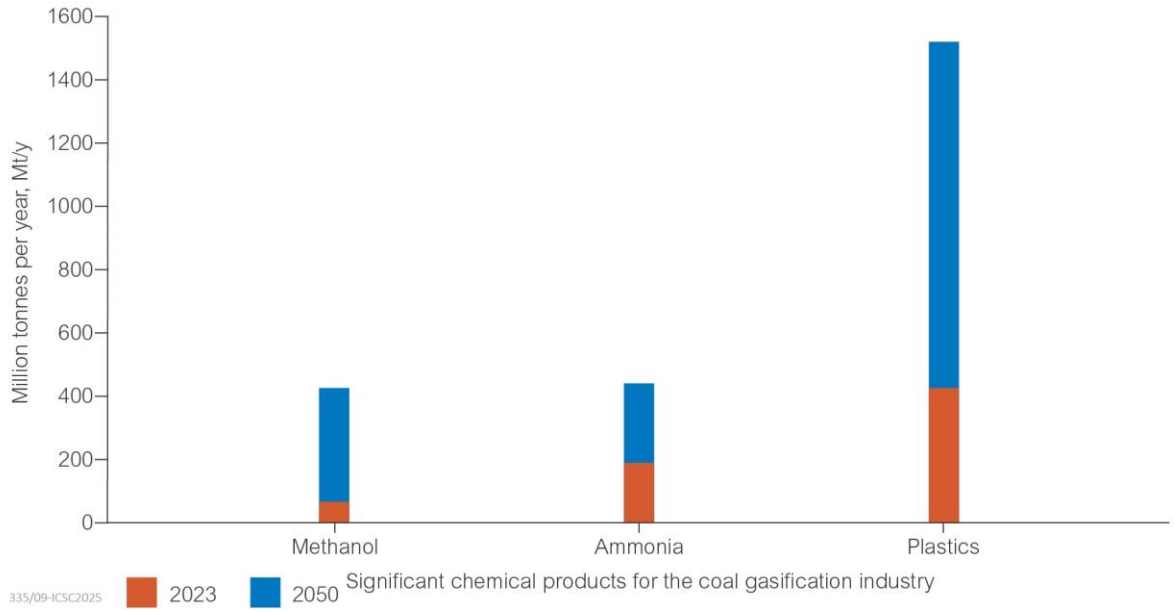

Figure 9 Projection of global chemicals demand to 2050 (Gabrielli and others, 2023)

Unlike combustion of coal in power plants, in the production of chemicals, part of the coal carbon is retained. This means CO_2 emissions are reduced per tonne of coal fed, although the products vary in carbon intensity and the production of hydrogen results in all carbon emitted as CO_2. However, the low H_2/CO ratio in the gasification primary product means that, in general, much of the carbon monoxide is shifted to hydrogen production to obtain a suitable mixture. For example, the H_2/CO ratio is less than 1 for raw syngas, whereas $2H_2/CO$ is needed for methanol, the most important intermediate in the coal-to-chemicals industry.

China will need to reduce the impact of coal chemicals production to realise its environmental goals, especially as chemicals production will increase substantially in the next decades and will include coal gasification products. Table 2 summarises the options available to lower the carbon impact of both petrochemicals and coal chemicals. The first entry is perhaps obvious, to lower consumption to reduce emissions; in the case of coal-to-chemicals this could be achieved by opting for petrochemical production of the same products.

TABLE 2 DECARBONISATION PATHWAYS (LI AND OTHERS, 2022)

Consumption reduction	Increase fertiliser efficiency Reduce fertiliser consumption Increase recycling of waste plastic, rubber and fibre Reformulate plastics to ease recycling
High-end production	Develop high-end low-volume products, including carbon materials Advanced materials and speciality chemicals
End product substitution	Develop bio-based alternatives
Efficiency improvement	Reduce energy consumption through enhanced integration Use renewable electricity Coal-based cross-industry production and process simplification
Fuel substitution	Electrify low- and medium-severity processes Use hydrogen and biomass instead of coal
Feedstock substitution	Develop low- and zero-carbon feedstocks, especially renewable hydrogen, plastic waste, CO_2 and biomass Renewable oxidising and reducing agents
Effluent gas treatment	Carbon capture, utilisation and storage

The following sections explore some of the options for the decarbonisation of coal chemicals products focused on polymers, carbon capture, and electrolytic hydrogen.

5.1 PLASTIC – POLLUTION AND RECYCLING

Using less plastic would reduce pollution, but trends are in the opposite direction, as demand for chemicals and polymers is set to rise by up to 50% to 2050. Over 1.5 billion people have no organised refuse collection, recycling is at modest scale, and plastics are usually downgraded due to the presence of other chemical components. Plastics contain non-covalently bound additives including flame retardants, heat stabilisers, antioxidants, plasticisers, adhesives and others, with some recycled products in domestic settings exhibiting toxicity. In all, over 10,000 chemical additives are employed in the industry creating a complex reuse problem and raising environmental hazards (Maddela and others, 2023). One option is to return the plastic to a base feedstock, and Hartwig and colleagues at

Berkeley, USA are developing a catalytic vapourisation technology that converts polyolefin plastics into gaseous propylene and isobutylene, separate from additive components. The pure feedstock can then be used to make virgin material rather than downgraded plastic. This process uses low-cost solid tungsten and sodium-based catalysis to moderate energy input and the next step is to prove the process at commercial scale (Sanders, 2024).

Returning used plastic as a recycled feedstock would alleviate the demand for fresh feedstock. Other initiatives to increase recycling or reduce the need for polymers are in progress, such as simplifying the range of plastics to enable easier sorting. However, this is challenging given the range of plastic properties desired. Another strategy is to modify packaging design, for instance, caps are now securely attached to bottles in the EU so that the entire package can be recycled, reducing waste by a surprising 10% in Europe (Sustainable Plastics, 2024). Also in Europe, there will be a ban on plastic packaging of fresh vegetables, mini hotel toiletries and fast-food containers. Lowering the use of plastic combined with improved recycling may reduce product demand in coming decades, which will have implications for the future of chemicals in China and the gasification industry.

Reformulation to find more easily recycled plastics is the subject of intense research. The use of traditional materials such as paper and glass have high energy consumption while there is complexity in introducing new materials into a sector where product simplification is preferred. The current emphasis is on the elimination of packaging where possible (UK Food Standards Agency, 2023). In the future, returning used material that is 'hard-to-recycle' to virgin plastic must be a prime goal for what is an essential material in the 21st century. The target of a circular economy is incompatible with recycled plastic production solely located in China, impacting its plastics industry.

5.2 CARBON CAPTURE

Achieving NZE requires massive decarbonisation of coal power, steel, cement, coal gasification and conventional chemicals (Eriksen, 2024). A recent ICSC review of CCS hubs and clusters (Mills, 2023) illustrates the advantage of combining several CO_2 sources but also recognises the need for government intervention to advance the technology to allay costs at this stage of development. CCUS is in development in China with close to 100 projects at varying stages, including hubs and clusters; in 2023 the China Northwest hub developed by China National Petroleum Corporation (CNPC)was a leading project (Mills, 2023; Zhang and others, 2023).

Coal gasification plants are uniquely prepared for capture as the CO_2 is already separated and available as a concentrated, nitrogen-free stream. Equally, the industry is new, and had a difficult 2023, with power prioritised, affecting its profitability. CCS technology has not been directly factored in, so sources and sinks can be mismatched, especially in Eastern China, but extensive storage capacity is present in the coal gasification Ordos region. A review of potential demand for CCS to 2050, is focused on thermal power plants and the cement industry, rather than steel and chemicals. However, in the

status report on China's CCS progress, chemicals are assigned 21 CCUS demonstration projects, expected to increase to 34 by 2030 (Zhang and others, 2023). Note that the emphasis is on CCUS with the cost of CO_2 recovery and handling mitigated by using CO_2 for enhanced oil recovery (EOR). Much of China's hydrogen is obtained from coal, and two CCUS projects are linked to coal-to-hydrogen generation.

A broad range of technologies for CCS is in development including pressurised oxycombustion, chemical looping, membranes, pressure swing adsorption (PSA), bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC). A recent ICSC report on BECCS gives further detail (Jones and others, 2023). BECCS has the potential for negative CO_2 emissions, although a cautionary note is, that given extra costs, BECCS currently requires government support to succeed (Jones and others, 2023). The first phase of implementation of CCUS in China is to abate 500 $MtCO_2/y$ from combined steel, cement and chemicals by 2060, noting that China's emissions from coal gasification and cement combined already exceed 2 $GtCO_2$ (Bourke, 2024). A first step is China's National Energy Investment Ningxia project to capture 500,000 tCO_2/y from its coal-to-liquids facility. In the power sector, a CCUS plant capturing 1.5 $MtCO_2/y$ is scheduled to come on stream in 2027 (Global CCS Institute, 2024).

Surveys indicate that sources of CO_2 can largely be matched with available reservoirs, except for in South-Eastern China. A combined storage capacity based on former gas reservoirs in Ordos, Sichuan, Bohai Bay and Tarim basins exceeds 15 $GtCO_2$ and ageing oil fields have a capacity for 20 $GtCO_2$ for initial projects; more storage is probably available in saline aquifers that require more investigation but may be of the order of 160–2400 $GtCO_2$. The CNPC Changqing hub and cluster project in the Ordos basin should be in operation by 2030 (Mills, 2023; Zhang, 2023).

The cost of CCS depends on the source and location of the plant as well as the selected technology, but China claims an advantage in recovery costs. For the coal and petrochemical industries with more concentrated sources of CO_2, the cost of capture is estimated at between 14–35 $\$/tCO_2$ with additional pipeline and reservoir injection charges. These prices are only possible in the West with substantial financial support, such as the 45Q credit in the USA that provides 50 $\$/tCO_2$ in the case of permanent storage rather than utilisation (Zhang, 2023; Mills, 2023).

Overall, the review concludes that many barriers remain to the implementation of CCS for coal gasification with the most significant being the abatement cost for capture, pipeline and storage, a lack of incentives and regulatory framework, and, especially for Eastern China, a potential geographic mismatch between CO_2 sources and sinks (Zhang, 2023). Another point to note is that the addition of CCS plant will increase energy consumption. However, these problems are common with other sectors and given that the industry will remain significant for many years, and that globally it doesn't matter where CO_2 is captured and sequestered, the coal gasification industry potentially offers the lowest cost

route to CO_2 sequestration when compared to power generation, steel or cement decarbonisation, and perhaps this should make it a priority.

5.3 HYDROGEN

The proposed hydrogen economy has received much publicity and scepticism given there have been previous false dawns on its availability as a cheap carbon-free fuel. In its 2023 review of hydrogen production, the IEA estimates that only 4% of publicised new projects have been approved out of a potential 38 Mt/y by 2030. The majority of these would use electrolysis and low carbon generation, while 10 Mt would be based on fossil fuels and carbon capture. Establishing a hydrogen economy with current hydrogen charges means that the production of fossil fuel-based hydrogen coupled with CCS offers an intermediate solution to support the development of the needed infrastructure (Zhu, 2023; Kelsall 2021). Hydrogen has potential as an energy storage medium where it can be generated by surplus renewable generation, stored and then supplied to a combustor during periods of limited generation, at night and during calm periods.

Hydrogen can also be a reactant with CO_2, which is one option for the production of synthetic aviation fuel, a sector in its infancy but seen as essential to meet CO_2 emission goals. Hydrogen has also been proposed as a transport fuel where battery power appears impractical, such as in heavy lorries and buses, with buses already proven in cities. However, there may be a specific advantageous application for coal-to-chemicals to replace water-gas-shift chemistry.

An industry view is that it will be many decades before electrolysis can supply the quantity of hydrogen needed for the future, with an IEA hydrogen scenario assessing demand to replace a proportion of fossil fuels, at 450 Mt/y by 2050. To put this in the context of power generation: 1 MtH_2 produced by electrolysis would need about 5 GW of power, equivalent to 50 million MWh. Currently, the USA's renewable energy capacity is about 91 GW, while China's renewable capacity is greater at 700 GW with a further 339 GW under construction (Yu and others, 2024a).

To develop a hydrogen economy, fossil fuel feedstocks combined with CCS will have to bridge the production gap, benefitting from relatively low carbon capture processing costs due to the concentration of CO_2 in the by-product stream (Ingram, 2024). The concern is that equipment and financing charges are rising, which may inhibit investment in electrolysis, constraining hydrogen availability. This would have knock-on effects on achieving sustainable production in industry, especially in the chemicals sector (IEA, 2023b).

Around half of the current 14 GW electrolyser production capacity is in China, which is a significant increase over the previous year, with a global capacity of just 1 GW in 2022, so hydrogen generation is gathering momentum. As recently as 2021 most hydrogen was produced by natural gas reforming and coal gasification (19%), with the rest obtained from refining processes (Zhu, 2023). For

electrolysis in China, an ambition is for ten times the 2024 tonnages of hydrogen produced to become meaningful to the energy transition in the future. Global hydrogen consumption was 95 Mt in 2022, but hydrogen continues to be used primarily to replace other sources in refining, while low emission hydrogen from electrolysis accounted for less than 1 Mt (Zhu, 2023).

The political backing for a hydrogen industry is already in place, with more than 40 governments publishing hydrogen strategies. In the USA there is a Hydrogen Production Tax Credit, the EU has formed Important Projects of Common Interest that are now available as sources of project funds, while Japan, South Korea and Australia all have hydrogen policies. However, China leads the development of electrolytic hydrogen linked to its advanced position in renewable generation, with over 60 projects announced, most located in Inner Mongolia suitable for use in coal chemicals (Tu, 2024).

5.3.1 Hydrogen electrolysis technologies

Renewable hydrogen is produced by the electrolysis of water, splitting water into hydrogen and oxygen, with the power drawn from variable renewable energy (VRE) such as wind and solar or from nuclear power generation. Where VRE is the power source the electrolyser cells must cope with idling to surging high current densities depending on the supply. This is a significant part of the challenge faced by the various designs: proton exchange membranes (PEM), alkaline, solid oxide electrolyser cells (SOEC), and the more recent anion exchange membrane (AEM). The development of electrolysis presents several challenges; the technology is currently dominated by alkaline electrolysis as the lowest cost producer at 1400 $/kW compared to more efficient PEM cells approaching 1770 $/kW. PEM electrolysers have the advantage of greater flexibility with a wider operating range and response to variable power input but are vulnerable to the cost and supply of precious metals (Zhu, 2023). The following gives a brief introduction to the different options and technical challenges; they are included in this study as there may be a role for hydrogen in decarbonising coal chemicals.

Proton exchange membrane

PEM electrolysis is the electrolytic separation of water in a cell containing a solid polymer electrolyte (SPE) that permits the conduction of protons (hydrogen ions) to a cathode, separation of product gases and acts as electrical insulation of electrodes. The principal components of the cell are the membrane electrode assembly consisting of the membrane, anode and cathode and a gas diffuser called the current collector (*see* Figure 10).

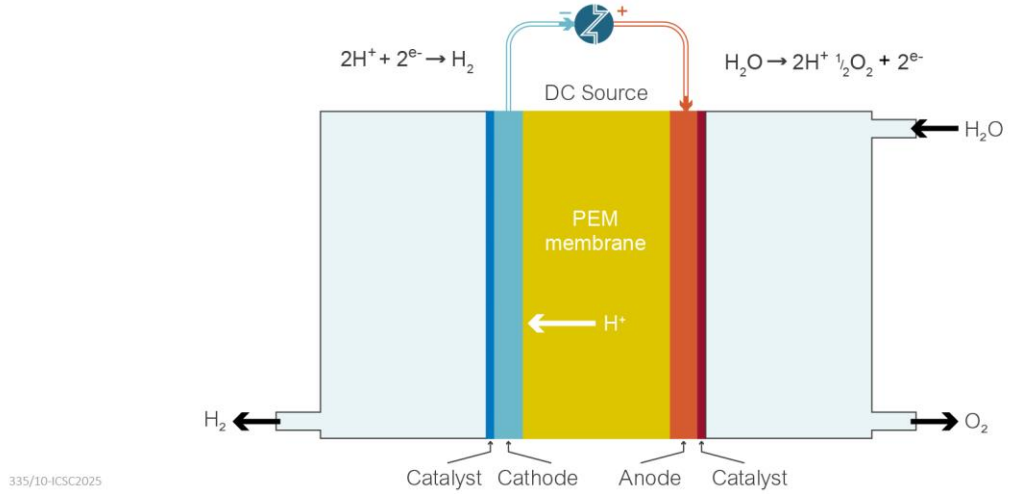

Figure 10 PEM water electrolytic cell (Cuff, 2024b)

The main advantages of a PEM are its compact dimensions, high hydrogen purity, and especially the ability to operate at high current density. This is helpful when there is a need to accommodate surges in supply from VRE. The disadvantages are cell stability, the cost of acidic electrocatalysts, and the high cost of platinum-carbon cathodes (El-Shafie, 2023). PEM technology is developing, with, for example, Electric Hydrogen claiming a breakthrough in enhanced current density, increasing the throughput of each cell, mainly through advances in cell membrane technology; their five-year aim is to produce hydrogen at 1.5 $/kg$H_2$ (Cuff, 2024b).

Alkaline

An alkaline electrolyser consists of nickel and cobalt oxide electrodes with a liquid potassium hydroxide electrolyte that circulates both electrodes. A separating porous diaphragm is located between the electrodes with hydroxyl ions passing through the diaphragm. Hydrogen and hydroxide are released at the cathode, oxygen at the anode. The key advantages of these cells are a low operating temperature of less than 100°C and that no catalysts are required. The disadvantages include corrosion of electrodes by the electrolyser alkaline solution (El-Shafie, 2023). The alkaline electrolyser is leading developments in China with a series of significant electrolyser projects powered by renewable energy and a further 750 MW capacity under construction in 2023 (IEA, 2023c).

In Xinjiang, NW China, Sinopec has built a 260 MW alkaline electrolyser bank using equipment from three different Chinese manufacturers, powered by local solar and wind farms that can produce up to 20,000 Mt/y of renewable hydrogen. After a year's operation, there are suggestions that the cells struggle to meet the surging nature of renewable power supply and utilisation is consequently below the maximum (Collins, 2023). Ningxia Baofeng Energy Group had the world record for its 30 MW electrolyser in 2022 and followed this with a 150 MW design that began operating in 2022.

Notably, Ningxia Baofeng Energy Group, a major coal-based chemicals manufacturer located in Central China, has announced an intent to build similar facilities each year to 2040 (Collins, 2022). Baofeng claims that the hydrogen production cost using its alkaline electrolyser is close to 1.2 $/kg, approaching the current China unabated hydrogen production cost from gasification of 1 $/kg. There are assumptions behind these figures, such as longevity of the electrolyser, generation rates and cost of electricity which mean they should be treated cautiously. These are costs that the US Department of Energy (USDOE) have made as a future target for its hydrogen production which currently stands closer to 3 $/kg, noting that the prices quoted by Baofeng in China are for 2022.

Solid oxide electrolyser cell (SOEC) and anion exchange membrane (AEM)

Alkaline and PEM electrolysers are commercially available whereas SOECs and AEMs are maturing technologies, with SOEC closer to commercialisation (IEA, 2023c). SOEC is considered more efficient than either PEM or alkaline technologies as a portion of the energy needed for electrolysis is provided as heat. An SOEC operates at 700–800°C using evaporated demineralised water as the feedstock. Steam flows through a metal structure possessing microchannels into electrolysis cells equipped with nickel electrodes, oxygen ions pass through the separator to the anode and oxygen leaves the cell, while hydrogen is collected, purified and compressed (El-Shafie, 2023).

The advantage of SOECs is primarily the lower voltage required than PEM or alkaline while avoidance of temperature gradients is beneficial to the structural integrity (Ramli, 2024). Topsoe is building a 500 MW SOEC manufacturing facility and targeting nuclear energy in preference to renewables to benefit from a controlled energy supply and a direct heat source to electrolytic cell arrays. The company has already signed agreements with companies planning small modular nuclear reactors (SMR) including Rolls Royce and ULC-Energy. An SMR-SOEC combination may produce hydrogen at a cost approaching 2 $/kg by 2050 provided there is high plant utilisation, down from the current USA pricing of 3.5 $/kg (Nuclear Engineering International, 2024). Note that hydrogen production costs are closely dependent on electricity costs, 0.05 $/kWh equates to 2.5 $/kg$H_2$. In the EU in the first half of 2024 electricity costs were closer to 0.3 $/kWh, and only a dedicated supply could be considered for hydrogen.

The final variant in electrolysis, AEM is based on hydroxyl ion transport through a membrane, rather than protons, as in a PEM electrolyser. Closer to an alkaline cell in concept the main advantage is non-noble metal catalysts. Still at the development stage, the barriers to commercial operation are the catalyst activity and AEM membrane conductivity (El-Shafie, 2023). It is this technology that is specifically mentioned in China's industrial plans to enhance electrolytic hydrogen production (Climate Cooperation China, 2024).

5.3.2 Renewable hydrogen and coal gasification

Products from coal gasification are more carbon-intense than from other sources. Certain coal gasification products such as hydrogen and ammonia have none of the original coal carbon present in the product but other products such as methanol and polymers have up to 30% of the original coal carbon locked in. The issue is that the hydrogen content of the syngas produced is too low and this is adjusted using water-gas-shift chemistry to increase the hydrogen to carbon monoxide ratio, but at the expense of more emissions of CO_2. One option is CCS. Another is to inject electrolytic hydrogen to raise the hydrogen content independently to match the CO present in the gasification stream, as depicted in Figure 11.

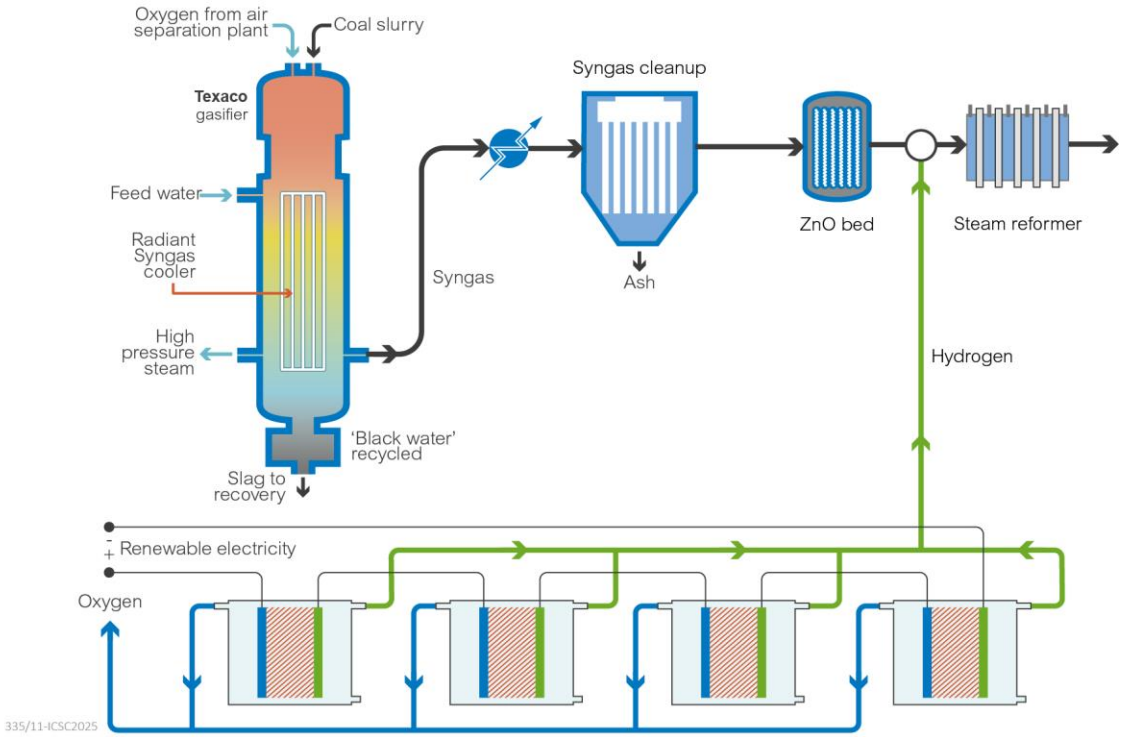

Figure 11 Adaptation of coal gasification to incorporate renewable hydrogen (Guo and others, 2023)

The addition of a separate supply of hydrogen allows more of the carbon monoxide to be incorporated into methanol, and in an extreme case with large volumes of hydrogen available, all the CO could be used in the product. CO_2 that is formed in the nascent gasification could also be converted. In this case, the water-gas-shift reactor duty changes to become a polisher unit rather than the source of over half of the hydrogen product, with some process savings. The oxygen obtained from electrolysis can also be supplied to the gasification reactor partly displacing cryogenic air separation reducing feed costs and making optimal use of the electrolytic cell. A system such as this could compete directly with petrochemicals on a sustainability basis with a focus on the energy required in processing rather than the proportion of the feedstock that is present in the product.

Clearly, the cost of hydrogen is key to such a process and Ningxia Baofeng Energy Group is claiming alkaline electrolytic hydrogen at close to gasification hydrogen prices, 1.2 $/kg compared to 1 $/kg from direct unabated hydrogen generation, with the gap potentially narrowed from savings on the water-gas-shift reactor (Collins, 2022). Permitting more of the carbon monoxide to be present in the final product has additional implications as the quantity of coal needed is substantially reduced with savings in mining and supply, and the output from a single gasifier is increased and could potentially supply a higher output of syngas to feed a larger process train.

5.4 COMMENTS

The principal future challenges for an existing and future coal gasification to chemicals industry are found in plastic product pollution and CO_2 emissions, given coal chemicals are more carbon-intense than petrochemicals.

For polymers, concern has changed from simply a waste issue to an animal and potentially human health matter. Solutions are hard to find, but using fewer raw materials would help, through reformulation, simplification, and recycling. This is a long-term option given the time it takes to establish alternative manufacturing. But the current trajectory is for production to increase by 50%. New research that returns plastic to its base components and separates out problematic additives that normally mean degrading products appears the most attractive solution and would eventually impact demand for new products from China.

Implementation of CCS with coal gasification offers one route to decarbonisation. The installation of CCS with gasifiers faces the same technical hurdles as other sectors, but the advantage is that a highly concentrated stream of CO_2 is produced, already lowering capture costs. Thus it may be more cost-effective to apply CCS to the coal gasification sector than the power sector in the first instance.

An alternative route to decarbonisation is to use electrolytic hydrogen to avoid converting carbon monoxide in the syngas stream to hydrogen and emitting CO_2. Not to diminish the challenge of successfully implementing electrolysis and the associated costs, but this solution has several positive aspects. They include increasing the production capacity of a single gasifier by up to threefold and lowering the amount of coal used, reducing water-gas-shift reactor demand to a polisher, avoiding the cost of sequestration and meeting the demands of new sustainability criteria by incorporating most of the coal carbon in chemical products, potentially higher than for petrochemicals which have a significant fuel by-product.

6 BEYOND CHINA – COAL GASIFICATION IN OTHER COUNTRIES

The idea of a secure feedstock supply that means industry is independent of imports and international markets is a compelling one for other countries in Asia and Africa, which lack significant oil and gas resources. Of these nations, other than China, India appears the likeliest to adopt coal gasification on a large scale, as Coal India Ltd (CIL) has announced an ambitious target (PIB, 2024). Projects in Indonesia have been mooted and some cancelled while new facilities are in progress in Africa. In all cases, the main objectives of these plants are the production of gaseous fuels, hydrogen and fertiliser, rather than a complete array of chemicals from coal.

6.1 INDIA

Gasification of coal is set to become a significant activity in India with a gasification target of 100 Mt/y of coal by 2030 with a focus on using lower quality, high ash, indigenous coal and lignite. Gasification to produce synthetic natural gas, methanol, and ammonia for fertiliser is considered a more sustainable application of coal than supplying power plants (PIB, 2024). The use of coal in this way releases less CO_2 than burning coal, but it is more carbon intensive than the direct use of natural gas and methane reforming to ammonia. However, low-cost natural gas is not a credible option in India. The Ministry of Coal has offered substantial financial incentives to promote new gasification projects amounting to up to 15% of project capex or $1 billion across projects. Initial projects are collaborations between CIL and other state-owned companies including Western Coalfields – a subsidiary of CIL, GAIL (India) Ltd a state-owned gas company, SAIL Limited a public sector steel company, NLC a state lignite company and BHEL, the largest public sector electrical/industrial company in India. Although projects involve several companies, the fact that this is overall a state initiative may increase the probability that these projects will proceed to operation over the next few years. The long-term intention is to establish gasification of Indian indigenous coal and to then attract private investment into the sector.

CIL-BHEL JV Project in Lakhanpur, Odisha, focuses on producing ammonium nitrate fertiliser with a capacity of 0.66 Mt/y and aims to commission in 2029. In the production of ammonia, all coal carbon-based CO must be shifted to CO_2 to maximise hydrogen production for use in the Haber Process.

GAIL CIL JV A facility at Sonepur-Bazari, West Bengal intended to produce 80,000 m^3/h of synthetic natural gas (SNG, methane), amounting to over 600 million m^3/y of gas from 1.9 Mt of domestic coal. The project has a commissioning date of 2029.

CIL-Steel Authority of India SAIL – CIL JV Project at Durgapur Steel Plant aims to produce syngas for direct reduced iron, enhancing steel manufacturing sustainability.

NLC-CIL Lignite to Methanol Project is developing clean energy products from lignite, including syngas, diesel, and renewable hydrogen.

Western Coalfields Limited (WCL) Coal-to-Ammonium Nitrate Project targets coal gasification into ammonium nitrate with a production capacity of 0.66 Mt/y.

The projects listed were announced in 2023 and full front end engineering design (FEED) studies should commence soon. The suite of projects indicates that India has a serious intent to gasify up to 100 Mt of coal partly to produce SNG aimed at lowering LNG imports, and to produce key chemicals, especially those for use in agriculture (Perez, 2024). Added together, CIL envisages a gasification industry about a quarter of the scale of the sector in China.

6.2 AFRICA

Coal gasification has declined in Africa although new projects have been proposed in Botswana and Mozambique. Sasol in South Africa led the coal-to-fuels operations worldwide but in recent times the plant is migrating from coal gasification towards natural gas autothermal reforming, using gas imports from Mozambique to provide syngas for its fuels and chemicals business.

6.2.1 Botswana

Land-locked Botswana has stranded coal resources of over 200 Gt and the government's 2011 coal road map identified coal-to-fuels as one option to monetise Botswana's coal. A coal gasification plant has been proposed that would use 3.2 Mt/y of coal to produce 12,000 bbl/d of diesel fuel, with commissioning planned for 2028 should construction commence in 2025 (Reid, 2021). The Ikaegeng XTL project cost estimate is currently $4.5 billion, up from an earlier figure of $2.2 billion discussed in 2022, making funding a major issue. The prospects for the project have diminished during 2024 as Botswana and Mozambique have undertaken an Africa Bank-sponsored study for a new rail and port project to permit the export of Botswana's coal. This is a simpler, although costly, solution and would be a competitor project to a coal-to-liquids plant, with the added issue that an export route would increase the value of the currently stranded coal resource (Bloomberg, 2024).

6.2.2 Mozambique

In Mozambique, Regius Fuels planned to build a 400 kt/y diesel and gasoline plant in a Fischer-Tropsch coal-to-liquids facility comprised of two trains with a total capacity of 10,000 bbl/d, together with a 415 kt/y fertiliser project. The incorporation of CO_2 with ammonia was intended to lower overall emissions compared to other coal-to-liquids schemes. However, first proposed in 2020 and still shown as an active project, construction of the H&H coal-to-liquids and urea plant has not yet begun (Regius, 2024).

6.3 INDONESIA

A new coal gasification industry suffered a severe setback when Air Products withdrew from $15 billion investments in a suite of projects that included a first $2 billion project in East Kalimantan. The original concept was to gasify 6 Mt/y of coal to make 2 Mt/y of methanol, with the methanol converted to produce thermosetting polymers from a formaldehyde intermediate (Reid, 2021). Coal gasification, endorsed by President Widodo and the Indonesian Government, was considered a national strategic project that would transform Indonesia's coal industry. One explanation for Air Products ending its involvement is the deterioration in international finance available for coal investments. Another is the rise in interest rates from 2% to 6% that impacts project profitability, and a third factor is concern over the uptake of co-product DME by potential users in Indonesia (Coca, 2023). The view is that analysis could not show a clear economic benefit for coal gasification amid concern that DME would require a subsidy to compete with imported fuel. Finally, coal gasification may have suffered from new international interest to support the development of a hydrogen economy, which has drawn investment from Asia to the USA, where Air Products aims to be a leader in hydrogen production and infrastructure (Air Products, 2024).

There is one coal gasification project that is linked to China which is still a prospect. This is a $560 million joint venture investment to produce 600,000 t/y methanol by Indonesia's Powerindo Cipta Energy and state-owned China National Chemical Engineering Corporation. CNCEC is a leader in coal gasification technology within China and may be seeking to apply its technology beyond China where the sector is slowing.

6.4 COMMENTS

A major initiative to build coal gasification capacity in Indonesia collapsed when Air Products withdrew amid concerns over markets for some products and more favourable projects elsewhere. Similarly in Africa, Sasol is transitioning from coal to 'gas to liquid fuels and chemicals'. The country where coal-to-chemicals may become significant is India, with five major projects in prospect across all sectors, with state backing for the industry. The ambition in India is to approach a quarter of the current scale of China, processing 100 Mt/y for coal-to-chemicals by 2030. India's advocates for the industry view coal-to-chemicals as a more sustainable use of coal, which is supported where local low-quality, coal carbon is converted to products such as methanol, but a stretch for hydrogen and fertilisers. However, no carbon mitigation measures are included in India's plans.

7 COAL FOR STEEL AND CEMENT – IMPLICATIONS FOR COAL GASIFICATION

The power sector is the primary source of CO_2 emissions from coal and will continue to attract the most attention as many OECD countries reduce dependence on coal power generation (Dale, 2024). However, heavy industry also depends on coal, and it is proving hard to adapt these industries to reduce emissions. The recent ICSC study on the decarbonisation of heavy industry assesses that by 2050 coal use will fall but remain significant at over one billion tonnes (Kelsall, 2023). This depends on the emergence of new technology that lowers the cost of decarbonisation such as CCS, low-carbon electricity and hydrogen. Coal fitted with CCS is viewed as the key technology for decarbonisation, while the share of China's steel derived from coal has increased over the last decade. Globally, the cost of CCS to decarbonise the steel industry is assessed to be $200 billion (Kelsall, 2023).

Developments in the steel and cement sectors have direct relevance to this study on coal gasification. Their efforts to mitigate emissions have major implications for a future coal gasification sector that continues to expand, with competing processes that offer the lowest cost routes to decarbonisation.

7.1 STEEL

Global steel production is close to 2 Gt/y with 75% produced using blast furnace basic oxygen furnace (BF BOF) technology. Most of these furnaces are in Asia and are less than 20 years old, with the remaining 25% capacity based on EAF technology, which is beginning to dominate beyond Asia. Figure 12 shows a snapshot of the steel industry in 2020, highlighting the large BF BOF capacity in China; most of the furnaces were installed over a short timescale. The average age of China's BF BOF fleet is 15 years (in 2024) and given industry norms, it is likely to be in use for another 25 years. This industry is not likely to close its young steel furnace fleet in the interim, but it is considered that younger plants offer a lower-cost route to decarbonisation than older units, with a longer period remaining to write down added capital costs (Kelsall, 2023).

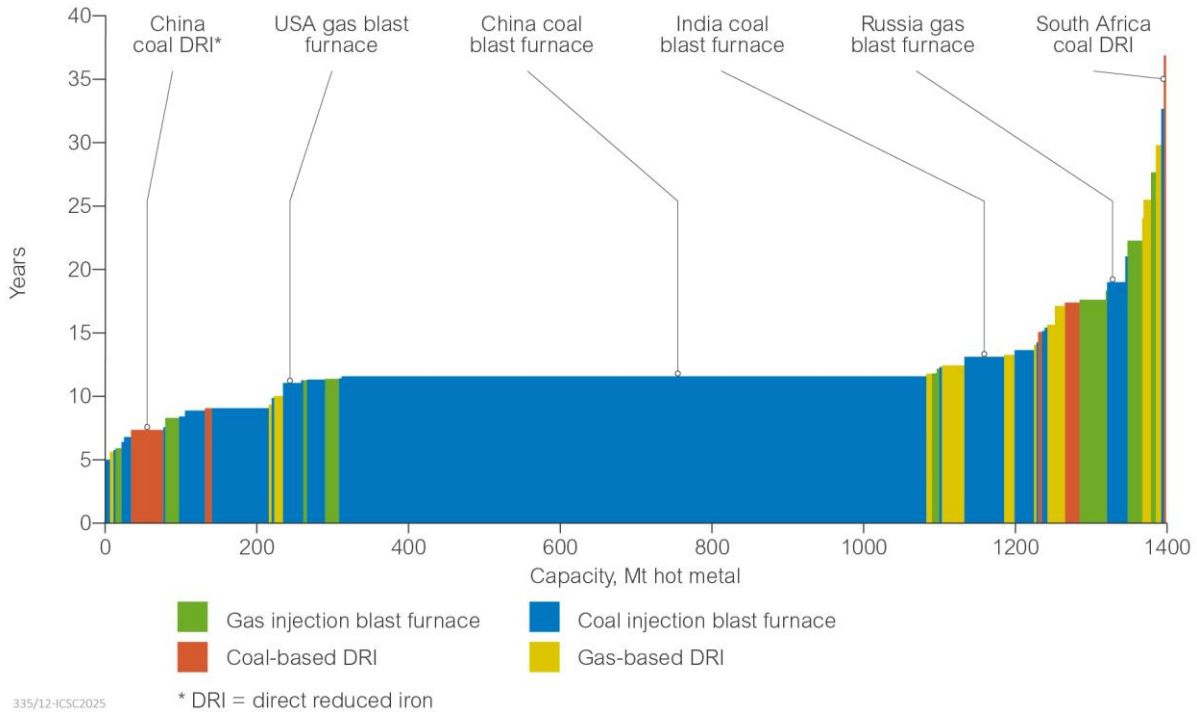

Figure 12 Steel capacity and plant age across the world (IEA, 2020)

The global steel industry emits 2.7 $GtCO_2/y$, about 7% of global emissions as almost all the coke is converted to CO_2 (IEA, 2020; Tiseo, 2024). BFs are large coal consumers, 1 tonne of steel corresponds to 770 kg of metallurgical coal and additional thermal coal is needed. A small by-product of coke production is used for chemicals, with China producing about 25 Mt/y of products derived from the coking process (*see* Figure 4). The close association between the steel industry and tar chemicals indicates that production in China will be sustained for the next decades as the coking industry supports the operation of the BF BOF fleet.

The general prospects for the steel industry are moderately rising demand driven by India and the Middle East, with EAF production set to more than double from the current 800 Mt by 2032 (Fortune Business Insights, 2023). Older blast furnaces, mostly located in OECD countries, will come under pressure to close to meet emissions targets, a situation made more likely by currently depressed steel prices. Although domestic steel production from iron ore is often viewed as a national security priority, in the UK the last BF BOF units belonging to Tata and British Steel are set to close as both companies seek to switch to EAF units processing scrap metal (St John, 2024).

BOF technology will be sustained in Asia; countries such as Indonesia have a large demand for steel and plan new blast steel furnace installations, perhaps up to 20 new plants, even as equivalent plants close in the West (Atkins, 2024). Projections are that BF BOFs will still account for over 70% of production in 2050, plants converted to use hydrogen comprising just 3%, with the remainder running EAF technology (Ferris, 2023).

Given the young BOF fleet, major reductions in China's emissions are unlikely to come from the steel industry unless a programme of CCS retrofit commences soon, or longer term if technologies such as EAFs or the novel hydrogen ore electrolysis or hydrogen-based DRI are introduced to replace existing plant (Kelsall, 2023). Currently, one project in Asia is testing a CCS retrofit to BF BOF, and 76 projects are assessing the potential implementation of direct reduced iron (DRI) hydrogen for post-2030 (Transition Asia, 2024).

7.2 CEMENT

The other major conventional user of coal is cement manufacture, where coal is the main reductant in the production of lime. Cement makes up between 10–15% of a concrete mixture, and most (about 80%) is used in making concrete. The production of cement dominates the energy used in making concrete and is the main source of associated CO_2 emissions (Kelsall, 2023). The energy consumption comes from crushing, grinding and blending raw materials (limestone, shells, chalk, marl shale, clay, slate, blast furnace slag, silica sand, and iron ore); burning the prepared mix in a kiln fired by coal, and grinding the burnt product clinker, with gypsum. Most of the cement kilns in China that comprise almost 60% of Asia's fleet have an average age of 14 years, aligned with the rapid growth of the steel industry to support a burgeoning construction sector (Kelsall, 2023).

bp Energy Outlook 2024 considers fitting cement plants with CCS to be the main strategy to reduce industrial CO_2 emissions. It will be deployed in the US cement industry in 2024 as part of a major effort to decarbonise heavy industry (Perilli, 2024). Carbon sequestration is an important tool, but CCS alone may be a high-cost solution at rates of between 30 and 45 \$/t CO_2 for capture alone. As emissions are 0.9 tCO_2/tonne of cement, the consequence to USA prices of implementing CCS would be a rise from 150 \$/t today to at least 180 \$/t which is a considerable load on the industry, although CCS costs are expected to lower over time (Dale, 2024; Cameron and others, 2023). The current aim is to lower global emissions from the cement industry by 20% by 2030, mainly by switching to alternative fuels and improving plant operation (Kelsall, 2023).

A complementary approach is to substitute the Portland cement with coal fly ash or ground blast furnace slag obtained as a waste by-product from power and steel plants; *see* Reid and others (2020) and Tang and others (2023) for a discussion of the practice and benefits of using fly ash. Before 2010, fly ash content was limited to 10–15% of Portland cement, but this is changing to include more fly ash and slag. In China, projects applied 25% fly ash substitution with additional ground granulated blast furnace slag (GGBFS) for Portland cement to produce concrete with increased water impermeability in the Macao-Hong Kong bridge/tunnel project, with a new limit of 40% fly ash replacement considered an upper bound. One example of a concrete structure using GGBFS is depicted in Figure 13, the 3.4 km Colne Valley Viaduct that is a key part of the High Speed Two (HS2) rail project in the

UK (HS2, 2024). A foundation section at HS2 Euston Station used Earth Friendly Concrete that is a mix of fly ash, GGBFS and geopolymer that has no Portland cement content.

Figure 13 Colne Valley Viaduct, UK HS2 rail project, UK (Wikipedia: Nathan Grier, 2024)

Allowing a higher degree of substitution of Portland cement has been considered impractical due to reduced exothermic reactions making setting times too long. A more gradual reaction time is beneficial in reducing micro-cracking in finished concrete and permits larger sections to be completed, but adding more fly ash would mean that concreting would take too long to complete.

In recent Australian research, the addition of 2% nano silica allowed up to 80% substitution of Portland cement by fly ash, where the silica acted to accelerate the hydration reaction. The cost of nano silica becomes key in this material, but as seen from the development of Earth Friendly Concrete, the trend is to maximise the use of waste materials to lower emissions (RMIT, 2024).

Reformulation of cement using coal combustion by-products offers reduced scale and cost impact of CCS required to minimise emissions from the cement sector. Adding more fly ash is also a potential route to provide concrete materials with superior structural properties while using fly ash and GGBFS lowers the cost of the finished concrete structure (Yu and others, 2024b). These findings indicate a potential route to lower emission cement manufacture without excessive costs.

The cement industry is incorporating these decarbonisation measures. Reformulation often means an improved material and CCS is being adopted in the USA. China's construction industry has slowed but that is not the case elsewhere, with India preparing for major infrastructure investment.

Decarbonisation technologies that include bio feedstock, CCS and increased substitution by fly ash and GGBFS would lower emissions but require further research to prove longevity (Kelsall, 2023).

7.3 COMMENTS

Coal power stations and the Chinese steel industry are both difficult and costly to decarbonise, and for steel, CCS implementation is still largely on the drawing board, while alternative technologies and feedstocks are in the development phase. Chinese industry possesses young fleets meaning that they will remain operational for the next decades and have comparable retrofit challenges. The cement industry is already using reformulation with steel and coal by-products to lower emissions and substitute for Portland cement. It may be possible to reduce the cement content further, but more evidence of long-term durability is required. In many cases, the use of fly ash for Portland cement improves bonding and durability of concrete especially in challenging environments. Where steel has CCS and technology decarbonisation options, cement has a reformulation opportunity.

So, what are the relative prospects for CCS in chemicals, cement, steel and power? The plants are generally young, with perhaps coal gasification the youngest average age after a period of rapid growth. Coal gasification has a unique advantage with a high concentrate CO_2 stream that would offer a lower cost route to sequestration, and its sites in Northern China, such as Ordos, may be geologically well matched with CO_2 sinks, more so than in the industrial eastern states.

8 CARBON PRODUCTS AND RARE EARTH ELEMENTS

The focus of this study is coal gasification, which consumes over 400 Mt/y of coal and has become a major industry since 2018. However, a separate development in non-energy uses of coal is the extraction of rare earth elements (REEs) from non-conventional deposits in coal mines. The REEs are comprised of lanthanides including those with magnetic properties such as neodymium, along with dysprosium and terbium. In addition to lanthanides, yttrium is prized both as an additive to aluminium and magnesium alloys and for the construction of powerful lasers. The REE content associated with coal is lower than conventional ores; an ICSC study on REEs from coal and coal wastes is available (Mills, 2024).

Much of the world's rare earth ore deposits are found in China, as is almost all the refining capacity for difficult purification processes that require strong acids, and usually involve radioactive elements. In 2023, China placed restrictions on the export of REEs and others; in the latest case gallium, germanium and graphite, all important to the semiconductor and automotive industries (Yang, 2023). These trade restrictions are in response to limitations on the export of manufactured semiconductors highlighted by the partial withdrawal of IBM, Apple and others from China as part of a developing trade disagreement between China and OECD countries (Chakka, 2024).

China's REE status means that it has the economic power to influence the development of key industrial sectors associated with the energy transition: electric vehicles (EVs) traction motors, wind turbine magnets, domestic appliances, servo motors in robotics, LED screens and many others (Reid, 2018). Over the last decade, China has targeted natural resource deposits in other countries; access to these resources may be linked to China's Belt and Road Initiative which aims to ensure raw materials for China and optimised export routes for finished products (Metzger, 2021).

As the trade war expanded in 2024, countries including the EU, USA and most recently Canada proposed tariffs on EVs to protect domestic products from price-advantaged Chinese cars. The EU proposed an increase in tariffs from 10% to 45%, but China wishes to avoid tariffs and may agree minimum price commitments or investments into Europe instead (Cheetham, 2023).

The current status is that the price of REE has fallen from its peak and as China controls the supply, this may be simply an outcome of lower demand or a strategy to hinder the growing number of developments outside Asia, including new prospects in Sweden and Brazil. The latest developments are some strengthening in prices due to the conflict in Myanmar, a significant source of rare earth ore (SMM, 2024).

8.1 RARE EARTH ELEMENTS AND GRAPHITIC PRODUCTS

The evolving trade barriers increase other countries' determination to find indigenous economic deposits and to develop appropriate processing techniques that meet environmental standards. There are several new prospects but the development of a new mine with approved permitting can take over 15 years (Mills, 2024). Generally, in coal mines, REEs may be present at less than 30 ppm, far below the concentration required for economic recovery. The ash from coal has concentrated levels of REEs, typically increasing concentrations by a factor of 8, but REE become encased in a glassy coating making recovery more awkward; nevertheless, there is mounting interest in extraction from ash waste ponds (Mills, 2024; Fatunde, 2024). There are cases where the levels of REEs in coal mines are sufficiently high that coal can become a resource of minerals essential for new technologies and that is the focus here.

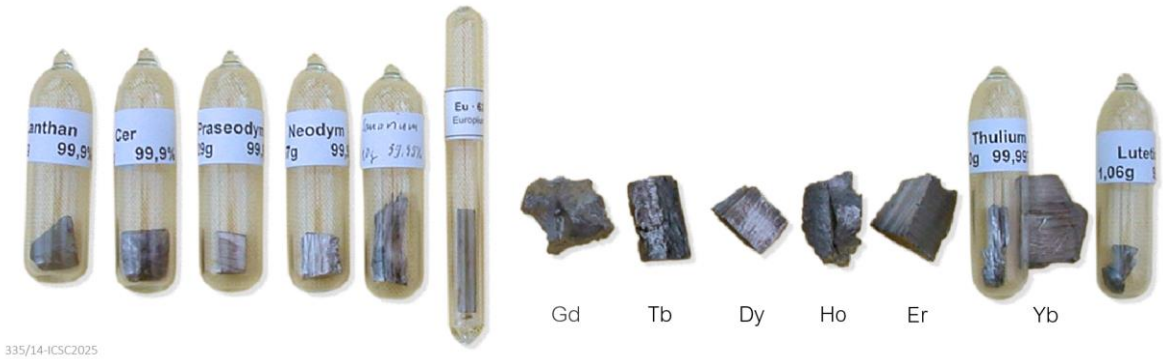

Figure 14 Lanthanides or rare earth elements (Wikipedia: Tomihahndorf, 2024)

The lanthanides that form the most critical elements, shown in Figure 14, include key magnetics for power and transport applications. The demand for neodymium for electronic, EV, radial and axial motors, specialist glass, and wind turbines continues to grow. For example, a wind turbine requires 300 kg of neodymium in the generator, and this is leading to a rising global market for critical elements expected to exceed 130 kt by 2030 compared to 93 kt in 2023 (IEA, 2024b).

The ICSC reports (Reid, 2018; Mills, 2024) refer to the Brook Mine in Wyoming, USA owned by Ramaco Carbon. The mine location means that it is no longer practical to extract coal for power plants as many have closed in the USA, so a different approach was adopted, converting low-cost coal into other products and rebranding coal as carbon ore. The intention was to process coal at the mine into finished goods, by chemically processing 15 $/t coal into valuable chemicals, fuels and graphitic products.

One option for the Brook Mine is to produce activated carbon, an important product given global freshwater shortages and the expansion of water treatment facilities; the remaining fraction would yield distillate fuels and feedstock for tar chemicals. As well as conventional coal chemicals, part of the novel thinking for this project is to produce graphitic carbon.

The plans for the Brook Mine have changed dramatically since 2021 with the discovery of REEs at the site. What was conceived as a coal mine with carbon product production on site has changed to a REE mine with coal products still important, but now a by-product. Ramaco has undertaken an extensive geological survey of the property with hundreds of boreholes drilled to evaluate the deposit. Of the 6300 hectare (ha) site, 1800 ha is fully permitted for mining. This zone is the focus of the exploration programme. The deposits are classed as unconventional as the REEs are located above and below the coal seams in soft clay amenable to conventional mining. The deposit is assessed as one of the most promising sources of REEs worldwide, even when compared to China's heavy REE resource, where REEs are found at higher concentrations but in hard igneous mineral matrices (Ramaco, 2024).

The focus is on the extraction of REE given the perceived vulnerability of industry in OECD countries to China's control of the supply of these critical elements. The discovery of germanium which is also subject to export controls in the Brook Mine deposit has only increased interest in the project (Atkins, 2024).

The coal will be recovered and separated from the REEs. The original plan to make activated carbon and co-products on-site still has merit and the emphasis is changing to maximise graphitic products production. The concentration of REE is much greater than for other known coal mine deposits, but still lower than for conventional REE ore, meaning a different processing route is needed, at least in the initial stages. Pilot refining plants have been developed for low REE concentrate, for example by Prof Honaker at the University of Kentucky, USA. The economics have delayed the implementation of the technology, but the clay matrix of the Brook Mine resource may be instrumental in lowering the cost and simplifying the methodology for REE recovery from coal (Clinton, 2018).

8.2 GRAPHITIC PRODUCTS

8.2.1 Graphene

Graphene is a carbon material that may be extracted from graphite and is made from a single sheet of carbon forming a honeycomb nanostructure only one atom thick. Graphene is strong, flexible, light and possesses high resistance. There are over 150,000 graphene-related patents with leading applications in energy storage and polymers, and other uses cover bioengineering, optical electronics, composite materials, ultrafiltration, and more (Reid, 2021). Thus, developments in graphene are still only at the beginning (Graphene Council, 2024).

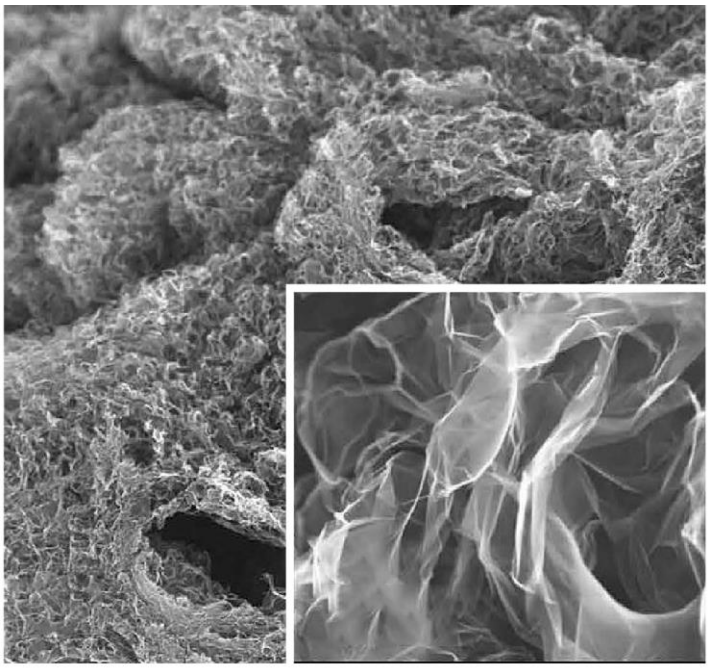

Figure 15 Scanning electron microscope (SEM) image shows the repeating structure of a graphene-nickel foam (Wikipedia: Paronyan and others, 2017)

Figure 15 is an image of graphene foam exhibiting the cellular structure of graphene. It is made up of single-layer sheets of graphene. Foams are highly conductive and have uses in lithium-ion battery electrodes and potentially for electrolysis catalytic applications.

The price of graphene varies depending on the quality of the product, but prices in the range of 100-400 $/g are quoted. For example, graphene oxide is suitable for composites and biotechnology at lower prices than carbon vapour deposition (CVD) graphene which can be used in flexible touch screens and battery components (Pistilli, 2024). Currently, the cost is dominated by the transfer of graphene from the substrate on which it is grown, and the feedstock price is not an important factor; commercial products are dominated by methane gas CVD production techniques. For studies reviewing products derived from coal, the interest is in the potential to use coal as a feedstock, in the expectation that mass production will eventually mean the feedstock becomes a significant cost factor, or researchers identify specific advantages of coal precursors. The market for graphene already exceeds $500 million with a substantial CAGR (compound annual growth rate) of over 40%, making it a material with huge potential to penetrate many market sectors.

Given the status of graphene, research in the coal-to-graphene field is advancing with some important findings. The main achievement is the demonstration of a range of technical options to produce graphene. Several methods listed below can yield graphene, some of them are dependent on the fact that graphene is already present in many coals. What is notable are the multi-pathways to yield graphene:

- Flash Joule Heating (FJH) – millisecond rapid heating;
- electrolysis – oxidising reactive carbon retaining graphene precursors;
- nitric acid treatment of powdered coal producing graphene oxide;
- molten salt coal to graphene; and
- chemical route to quantum dots.

The electrolytic and chemical routes to graphene work mainly by reacting away amorphous carbon in coal leaving crystalline groups of carbon atoms that can be extracted as quantum dots or used to build graphene sheets, which are the more valuable form of graphene. In contrast, FJH instantly vapourises and disassociates coal into individual carbon atoms, which coalesce on gradual cooling to form graphene. In this case, graphene is an intermediate carbon form that is preserved by cooling. The FJH technique can operate on other compounds with a high carbon content including bio feedstock, but the easy availability of coal is potentially attractive. Electricity needed by FJH can be sourced from renewable supplies and there are reports of scale-up in an automated system that can produce graphene from metallurgical coke at a rate of almost 1 kg/h (Eddy and others, 2023). The FJH technique has also been trialled on anthracite in the laboratory with claims that this is a cost-effective route to making well-defined graphene structures (Liu and Luo, 2024).

CVD production techniques dominate graphene production, but coal-to-graphene has shown 'proof of concept' at a modest scale and is an option for the future. The use of coal as feedstock will depend on many factors, but relative cost as the price of graphene inevitably falls will be the most important.

8.2.2 Pitch carbon fibre

The attraction of coal tar pitch carbon fibre is the low-cost precursor material that makes this material good value for energy production and storage applications. For example, electrospinning methods turn pitch carbon fibres into supercapacitor anodes. The pitch must be carefully prepared to remove the non-soluble material which produces flaws, but the SEM images in Figure 16 show well-formed spherical fibres with a fine porous structure. This represents a significant advance in the manufacture of quality coal tar fibres (Daulbayev and others, 2021).

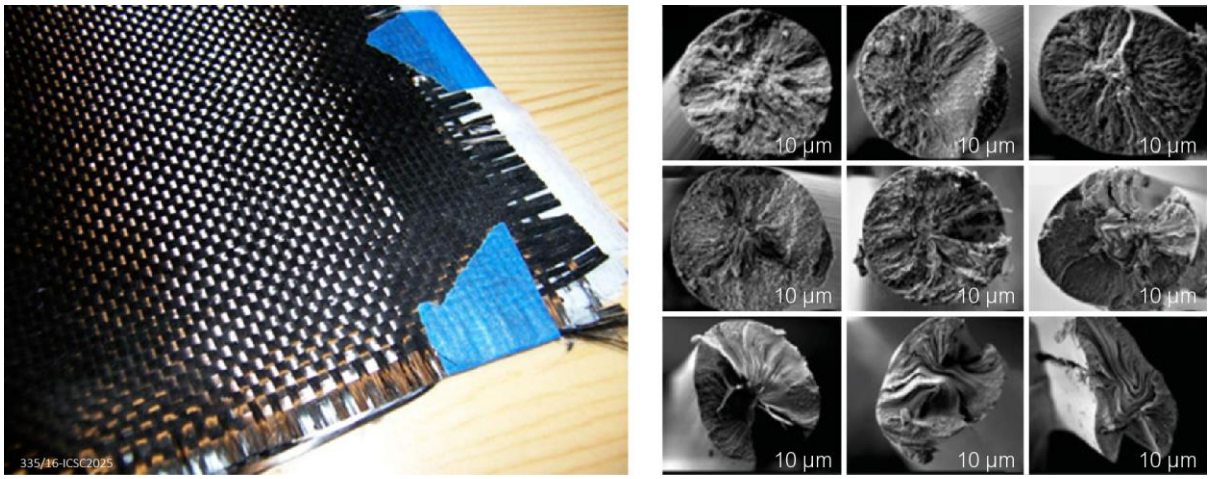

Figure 16 Fabric made of woven carbon fibre filaments (Wikipedia: Hadhuey; SEM images of pitch carbon fibres (Daulbayev and others, 2021)

The technical demands associated with pitch carbon fibre manufacture are: the avoidance of defects that affect strength; and the fibre porosity which influences both strength and electrical properties. Sometimes pitch and polyacrylonitrile (PAN) fibre are combined to achieve lower cost material with the required properties, given that PAN fibre has higher strength and cost.

Mitsubishi is a leading producer of pitch-based carbon fibres. It makes Dialead, the main pitch fibre material for aerospace applications with a high tensile strength of 3.6 GPa and conductivity of 140–800 Watts/metre/Kelvin (W/m/K), while the main European producer, Solvay's Thornel P-25 possesses a lower tensile strength (1.56 gigapascals, GPa) and thermal conductivity (26 W/m/K). These data for commercial pitch fibres compare to PAN fibres at near 20 W/m/K. and 5 GPa tensile strength. Thus, pitch fibres can be close in strength but, more significantly, exhibit exceptional conductivity (Dialead, 2024).

The market for carbon fibre has increased rapidly in recent years, from $4.7 billion in 2022 and it is expected to double by 2030 (Grand View Research, 2023). PAN fibre dominates the market, with 96% of carbon fibre revenue. This partly reflects the additional skills required to make high-quality pitch fibres that include preparation of the tar and formation of mesophase pitch prior to melt spinning. However, the dominant reasons are that pitch fibres struggle to compete in strength with the market seeking higher strength-to-weight ratios for rapidly increasing transport applications, and PAN fibre already dominates the composites market.

The use of mixed PAN and pitch fibres together with graphene strengthening of PAN fibre and new energy applications where strength is less important could raise demand for lower cost pitch fibre in the future. One new application is for direct air capture (DAC) where high surface area/high electrically conductive pitch fibre, possibly coated with sorbent material, may be ideal for the capture of CO_2 when coupled with electrical resistance CO_2 discharge (Atkins, 2023). In carbon capture, the

economic target is less than 40 $/tCO$_2$, with 10 $/t CO$_2$ quoted for 'coal-to-chemicals' benefiting from a concentrated CO$_2$ supply. The target for DAC with 400 ppm CO$_2$ present in atmospheric air, is much higher at 250 $/t CO$_2$, which is met by this fibre capture technique at 160 $/t CO$_2$ assessed (Lee and others, 2023).

8.2.3 Graphite

China possesses the largest global deposit of natural flake graphite, with reserves of 78,000 t, followed by Brazil with 74,000 t (Figure 17). However, in 2023 China placed restrictions on the export of both this and synthetic graphite produced from needle coke that can be obtained from petroleum or coal tar (FTI, 2023).

As graphite is a key component for batteries and industrial electrodes, the restriction of exports has led to renewed interest in making synthetic graphite. There are already a few synthetic graphite producers, including Anovion (USA), Novonix (Australia), Resonac Holdings (Japan) and Vianode (Norway) with others in China Kuntian New Energy Technology, Shanshan Technology and BTR New Energy Materials. There are 125 battery gigafactories in China, ten times the number elsewhere, reflecting the importance of graphite to the Chinese economy and the reason for its supply controls (Barnard, 2023).

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Figure 17 Natural graphite showing layered structure discovered in New England, USA (Wikipedia: Rob Lavinsky, 2010)

Synthetic graphite is produced by the Acheson process. Graphite is obtained by the high-temperature processing of carbon with quartz, at temperatures exceeding 1700°C. Silicon carbide is the primary product. Further heating beyond 2500°C leads to synthetic graphite as the silicon is evaporated. The most recent version of the process uses a Castner lengthwise graphitisation furnace where carbon/silica rods are heated for up to 20 hours and the rods are in contact with carbon electrodes so that the 300 amp current flows through them. Recent developments have focused on the power

density and thermal efficiency of the furnace to reduce the power demand of what is an energy-intensive process (Shang and others, 2024).

A high energy consumption process does not fit well with the drive to lower emissions; most synthetic graphite is produced in Inner Mongolia where the electricity has historically been obtained from coal power plants. The main feedstocks for synthetic graphite are coal tar pitch and calcined petroleum coke; pet coke is preferred but coal tar pitch-based coke is cheaper. The coal-to-synthetic-graphite process consists of distillation to remove anthracene oil, which is too volatile, to produce pitch which is then carbonised to needle coke. The needle coke is then shaped, baked, pitch-impregnated and rebaked, and finally graphitised (Li and others, 2024).

An alternative electrochemical process to produce graphite at lower cost is in development at Oak Ridge National Laboratories (ORNL), USA in association with Ramaco Resources. Instead of coal tar, the process begins with coal char, a devolatilised coal which is a lower-cost alternative. It is converted to graphite at milder conditions of 850ºC. In addition to the low reaction temperature, electrolysis of the char is complete within five hours, which is much faster than the Acheson process. The mild cathodic polarisation of amorphous carbon could replace high-temperature processing with coal char acting as the anode in the electrolysis cell. Several process steps are eliminated, and this method offers substantial, or even transformational cost savings in manufacturing synthetic graphite. The aim is not to produce the highest quality graphite but to make a material that is suitable as a replacement for graphite in many applications (Yurchick and others, 2024; ORNL, 2024). The field is attracting other researchers with the prize of a mild electrochemical graphite process. One example is graphite from CO_2 feedstock and other amorphous carbon sources such as carbon black, using similar techniques to ORNL (Zhu and others, 2023).

8.3 COMMENTS

During 2024, several potential REE resources have been identified outside China including Sweden, Brazil and even undersea deposits in Japan. For the coal industry and Western nations, the discovery of REEs together with gallium and germanium at the Brook Mine in Wyoming is potentially of economic significance, as this mine is already permitted, overcoming a significant barrier. The REE matrix is advantageous in the development of less polluting refining methodologies, the reason for China's dominant technical position in REE (Mills, 2024). REE levels are lower than in conventional ore, but there are concentration methods available, so recovery of these elements is practicable. The coal associated with critical elements also has the potential to support the economic case for the mine, and the original plans to make carbon products remain important, including carbon fibre and graphite, another material controlled by China. The focus for Ramaco Resources is metals recovery, but on carbon products, the targets are evolving too, and what is sought are materials of sufficient quality to meet the needs of applications, perhaps easing the route into production.

Since the publication of the ICSC report (Reid, 2021), the prospects for pitch-based carbon fibre have improved. PAN fibres exhibit higher strength, but the lower cost pitch-based fibres appear ideal for a suite of applications in energy storage. Where cost is key then the use of mixed fibres is another avenue that has not been fully explored and offers a new outlet for pitch fibre as cost reduction is targeted, for instance, to overcome the higher manufacturing cost of heavy EVs.

9 CONCLUSIONS

This century has witnessed rapid industrialisation in China in coal power, steel, cement, and chemicals. The achievements are remarkable; for instance, the blast steel furnace fleet now accounts for half of global production. It came on stream in a short timeframe, as the average age of the fleet is only 15 years old. Coal gasification is another industry that has grown rapidly, scaling up from only a few plants in 2018 to become a major manufacturing route to chemicals within five years. The gasification industry is not as carbon-intensive as steel and cement making, as a significant proportion of the coal carbon can be present in the products. Nevertheless, it is a more carbon-intensive way of producing chemicals than the petrochemical route. This may create a vulnerability as importing nations seek more sustainable routes to plastics. While there are new coal gasification facilities under construction, the predominant number of new polymer plants are located near the coast and will be petrochemical based. There are new facilities, such as Sinopec's Inner Mongolia $4 billion coal mine to 'coal-to-chemicals' project using 10 Mt/y of coal to make 800,000 t/y of olefins. An expectation is that the sector will increase by around 20% by the end of the decade, a much slower growth rate than previously experienced. A key driver of feedstock security is losing momentum given there is already a significant industry, but also due to concern about climate change and overcapacity in coal-to-chemicals. However, 'coal chemicals' is already a global scale sector and as a young industry it will be a contributor for decades and demand will increase to mitigate emissions.

Carbon capture

Carbon intensity can be addressed by carbon capture and storage. Coal gasification plants offer a technically easy path for capture as they produce a high-concentration CO_2 stream. There are CCUS units under construction and some in operation to decarbonise chemicals production; with overall capacity to remove up to 500 $MtCO_2/y$, almost half of the current annual emissions from the coal chemical industry. The issue is that while the carbon capture cost is relatively low, there does need to be alignment with storage to limit pipeline costs. CCS may be an appropriate technical solution for reducing CO_2 emissions for some gasification plants and coal gasification units offer an easier path than for other heavy industries.

Hydrogen

There are other options to increase sustainability of the chemical sector that include using less feedstock, and alternative bio feedstocks, but perhaps the most interesting option is to co-feed electrolytic hydrogen to change syngas composition. Adding more hydrogen reduces the need to convert carbon monoxide to carbon dioxide to obtain the correct H_2/CO ratio needed to make methanol, the key gasification intermediate. Water-gas-shift chemistry is the main route to convert carbon monoxide to CO_2 and hydrogen, but adding hydrogen independently means more coal carbon can be incorporated into products and less CO_2 emitted. The other benefit is that total syngas

production increases as more of the coal-sourced CO is converted to methanol, lowering the amount of coal needed to below three tonnes of coal per tonne of methanol.

The argument against hydrogen as a fuel is that it is a costly inefficient process that makes little sense when the product is a fuel that is hard to store and transport (Liebreich, 2023). The argument for electrolytic hydrogen is rather different when it is used as a local chemical feedstock. The cost of electrolytic hydrogen must be competitive, and one producer claims close to coal gasification hydrogen cost (1.3 $/kg compared to 1 $/kg for gasification hydrogen). This is much lower than costings from most nations, and surprising at this stage of development (Collins, 2022). The other factor is that the integrity of the electrolyser must be sustained using intermittent renewable power, an active challenge to all those seeking to make hydrogen this way. New installations will be powered by dedicated solar farms and wind turbines. The expansion of hydrogen production in China suggests this is a credible option that fits with China's drive to add renewable generation and would meet future European product sustainability specifications. Although adding cost, technical barriers would be alleviated by providing a constant source of hydrogen to avoid the variable operation of electrolysers and water-gas-shift reactors.

Plastic waste

Carbon intensity is one threat to the coal gasification industry, another is the issue of plastic waste. Plastics are present in almost all products and are not easily substituted; most alternatives require more energy input. Less than 10% of plastics are recycled. There are initiatives to improve recycling and to reduce single-use plastic, but plastics are already present in the environment and more accumulates each year. There are promising research initiatives that would support a circular economy, and leading these is a technology that converts plastic back to gaseous base components to make virgin plastic. The development of a circular economy in plastic requires local polymer production and could impact the demand for fresh coal chemicals in China.

Plastic can persist in the environment for decades but is subject to mechanical breakdown into nanoparticles as it disintegrates. These particles appear in natural systems: water, plants and animals including humans. The impact of this is not yet clear but early indications are that the presence of polymer nanoparticles accelerates some diseases such as cardiovascular conditions. The manufacture of polymers is set to increase markedly in the coming decades and is likely to come under more scrutiny, particularly as the health implications may present a disquieting issue for investors, companies and governments, not just for coal chemicals but for petrochemicals too.

Critical elements and graphitic carbons

China's near monopoly position in critical elements that include the resource and refining of rare earth elements, germanium and gallium and graphite, concerns other nations as they are critical to 21st century industries. Outside China, countries are seeking alternative sources with developments

commencing in Sweden and Brazil among others. The ICSC focus is on the connection to coal, including coal mines, coal waste streams such as acid mine drainage, coal tailings, and fly ash (Mills, 2024; Reid 2021). The concentration of REEs in the Brook Mine, USA, lies between that of coal waste and ore in conventional mining, but the deposit has no radioactive elements, REEs are more easily extractible by conventional mining methods, and the overall size of the deposit is substantial and of international significance. The original intent at the mine was to produce coal carbon derivatives at the Minehead using low-cost coal and avoiding transport costs for raw coal. The most attractive carbon products considered are graphitic such as carbon fibre and synthetic graphite. The focus now is on extraction and processing of rare earth elements. New thinking seeks to make products using lower energy methods that are of sufficient quality only for applications but are more appropriate to an industry seeking to minimise emissions. The mine as a carbon and mineral resource sets a new vision for the industry.

Closing comments

The coal gasification industry at scale is relatively new and a large consumer of coal. It has been established in China over a short period and with success in reactor technology deployment and downstream product quality. The sector provides China with a degree of indigenous feedstock security, but as an already major contributor to chemicals, dominant in methanol, this driver is now less important.

New coal-to-chemicals projects are planned but the momentum has lessened. Coal-to-chemicals was outside China's CO_2 emission reduction plans, but this is no longer the case, and it may be more cost-effective to retrofit this industry than others such as steel or power. China is rapidly expanding hydrogen production by electrolysis, and an independent source of hydrogen could transform the carbon profile of the coal-to-chemicals industry; much more coal carbon can be incorporated into products and CO_2 emissions minimised. There are technical difficulties but given the coal chemical industry is already in place and will be in production for decades, this way of utilising hydrogen may be more impactful than any other.

Plastic recycling is important and technologies that return basic reactants appear most promising as these avoid additive issues; a growing recycling sector could eventually reduce demand from China for chemicals. The pervasive nature of nanoplastics and their presence in humans mean plastic waste is potentially a more serious issue than was originally thought. This could fundamentally affect the industry in the future.

The concept of coal as a carbon resource has been growing, aided by the emergence of new allotropes of carbon with a burgeoning range of products. The graphitic carbon sector is of especial interest although coal often competes with gas feedstock where processing to obtain pure products is easier. The role of coal may be improved if different product qualities are needed, for instance, carbon fibre

for capture plants and energy storage requires high conductivity but modest strength. This different approach could unlock the coal-to-carbon sector. The coproduction of minerals and coal at a mine opens new opportunities for coal as a resource. The fact that a coal mine can be an important resource for critical elements and carbon products is a new development for the industry.

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