Coal-to-oil, gas and chemicals in China

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Abstract

This report provides a review of the Chinese energy security concerns, since imports are providing an ever increasing proportion of the oil and gas used compared to domestic supplies. Due to the relative paucity of Chinese oil and gas reserves, the government has adopted a policy of diversification by securing supplies via overland pipelines and by tankers from various sources. At the same time, due to its abundant coal availability, China has initiated very significant industrial development and demonstration programmes to establish certain coal transformation processes. These cover coal-to-oil, gas and key chemicals, namely olefins, dimethyl ether and ethylene glycol. These programmes are at the stage where some very large industrial-scale projects are being constructed while for coal-to-oil, a major demonstration and three industrial pilot units are already operational. As such, over the next few years, China could establish first user advantage for many such processes. However, it is not at all certain that the originally perceived deployment of commercial-scale technologies will follow. For example, concerns have been raised regarding excessive use of coal and water to produce quantities of product that will not significantly reduce the projected import levels of oil. At the same time, chemicals made from coal may struggle to be competitive with imported materials produced from low cost gas supplies. Consequently, the state government has reined in both the scope and the pace of the originally expected developments. While some technologies may proceed beyond the demonstration stage, the very large investments necessary to establish significant capacity may not represent the best use of Chinese financial capital. Consequently, the future of all these coal transformation projects will depend on how China deals with the increasing challenges of balancing economy, energy and environment, as part of its aim to establish sustainability of its long-term development while, at the same time, addressing shorter term issues such as matching supply and demand.

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Abbreviations

bbl/d	barrels per day
°C	degrees centigrade
CAS	Chinese Academy of Sciences
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
COS	carbonyl sulphide
CTC	coal-to-chemicals
CTL	coal-to-liquids
CTO	coal-to-olefins
DCL	direct coal liquefaction
DME	di-methyl ether
EOR	enhanced oil recovery
Gt	gigatonnes (1 billion tonnes)
H_2	hydrogen
H_2S	hydrogen sulphide
HTFT	High Temperature Fischer-Tropsch
ICL	indirect coal liquefaction
IPR	intellectual property rights
km	kilometre
kt	thousand tonnes
LTFT	Low Temperature Fischer-Tropsch
LNG	liquified natural gas
LPG	liquified petroleum gas
Mt	million tonnes
MPa	megapascal
MTG	methanol-to-gasoline
NDRC	National Development and Reform Commission
PE	polyethylene
PM_{10}	particulate matter under 10 microns in diameter
PP	polypropylene
PVC	poly vinyl chloride
RMB	Reminbi
SNG	synthetic natural gas
SO_2	sulphur dioxide
SOE	state-owned enterprise
UCG	underground coal gasification
US DOE	United States Department of Energy
US$	United Sates dollars
VOCs	volatile organic compounds

Currency converter

All costs quoted in this report are given in the units used in the original references. These are either the Reminbi (RMB), China's currency, which has been used in various Chinese estimates of equipment costs, or US dollars (US$), which have been used where such estimates have been attributed to, say, an international technology supplier. The current exchange rate is 6.8 RMB:1 US$. However, caution must be used as while the RMB: US$ exchange rate was traditionally constant, it has changed significantly since the onset of the global financial crisis.

Contents

1 Introduction

1.1 Background

A key part of Chinese energy policy is to ensure security of supply, and this is a critical issue since the country is rich in coal resources but has comparatively limited supplies of oil and natural gas. Over the last decade, there has been a very rapid and extensive industrialisation of the economy, which has been fuelled to a very significant degree through the massively increased use of coal, as has been discussed in previous reports (Minchener 2004, 2007, 2009, 2010). At the same time, there has been a significant increase in the use of petroleum products in the transport sector while both oil and gas have also been the starting point for transformation to other key products in the chemical sector. This has led to national demand exceeding domestic supplies, with an ever increasing level of imports. Oil prices have shown considerable volatility, within a generally upward trend, while gas prices are now starting to cause concern, all of which have caused additional strains within the Chinese system.

To put that in perspective, China first became a net oil importer in 1993 (*see* Figure 1) since when the gap between domestic supply and demand has grown very quickly (EIA, 2009). This is particularly the case in the last ten years when China's oil demand has rapidly outstripped domestic oil production. Imports now account for over 50% of China's oil supply.

The situation is similar for natural gas. Although this fuel currently accounts for just under 4% of China's primary energy consumption, the expectation is that it will increase towards 10% over the next decade and demand is growing far quicker than domestic production, with ever greater shortfalls projected in the period to 2020 (People's Daily, 2010b).

Besides the primary fuels themselves, oil and gas are also the raw materials for transformation to a range of chemicals and associated products for which there is a very strong market in China. Over the last decade, China has increased significantly both chemical production and consumption. Figure 2 shows

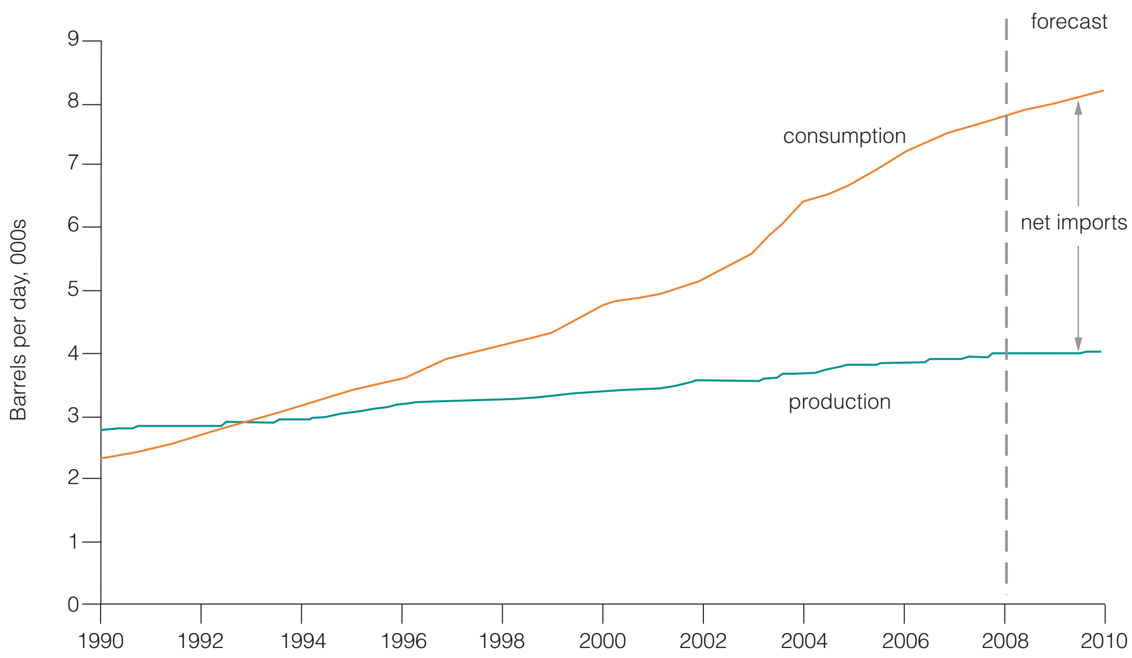

Figure 1 China's oil production and consumption 1990-2010 (EIA, 2009)

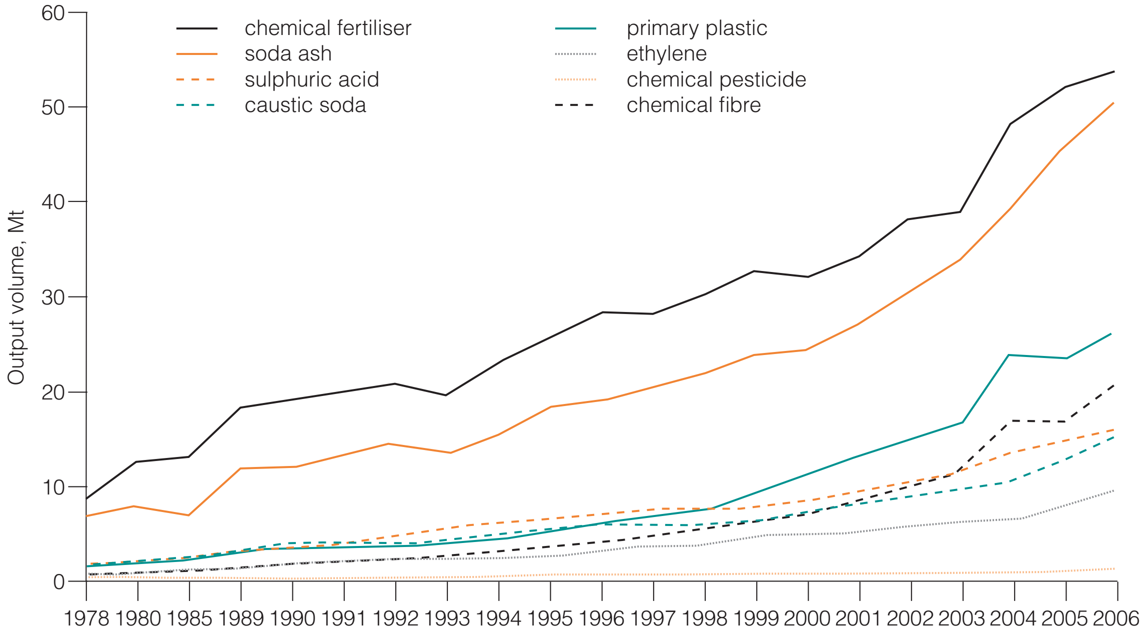

Figure 2 Chemicals production output in China from 1978 to 2006 (China Knowledge, 2007)

Table 1 Top ten chemicals production companies in China for 2006 (China Knowledge, 2007)

Ranking	Company	Annual revenue, billion RMB
1	China Petrochemical Corp	1065
2	China National Petroleum Corp	894
3	Sinochem Corp	184
4	China National Offshore Oil Corp	132
5	China National Chemical Corp	68
6	Shanghai Huayi Group Corp	29
7	Tianjin Bohai Chemical Industry Group Corp	26
8	Shandong Haihua Group Corp	19
9	Sichuan Hongda Chemical Corp	17
10	Jiangsu Sanfangxiang Industrial Company	17

the output for the major chemical products from 1978 to 2006, by which time the gross industrial output of the chemical industry reached RMB 2.2 trillion in revenue terms (China Knowledge, 2007).

The top ten chemical production companies within China in terms of revenue for 2006 are listed in Table 1. These are all state-owned enterprises, with the top four being from the petrochemical sector. In recent years, there has also been a significant influx of foreign companies into China's domestic market, with several organisations setting up co-operative ventures, particularly to manufacture higher value products and speciality chemicals.

The increasing demand for oil and gas plus the need to maintain supplies of chemicals and other products, which cannot be met from domestic sources, represents a potentially significant energy security issue for China. The state government is implementing a wide range of measures to secure oil and gas from a diverse range of sources while also introducing energy efficiency measures in various production processes. As part of this initiative, there has been a strong interest in using coal rather than oil or natural gas as an alternative raw material for the production of transport fuels, gas and chemicals. Consequently, from 2004 onwards, China embarked on a structured programme of research and development, together with large-scale demonstrations, leading towards the establishment of a coal-based transformation industry to replace, at least in part, the use of oil and gas in the various fuel and chemicals sectors. This push has resulted in some very significant new entrants becoming involved in this sector. Thus the stakeholders that are establishing the large development and demonstration projects are mostly the major coal producers and power generation companies, all of which are seeking to diversify their business interests

1.2 Scope of the report

This report provides a review of the overall coal-to-chemical products sector in China, which includes various coal-to-oil and coal-to-gas developments together with the key coal-to-chemicals initiatives.

Following this introduction, Chapter 2 provides an overview of the coal conversion routes available for producing synthetic oil, gas and chemical products, which includes comment on their advantages and limitations. In all countries, irrespective of the technologies available, their deployment will depend on the government's policies and initiatives. Consequently, Chapter 3 describes the Chinese rationale for developing the various coal transformation products, including various national targets. This includes a review of the changes in policy during the last five years as a result of government resource and environmental concerns. Chapter 4 provides an overview of progress to date in establishing the technologies in the key market sectors. Chapter 5 highlights the key national coal transformation projects, including the various coal-to-oil demonstrations and other large-scale projects together with some major coal-to-chemicals developments. With all such projects, there are numerous other considerations beyond the technical performance of the process units and these are discussed in Chapter 6. Finally, in Chapter 7, the implications for future development and deployment of coal-to-oil, gas and chemicals within China are reviewed.

2 Overview of coal conversion routes

The main process routes have been covered extensively in a previous Clean Coal Centre report (Couch, 2008). Coal is a solid with a high carbon content and a low hydrogen content, typically only 5%, while transport fuels (gasoline/petrol, diesel and jet fuel) are currently derived overwhelmingly from crude oil, which has about twice the hydrogen content of coal. For coal to replace oil, it must be converted to liquids with similar hydrogen contents to oil and with similar properties. This can be achieved either by removing carbon or by adding hydrogen, while also largely removing elements such as sulphur, nitrogen and oxygen (Williams and Larson, 2003). There are two contrasting approaches to providing liquid fuels and other products from coal (Couch, 2008), as described below.

2.1 Direct conversion

In the direct conversion of coal, usually referred to as direct coal liquefaction (DCL), pulverised coal is treated at high temperature and pressure with a solvent comprising a process-derived recyclable oil slurry (Figure 3). The hydrogen/carbon ratio is increased by adding gaseous H_2 to the slurry of coal and coal-derived liquids, with catalysts added to speed up the required reactions. The liquids produced have molecular structures similar to those found in aromatic compounds and need further upgrading to produce specification fuels such as gasoline/petrol and fuel oil. Liquid yields in excess of 70% by weight of dry ash free coal feed have been demonstrated for some processes, albeit under favourable circumstances. Overall thermal efficiencies for modern processes are generally in the range 60–70%.

Processes have been developed to use coals from low rank lignites to high volatile bituminous coals. Higher-rank coals are less reactive and anthracites are essentially non-reactive (Additrontech, 2010).

There are two main variants of DCL, depending on whether or not the initial dissolution of the coal is separate from the conversion of the dissolved coal into distillable liquid products (Couch, 2008). Thus a single-stage liquefaction process provides distillates via either one primary reactor or a train of reactors in series. In contrast, a two-stage process provides distillates via two reactors or reactor trains

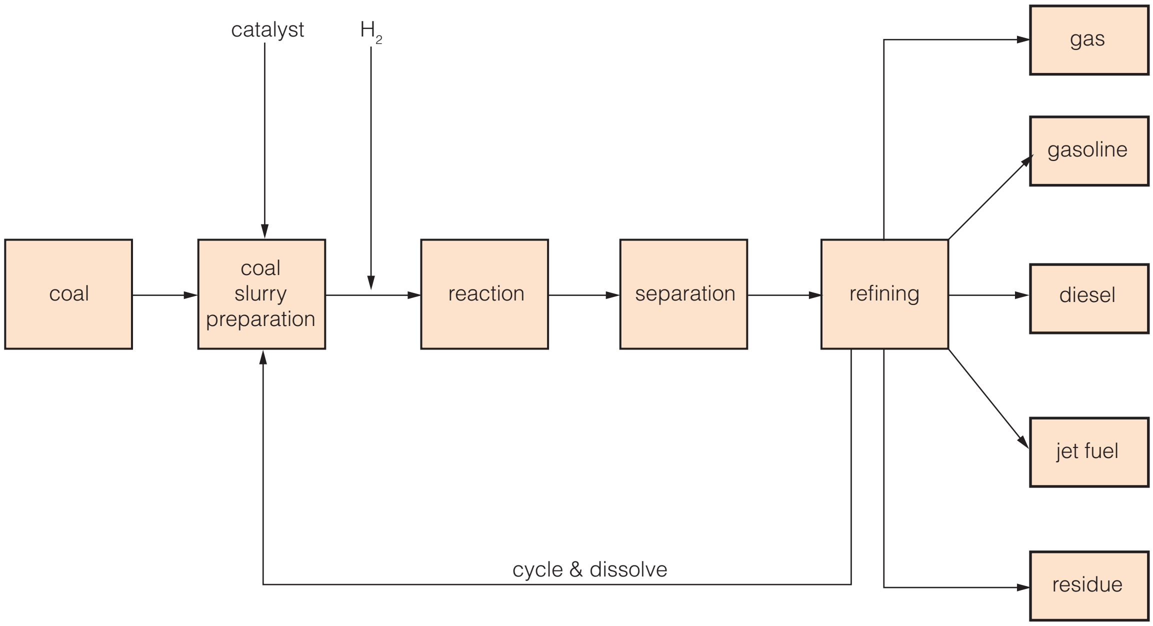

Figure 3 Simple process scheme for the direct coal liquefaction process (Deutsche Bank, 2007)

in series. The main function of the first stage is the coal dissolution, and it is operated either without a catalyst or with only a low-activity disposable catalyst. The heavy coal liquids are hydro-treated in the second stage in the presence of a high-activity catalyst to produce distillable products (DTI, 1999).

Hydrogen is also needed to reduce the oxygen, sulphur and nitrogen present. These are removed as H_2O, H_2S and NH_3 respectively. A range of partially refined gasoline-and diesel-like products, as well as propane and butane, can be recovered from the synthetic crude by distillation.

The range of liquid products produced by direct liquefaction depends on four major variables:
- the nature of the coal being processed;
- the solvent or solvent mix used;
- the process conditions, including temperature, pressure, residence time and catalyst;
- the number of reactor stages used, and the subsequent refining of the initial products.

The technology has yet to be proven at full commercial scale although China is now leading the way with a major demonstration (*see* Section 5.7).

Work has also been undertaken to develop a variant on the direct liquefaction processes, which is known as co-processing and involves the simultaneous upgrading of coal and a non-coal-derived liquid hydrocarbon. The latter serves as the slurrying and transport medium for the coal. It is usually a low-value high-boiling point material, such as bitumen, an ultra-heavy crude oil or a distillation residue or tar from crude oil processing. There is no solvent recycle loop and the underlying process may be either single- or two-stage. In practice, co-processing technologies are based on adaptations of existing direct liquefaction processes to a once-through non-recycling process, with most of the liquid product deriving from the oil rather than from the coal (DTI, 1999).

The overall aim of co-processing is to upgrade the petroleum-derived solvent at the same time as the coal is liquefied, thereby reducing capital and operating costs per unit of product. However, the non-coal-derived solvents are poor physical solvents for coal and poor hydrogen donors. This results in a relatively low conversion of the coal-to-liquid products. The economics, therefore, depend predominantly on the differential between the heavy liquid feedstock cost and the price of conventional crude oil. The addition of a low-price coal to the feed improves the process economics by reducing the average feedstock cost. Compared with other liquefaction routes, capital costs are generally significantly lower per unit of product.

Although some co-processing technologies have been developed to several tonnes per day industrial plant scales, they have not been developed to the same degree as other liquefaction processes.

2.2 Indirect conversion

This is a high temperature, high pressure process that first requires the gasification of either coal, other fossil fuels, biomass or coal/biomass mixtures to produce a syngas. For indirect liquefaction, this syngas is then converted to liquid fuels via two methods: the Fischer-Tropsch (FT) process or the Mobil process (Radtke and others, 2006). In the FT process, which is more common, the syngas is cleansed of impurities and subjected to further chemical refinement to produce sulphur-free petroleum products. In the Mobil process, the syngas can be converted to methanol, which is subsequently converted to petroleum products via a dehydration sequence (AAAS, 2009)

Oxygen blown gasification of the coal produces a syngas consisting mainly of carbon monoxide (CO) and hydrogen (H_2), which can be modified as necessary by using the water gas shift reaction in which water and CO react to form carbon dioxide (CO_2) and hydrogen, thus increasing the H_2: CO ratio. The syngas contains a number of impurities, including particulates, sulphur compounds (in particular H_2S

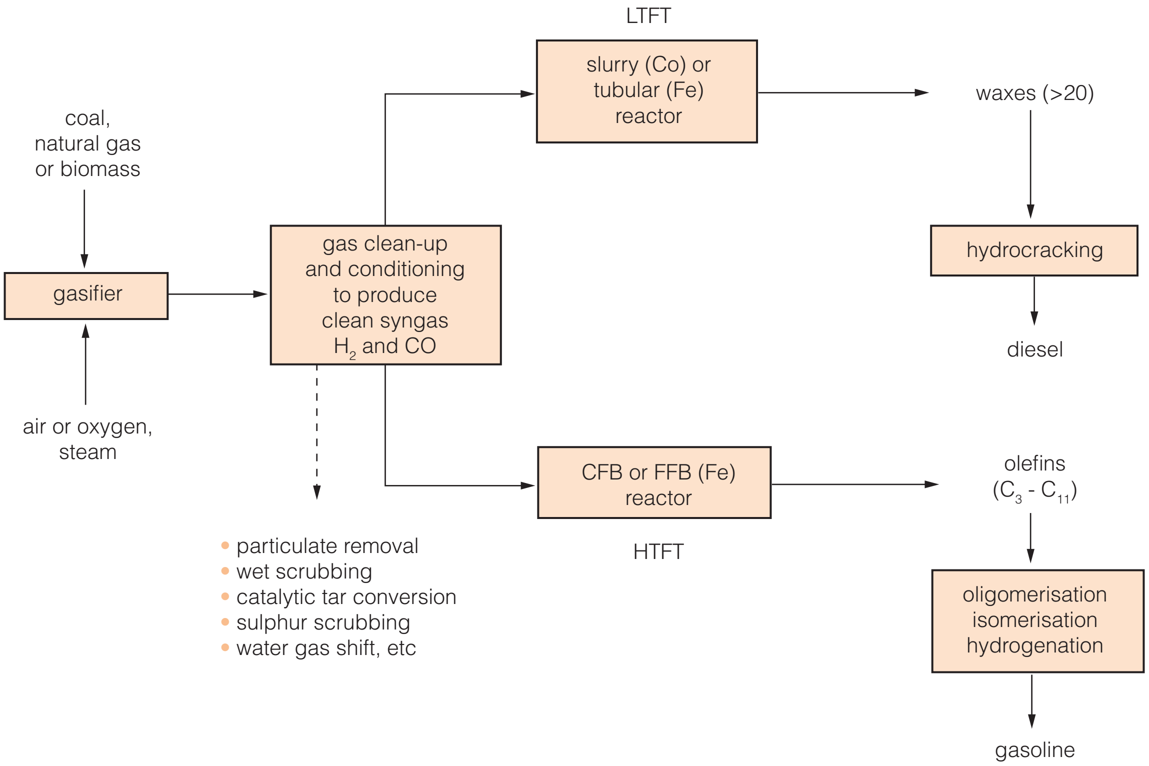

Figure 4 Flow diagram of the two generic routes to synthetic transport fuels using Fischer-Tropsch synthesis (Spath and Dayton 2003)

and COS) and nitrogen, which are removed in a series of clean-up stages after which the CO_2 is separated. The cleaned syngas molecules ($CO+H_2$) are subsequently catalytically combined/rebuilt to make the distillable liquids. These can include hydrocarbon fuels such as synthetic gasoline/petrol and diesel, and/or oxygenated fuels, together with a wide range of other possible products.

For FT synthesis, there are two main operating modes (Figure 4):

- high temperature (HTFT) technology, which operates at 300–350°C with iron based catalysts to maximise the petrol/gasoline fraction;
- lower temperature (LTFT) technology, which operates at 200–250°C with cobalt based catalysts and maximises the production of diesel.

For methanol synthesis, the carbon monoxide and hydrogen in the syngas are reacted over a catalyst, to produce the required liquid product. Linked to this is the production of di-methyl ether (DME), which involves de-watering methanol in the presence of a dehydration catalyst such as alumina (*see* Section 4.5).

Although more complex, indirect coal liquefaction (ICL) has a number of advantages over DCL. Thus:

- the principal product from the first stage is a gas which leaves behind most of the mineral matter of the coal in the gasifier, apart from any volatile components;
- undesirable components, such as sulphur compounds, are more readily removed from the gas;
- it is easier to control the build-up of the required products;
- there is good operational flexibility in that syngas made from any source (coal, petroleum residues, natural gas, or biomass) can be used;
- the CO_2 produced, in principle, can readily be captured for subsequent storage;
- the end products have near-zero aromatics and no sulphur. With minimal further refining it is possible to produce ultraclean diesel or jet fuel.

Besides synthetic transport fuels, the indirect conversion route offers the means for the production of chemicals and other feedstocks. Thus HTFT offers significant possibilities for chemicals production and the large quantities of light hydrocarbons produced can be used to make a substitute/synthetic natural gas (SNG). LTFT produces paraffin-rich products that are suitable for making synthetic diesel and waxes.

Each stage of these process variants involves commercially proven components and the technology has been used in South Africa on a commercial scale for many decades (Sasol, 2010).

3 Chinese government policies and initiatives

3.1 Rationale for development of the coal-to-chemicals sectors

As is shown in Figure 5, there is a very wide range of primary and secondary products that can be produced from coal.

As part of the nation's industrialisation programme, coupled with security of energy supply concerns, the sate government decided to establish coal-to-oil, gas and chemicals technologies in order to take advantage of the availability of indigenous coal supplies, introduction of advanced technologies, large high value market, and flexible downstream capability in terms of product slates. Thus, since 2004 and then under the 11th Five-Year Plan (2006-10), there has been a major development and deployment programme under way within these sectors, which in Chinese terminology are all grouped as coal-to-chemicals. China's strategy is to develop coal-to-chemicals (CTC) options that offer upstream integration with coal mines, while also allowing for the plants to be integrated to

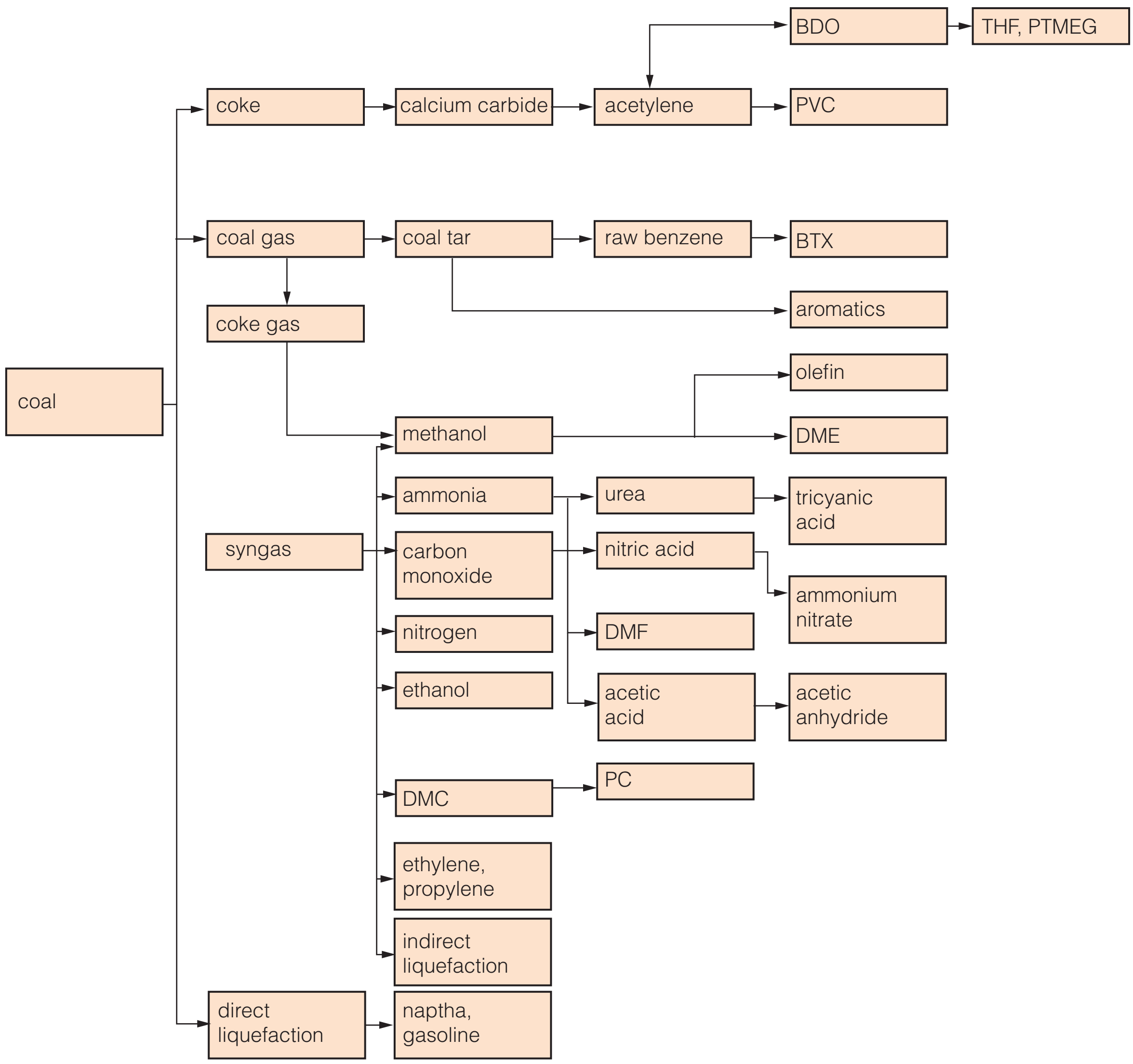

Figure 5 Simplified flowsheet of the various coal transformation routes (Deutsche Bank, 2007)

downstream derivatives. The aim is to develop various coal transformation techniques, with an intention to bring forward the more promising industrial options, either directly or via large-scale demonstration programmes, to achieve commercial-scale operation.

This is a large programme. Thus in 2006, the NDRC declared in its Mid- & Long-Term Development Plans of the Coal Chemical Industry that the Government was going to invest RMB 1000 billion over the next 13 years, of which 50% would be spent on equipment and 10% on technology (China Business, 2006). However, it is not a fast track approach. The 11th Five-Year Plan for China's Coal Industry, published in January 2007, suggested an orderly and steady progression towards the construction of demonstration projects for coal chemicals production. The driver at that time was to provide a solid foundation for the industrialisation to take place in the following decade. This approach was reinforced in the Notice of State Council to Issue the Comprehensive Energy-Saving and Emission-Reducing Scheme of June 2007.

This cautious approach was in sharp contrast to the plans for China to introduce advanced coal fired power plants and to upgrade the electricity transmission system while also rapidly developing renewable energy (Minchener, 2010).

In May 2009, China's State Council released details of the Restructuring and Revitalization Plan for the Petrochemical Industry. This is a three-year action plan aiming to help the Chinese petrochemical industry seize opportunities during the world economic slow-down, to carry out restructuring, upgrade their technologies and improve overall competitiveness. In addition to the general policy guidelines such as encouraging innovation, production of more high-end products, environmental protection and exploring business opportunities overseas, the plan added specific goals for completion by end 2011. These included the definition of five model industrial development projects, namely coal-to-oil via liquefaction, coal-to-natural gas, methanol-to-olefins, methanol to DME and coal-to-ethylene glycol. The aim is to establish appropriate technologies in the next 15 years such that their deployment will meet technical and economic requirements while also being in accord with resource conservation and carbon intensity targets. It was further stated that these activities will assist China toward self-sufficiency and the ownership of globally competitive technology for the newer coal-to-chemicals sectors (Market Avenue, 2010a).

3.2 Plan to establish geographical economies of scale

Since 2007 the NDRC has begun to establish seven major bases for the coal chemical industry, which include the middle and lower reaches of the Yellow River; Eastern Inner Mongolia; Eastern Heilongjiang Province; a combination of Jiangsu, Shandong, Henan, and Anhui Provinces; Middle China; the combination of Yunnan and Guizhou Provinces; and Xinjiang Province. These are shown in Figure 6 (Galleon, 2009)

The bases of the middle and lower reaches of the Yellow River, Xinjiang Province, and Eastern Inner Mongolia will focus on the intended very large-scale production of methanol, dimethyl ether and coal-to-oil.

In order to promote the transportation of coal-based products to market, in 2007, China began a major investment programme for the construction of four major pipelines (Market Avenue, 2010a):

- a 1800 km-long pipeline from Hulun Buir (Inner Mongolia) to Huolinhe (Inner Mongolia) to Fuxin (Liaoning Province) and to Jinxi (Liaoning Province) with the annual transportation capacity of 10 Mt of methanol (RMB 5 billion);
- a 2000 km-long pipeline from Ningdong (Ningxia Province) to Yulin (Shaanxi Province) to Ordos (Inner Mongolia) and to Jingjintan Harbour (Hebei Province) to transfer the fuel produced in the middle and lower reaches of the Yellow River (RMB 8 billion);

Figure 6 Geographical representation of the seven coal transformation bases in China (Galleon 2009)

- a 400 km-long pipeline from Yining (Xinjiang Province) to Duzishan (Xinjiang Province) for the transportation of oil products, where the pipeline would be connected with the existing Duzishan-Lanzhou (Gansu Province)-Chengdu (Sichan Province) pipeline, and would annually transport 10 Mt of coal-based oil products to Southwest China (RMB 1.2 billion);
- a 200 km-long pipeline from Duolun (Inner Mongolia) to Beijing for natural gas transportation.

3.3 National targets and expectations for coal transformation products

The original plan of 2006 shows very limited increases in the production capacity of traditional coal chemicals, such as coke and chemical fertiliser, and a reduction in that of calcium carbide, in line with the intention to bring supply into balance with demand.

In contrast, the intended scale of the changes and increase in capacity for the 'new' coal-to-chemicals appears to be significant despite the declared intention of a steady development programme (Table 2). However, to put these numbers in context with China's projected oil needs, even with this massive increase in coal-to-oil products, they will make up just 4% and 10% of the projected imported oil product needs in 2015 and 2020 respectively (China Business, 2006). For coal based olefins, these will account for 3%, 9% and 11% of the total olefin output in 2010, 2015 and 2020 respectively. In the case of methanol, by 2020, coal-based product will account for 94% of the total supply. The production of dimethyl ether and olefin, both transformed from methanol, is expected to consume a combined total of 12 Mt of methanol in 2010, 33 Mt in 2015 and 54 Mt in 2020.

This ambitious target faces huge challenges. As noted, various coal chemical processes will be

Table 2 NDRC plan for production of the main coal based chemical products (Yue, 2010, China Business 2006)

Product	Expected production in 2010, Mt	Expected production in 2015, Mt	Expected production in 2020, Mt
Methanol	16	38	66
LPG	3	4	5
DME	5	12	20
Olefin	1.4	5	8
Ethylene glycol	0.8	1.2	n/a
Oil products	1.5	10	30

established in succession and in each case there will be technical challenges, including process integration with stable operation, catalyst optimisation, proving of control systems and achieving acceptable energy efficiency and environmental performance. This will require massive capital investment if such processes are to be established in sufficient numbers. At the same time, the profitability of such investments will be dependent on several factors including the price ratio for oil, gas and coal, which can vary especially due to oil price volatility.

3.4 Subsequent State and Provincial Government interactions

In 2003, when world oil prices were rising and supply was tight, Chinese companies showed great interest in coal-to-oil and coal-to-chemicals projects. This position was supported very strongly by local and provincial governments that were keen to establish infrastructure projects. Consequently the state government decided to establish a series of pilot coal-to-oil and coal-to-chemicals projects during the 11th Five-Year Plan period (2006-10), to lay the foundation for subsequent industrial-scale production.

At the same time, as part of its reform programme, the state government conducted various strategic studies on future energy requirements within China, with the recognition that the development and use of coal resources will dominate the energy mix for the foreseeable future (Zhou and others, 2003). Policies to address many of these key issues were included within the framework of the 11th Five-Year Plan for the coal industry. First and foremost, China moved away from its previous position of giving major state-owned enterprises (SOE) significant freedom of action, with the decision to ensure absolute control over the key sectors (People's Daily, 2007). These comprise the arms industry, power generation and distribution, petroleum and petrochemical products, telecommunications, coal, civil aviation, and shipping. The approach varies a little depending on the specific sectors. Thus in power generation and distribution, oil and chemicals, telecommunications, and armaments sectors, the government declared that the SOEs should either be solely owned by the state or else the state should have a majority shareholding. For the coal, aviation and shipping industries, it was announced that the state should always have a controlling stake in the SOE.

This led to the state government adopting a centralised management approach for key industries, with the emphasis on energy conservation, environmental acceptability and conformity with the 11th Five-Year Plan. This included the coal-to-chemicals sector, not least since the new technology options were neither technically nor commercially proven.

Despite this, as in many key energy sectors, there continued to be moves at provincial and local government level to establish investment projects with industry that would raise revenue and secure employment. There was an upsurge of local governments and enterprises starting small coal-to-oil projects, mostly in the coal-rich areas in the northern regions. There appeared to be little appreciation that such projects would have adverse financial and environmental consequences and also be wasteful of resources. This was completely at variance with the state government's declared cautious approach and consequently led to a series of moves to counter the provincial initiatives.

In July 2006 the NDRC limited the various coal transformation activities with the issue of the Notice on Management of the Construction and on Improving the Health of Coal-to-Chemical Industry. This required that all the authorities stop the approval of coal-to-oil projects until such time that the government completed the development of a national plan (China Institute, 2006b). They reinforced this by declaring that State approval would not be granted for any coal-to-oil project if the intended production capacity should be less than 3 Mt/y. Since the nominal capital investment for one tonne of coal-to-oil processing capacity was RMB 10,000 in 2007, the 3 Mt annual capacity would require an investment of RMB 30 billion, which would be beyond the financial capabilities of most enterprises, without state government support (3E, 2008). Alongside this constraint, the government advised that it would not approve coal-to-methanol and DME projects that were under 1 Mt annual capacity, and coal-to-olefins projects under 600 kt annual capacity.

The 11th Five-Year Plan for China Coal Industry, published in January 2007, suggested an orderly boost to the construction of demonstration projects for coal transformation and, in particular, to promote the establishment of coal-to-oil demonstration projects. In the Notice of State Council to Issue the Comprehensive Energy-Saving and Emission-Reducing Scheme, released in June 2007, the Chinese Government claimed for a second time that alternative energy would be gradually developed as part of a mid- to long-term plan so as to promote large-scale demonstration projects for direct and indirect coal-to-oil, coal-based dimethyl ether and olefin items.

While this dampened enthusiasm to some degree, it was not enough and in late 2008, the NDRC moved again to control the business risk of the country's coal-to-oil industry, for which the economic case had yet to be proved (Alexander's gas and oil connections, 2009). Accordingly, it officially halted all coal-to-oil projects nationwide, except two involving the Shenhua Group. These were the direct liquefaction demonstration project that was close to start-up and the indirect coal liquefaction project jointly planned by the Shenhua Ningxia Coal Group and the South Africa-based Sasol Ltd. In the case of the latter, this was allowed to proceed with design and engineering studies on the understanding that the partners could not proceed to the actual construction phase until a case for this had been approved by the NDRC.

This directive, combined with the impact of the global financial crisis, cooled enthusiasm for many CTL projects in China. However, certain companies other than Shenhua managed to keep their projects active, presumably on the basis that construction was essentially complete (*see* Chapter 5 for individual project descriptions). At the same time, some design and feasibility studies on other projects have continued.

At the end of 2009, the state government reaffirmed its intention to restructure the coal chemical sector by eliminating outdated coal chemical production capacity, supporting technological innovations and strengthening policy guidance, in order to establish a sustainable industry (Global Times, 2009). The Ministry of Industry and Information Technology stressed that the government would continue to maintain the market entry threshold for new developments such as coal-to-oil while increasing the phasing out of obsolete overcapacity for various coal-to-chemicals processes. Thus revisions have been produced to the entry conditions for synthesis ammonia production, the calcium carbide industry and the coke industry, where outdated capacity has been closed. In addition, from 2010-13, the government will ban new projects that simply enlarge capacity (People's Daily, 2009; HKTDC, 2010).

4 Progress to establish opportunities in key market sectors

4.1 Coal-to-oil

According to the NDRC, in 2009, China's crude oil output was about 189 Mt (equivalent to about 3,800,000 bbl/d) but this provided only 48% of the country's demand (Peoples Daily, 2010a). According to Sinopec, it would appear that domestic production is likely to remain in the range 180 Mt to 190 Mt, with an annual growth rate of 1% to 2%, and it was noted that it had not been easy to maintain production above 180 Mt. In contrast, since 2000, China's annual oil demand growth has been 5% or more. For 2010, the expectation is that crude oil imports are likely to go up by over 9% to 212 Mt. Indeed in the first half of 2010, domestic crude oil production increased (year on year) by 5.3% to 98.5 Mt while crude oil imports increased by 30.2% to 118 Mt (E-to-China, 2010).

China has adopted a policy of diversifying and increasing imported oil supplies while at least seeking to maintain its domestic supply levels as well as starting to exploit alternative sources such as oil shale. This includes reducing its heavy reliance on oil supply by tanker via the Malacca Straits bottleneck through the establishment of overland pipelines from Russia, Central Asia and Burma. A major project is the Russia-China oil pipeline, which links Skovorodino to Daqing City in Helongjiang Province (Journal of Energy Security, 2009). This is expected to be operational by the end of 2010, with an annual capacity of 15 Mt of crude oil. Construction is under way on Burma-China oil (and gas) pipelines to link Burma's Kyaukphyu oil field to Kunming in Yunnan Province, and then to Guizhou Province and subsequently to Chongqing. Annual capacity will be 20 Mt of crude oil. Full operation is expected in 2013.

As well as diversifying its import sources, China is taking advantage of the current relatively weak international prices to boost its strategic reserves. It has also indicated that it will expand such oil reserves by developing private storage capacity, in addition to the second phase of state oil stockpiles (Li E, 2010a).

Alongside these initiatives (Zhang, 2007), the state government is also interested in developing coal-to-oil projects (*see* Chapter 5). While the 2006 plan, presented earlier, is ambitious in terms of technology deployment, it actually offers modest levels of output up to 2020 when compared to the current and projected level of imports. Even if the various demonstration projects are technically successful, the economic case to deploy commercial-scale units may not be especially strong, given the pricing uncertainty of oil and, to some degree, coal (*see* Chapter 6).

4.2 Coal-to-synthetic natural gas

Although gas currently accounts for just under 4% of China's primary energy consumption, demand is growing far quicker than domestic supplies, with ever greater shortfalls projected in the period to 2020. In 2009, China's natural gas consumption was 88.7 billion m^3, of which 83 billion m^3 were produced domestically. According to government forecasts, the demand for natural gas is expected to reach 200 billion m^3 by 2020, which, if correct, could result in an import need of about 80 billion m^3 as domestic supplies are not projected to increase sufficiently. In fact the problem could be even greater as, recently, it has been suggested by PetroChina that demand may reach 300 billion m^3 by 2020 (China Knowledge, 2010).

The Chinese Government is currently drafting plans for the mid to long-term development of the natural gas industry (People's Daily, 2010b). Objectives include the further acceleration of exploration, development and use, optimisation of energy supply structures and enhancing national energy security (Research and Markets, 2009). Within this framework, China has been looking to acquire natural gas and liquid natural gas (LNG) assets overseas and working toward further developing its domestic production resources. The latter include coal-bed methane and potential shale gas resources

With regard to imports, China is seeking to bring in natural gas from neighbouring countries to the North-west and South-west of the country, while introducing LNG by tanker from various countries into its Southern and Eastern regions. Besides establishing suitable storage and transport infrastructures, there is a timing issue to consider. At present there are excess supplies in the international market although, as the global economy begins to recover, China is likely to find it increasingly expensive to acquire such natural gas and LNG assets. Consequently, it is seeking to tie up numerous deals on a long-term basis for such supplies (China Economic Review, 2010). According to the NDRC, China expects to import more than 15 billion m^3 in 2010, either through natural gas pipelines or LNG terminals. By way of example, China's gas imports grew to 4.5 billion m^3 in the first four months of this year, which is a 206% increase compared to the same period in 2009 (Li E, 2010b).

For natural gas, there are two major pipeline routes. The major link is the China-Central Asia gas pipeline into Xinjiang, from where the gas is transported to Shanghai. There are plans to extend the pipeline to South China's Guangdong Province by the end of 2011. The gas is supplied from Turkmenistan and, in due course, will also be delivered from Kazakhstan, with expected annual capacities of 30 billion m^3 and 10 billion m^3 respectively. The first stage of the pipeline was completed in 2009, while the second stage, adding a second pipe and increasing capacity up to 40 billion m^3, is expected to be completed by the end of 2011. As part of this arrangement, the China National Petroleum Co (CNPC) and the Kazakh oil and gas company (KazMunayGas) will jointly explore the feasibility of accessing Caspian Sea gas resources. CNPC recently signed a framework agreement to buy 10 billion m^3 of natural gas a year from Uzbekistan's national oil company Uzbekneftegaz, which will require a connection between the Uzbek gas transmission system and the China-Central Asia gas pipeline. CNPC has also signed an agreement with the Myanmar National Oil and Gas Company to establish both natural gas and oil pipelines from Myanmar to Yunnan Province. The annual natural gas transport capacity will be 12 billion m^3.

For LNG, China has signed deals with Qatar, Australia and Iran (Priestley, 2010). To support the distribution of these supplies, China is building a LNG terminal network and associated storage facilities in the eastern and southern coastal regions (Priestley, 2010). So far, three terminals are in operation while another seven are planned for completion by the end of 2014 (Li, 2010b). It is understood that the contracted annual capacity of LNG is expected to rise to 46.2 billion m^3 (33.5 Mt) by 2015 (Reuters, 2010a).

With regard to domestic resources, the National Energy Administration announced that China would further develop major gas fields in central and western China as well as offshore gas resources to maintain the rapid increases in domestic gas output. This will include a third gas pipeline linking Shaanxi Province and Beijing and a new pipeline connecting Qinghuangdao City in Hebei Province to Shenyang, capital of North eastern Liaoning Province (Articles base, 2010).

At the same time, China is also considering alternative approaches, including the conversion of coal-to-synthetic natural gas. Coal gasification has been part of the central government's development plans for several years and is included among the five demonstration projects in the coal sector. However, in line with its cautious approach to coal transformation initiatives, China has moved slowly by limiting approval for construction to three major coal-to-gas projects, which are being taken forward by the China Datang International Power Generation Co and the Huineng Coal Chemical Company. When completed, these will provide in total some 12 billion m^3 of synthetic natural gas and

LNG equivalent (*see* Chapter 5). It has also announced that further approval of coal-to-gas projects will be partly contingent on the use of domestically developed technologies and equipment that is made in China (Downstreamtoday, 2010). There are already several proposals for further projects, similar in size to the three that are being built, where permission has yet to be granted by the NDRC.

Thus, in 2009, CNOOC announced that it will spend about RMB 80 billion on two big projects to turn coal into synthetic natural gas. Subject to approval, one of the two projects, jointly developed with Datong Coal Mine Group Co, will be located in Shanxi Province, while the other one will be located in the Inner Mongolia Autonomous Region (Sxcoal, 2009a). The former will have an annual output of 4 billion m^3 at a capital investment of RMB 30 billion, while the latter will cost RMB 50 billion for an annual output of 6 billion m^3. Gas production in each case is provisionally scheduled to start within five years.

China Huaneng Group, the country's largest power generation company, is formulating plans for a plant to produce 6 billion m^3 per year of gas by 2016 in the Xinjiang Uygur Autonomous Region (Platts, 2010). If the go-ahead is received, the first phase of the project will begin operation late in 2013 with an annual production of 4 billion m^3. The second phase is planned to be built over the period 2012-16. The total investment in the project is estimated at RMB 38 billion (Energy Tribune, 2010). It is claimed that the cost will be lower than for imported gas from central Asia. It is understood that local permission to proceed with this plant forms part of a RMB 100 billion strategic co-operation agreement for energy development between Huaneng and the Xinjiang provincial government. Huaneng will invest over the next ten years to build up their Zhundong and Tuha energy bases, to include a variety of fossil and renewable energy projects (Reuters, 2010b).

Meanwhile, China Power has announced that it intends to build a coal gasification plant in the next two and half years with yearly gas production expected to be about 2 billion m^3 (Energy Tribune, 2010).

4.3 Coal-to-methanol

Methanol is a key chemical with a wide range of uses, both directly and as a raw material for downstream derivatives. It has been made from coal, coke, natural gas, heavy oil, naphtha, coke oven gas, and acetylene off-gas. The drive in China is to rapidly and significantly increase methanol production and to switch from petroleum and natural gas (55% and 15% in 2009) to coal (currently 30%) as the raw material. The targets set by the NDRC in the Exposure Draft of Mid- & Long-Term Development Plans of Coal Chemical Industry, which was issued in 2006, are shown in Table 3 (Market Avenue, 2010a). This suggested that demand will rise rapidly, with domestic producers being able to supply all of China's needs.

Table 4 provides an overview of methanol production and consumption over the last five years (AsiaChem, 2010a). This shows that deployment of methanol projects has increased, with production capacity rapidly exceeding near-term demand, well in excess of government targets. This has meant that most production facilities have operated well below maximum output levels. At the same time, the recent rise in imports indicates a lack of competitiveness for some regions of China (Allbusiness, 2009).

At the end of 2009, there were over 180 methanol companies, most of them with an annual production capacity of less than 200 kt. Many of the smaller and higher cost companies will probably go out of business in the absence of new market opportunities since the Chinese market appears to be vulnerable to low spot prices for imported methanol. The lower cost producers, which use natural gas as the starting material, are in Malaysia, Saudi Arabia, Indonesia and New Zealand, and in 2009 they had a significant impact on imports to China. Further low cost supply additions are expected in Oman and Egypt (ICIS, 2010a).

Table 3 NDRC targets for supply and demand of methanol in China (Market Avenue, 2010a)

	2005	2010	2015	2020
Demand, Mt	6.7	16.2	24.5	64.9
Domestic supply, Mt	5.4	16.0	25.0	66.0
Import, Mt	1.4	0.8	0.5	0.4
Export, Mt	0.1	0.6	0.8	1.5

Table 4 Methanol production and consumption in China (AsiaChem, 2010a)

Year	2006	2007	2008	2009	2010 (estimate)
Capacity, Mt	13	19	27	33	51
Annual production, Mt	9.0	10.8	11.1	11.2	17.0
Annual import, Mt	0.6	0.8	1.4	5.3	4.5
Annual export, Mt	negligible	0.6	0.4	1.0	1.0
Apparent consumption	9.6	11.0	12.1	15.5	20.5

In terms of applications, the traditional use of methanol has included the production of formaldehyde, agricultural and pharmaceutical chemicals. The new approach is to develop the means to use methanol as a raw material for downstream products with large market capacity, economic scale and high value. The likely prospects include:

- methanol blended with gasoline/petrol;
- methanol to DME as a substitute for diesel and LPG (*see* Section 4.5);
- methanol to olefin, thereby extending into the petro-chemical industry sector (*see* Section 4.4);
- methanol to poly-methoxy-dimethyl ether (DMMn), which is a new clean diesel-component;
- DMMn via methanol and blended with diesel, which is the indirect route to use methanol as the substitute fuel.

For methanol-blended fuels for transportation in China, the enabling legalisation and the national standards for blended gasoline with 85% methanol came into effect on 1 December 2009 (Businessgreen, 2009a). This M85 fuel has a methanol content of between 70% and 95%, with gasoline comprising the remainder. However, this fuel can only be used with specially designed engines and even with a proposed government subsidy to help pay for vehicles to be retrofitted, its market impact is at best uncertain. A standard for M15 fuel, which has a 15–20% methanol content and does not require engine retrofitting, has yet to be approved, possibly due to lobbying from the petrochemical industry fearing some loss of market share in the transport fuel sector. Should this be approved, it will help to support China's methanol industry. For both blends, there will be a need for production facilities and a retail distribution network (AllBusiness, 2009).

The use of methanol to produce DME is potentially attractive. However, to date, demand has been low so methanol use has not increased. The introduction of large DME production units from 2010 may change this, subject to sufficient demand for the end product, which again will require infrastructure development and enabling legislation. Consequently, the future for methanol use in China, either through blending for fuel applications or as an intermediate in the manufacture of other higher value derivatives is far from certain.

As part of the downstream value added approach, China is also undertaking an industrial-scale methanol to gasoline/petrol trial. Thus the Shanxi Jincheng Anthracite Mining Group (JAMG) has built a fixed bed methanol-to-gasoline (MTG) plant with an annual capacity of 100 kt. This is based on the Mobil process and was licensed to JAMG by Uhde GmbH. The total planned investment was RMB 1.7 billion. This project is the first one in China to use low-grade anthracite, which has high sulphur content, high ash content and high ash melting point, as the coal feedstock. Construction started in 2006 in Shanxi Province while commissioning and operation started during 2009 (MOST, 2010). Initial operations are reported to be technically successful.

Synfuels China has developed a domestic variant of the process, incorporating a one-step fixed-bed gasification technology, which has been licensed for a similar sized project in Yunnan Province (MOST, 2010).

4.4 Coal-to-olefins

China has a growing requirement for olefins, especially polyethylene (PE) and polypropylene (PP), with total olefin demand in 2009 close to 23 Mt of which 11.5 Mt were imported (Plasticsnews, 2010). Thus, in principle, coal-to-olefins offers a means to address this shortfall and ultimately to reduce the proportion of imports required. Accordingly there has been a rush of projects proposed with a total annual capacity of 20 Mt by the end of 2009 (AsiaChem, 2010b).

However, coal-to-olefins (CTO) is not a mature technology, and such facilities need significant capital investment. As with other coal transformation processes, coal-to-olefins production requires large quantities of coal, high water consumption, and significant energy usage. In addition, the transportation costs are higher than for other processes since the product cannot be transported by pipeline. At present, trucks are likely to be used to move the resin end-product from the plants close to the coal mines in North-West China to the eastern and south-eastern regions where it is used in various other processes. This situation should improve once new rail and road systems are built. Consequently, the government is at this time only allowing a few demonstration projects to proceed and will want to assess their economic and environmental performance before deciding whether to proceed with the deployment of commercial-scale units.

There are three major coal-based demonstration projects, Shenhua Baotou, Shenhua Ningxia and Datang Duolun, in which coal is gasified then synthesised into methanol, the methanol is transformed into olefin and the olefin is then polymerised into polyethylene and polypropylene resins. These will be the first industrial-scale plants in the world to produce plastic materials from coal. They will have a cumulative annual production capacity of 1.56 Mt polyolefin, which is equivalent to some 7% of the country's current capacity (ICIS, 2010b). As such, they have the potential to be an important supplement to the Chinese olefins (oil based) supply and a major development direction for the coal chemical industry. Descriptions for each project are given in Chapter 5.

Although the promotion of coal-to-olefin projects is not assured, Shenhua is taking forward plans that could see co-operation with Dow Chemicals lead to a major commercial-scale chemicals complex, including significant coal-to-olefins capacity (ICIS, 2010c). This is considered further in Section 5.11.

4.5 Coal-to-dimethyl ether

Traditionally, liquefied petroleum gas (LPG) has been used for residential heating and cooking, and for small industrial applications, with much of the demand being met by various Chinese refineries. However, in order to meet the rising demand, a proportion has been imported, especially into Southern

China. Due to the limited transport infrastructure associated with LPG, bottled product is still widely used in many Chinese cities, making it expensive to transport over long distances (China Institute, 2006a).

The market has grown steadily (over 14%/y on average since the 1990s). In 2005 total demand was 21 Mt, of which some 25% was imported. This is forecast to rise to 26 Mt by 2010, with a speculative estimate of 40 to 50 Mt by 2020, and with the proportion of imports increasing due to the problems with raising domestic oil production levels, as noted earlier. However, the growing introduction of alternatives such as natural gas and LNG could well weaken that demand. Domestic natural gas prices are lower than those of LPG, while it is also easier and less expensive to store and transport, although the pipeline network is far from comprehensive. Indeed, in view of an expected gradual slowdown in LPG demand, China's refineries have begun to limit LPG output. Increasingly, instead of selling it as an end-product, many of them are using LPG as a feedstock to make more value-added products, such as ethylene, (MCGroup, 2007).

That said, the market is large and still growing, while imports are expected to continue (Bnet, 2007). Since imported LPG prices follow international oil prices, then, as oil prices rise in the future, importing LPG will become an increasingly expensive option for China, especially for the inland provinces where additional transportation costs are involved. Thus there is considerable interest in substituting DME to replace LPG and some other fuels for various applications. This is because DME has properties that are very similar to LPG and diesel, under different applications, and, since it can be manufactured from coal, it should be competitive in many regions of China with imported LPG although this will depend in part on the imported oil price. Consequently, the focus in China has now shifted to the use of DME as a full or part (by blending) substitute for LPG, for use in domestic heating and cooking applications, and for diesel, for some transport options (CBI China, 2008).

In all cases, significant markets need to be established if coal-derived DME is to become a viable commercial household fuel and a transport fuel in China, which will require successful demonstrations of its production, distribution, and utilisation. Some significant testing of DME as a household fuel has already taken place and it has been shown that it is better than LPG for storage, combustion safety and burning quality. Meanwhile, as DME has very high hexadecane value and is potentially very suitable for use in compression ignition engines, it appears to be an acceptable substitute for diesel.

With regard to DME production in China, this rose from some 20 kt in 2002 to about 320 kt in 2006, at which time some 280 kt were used as a replacement for LPG, with the remainder used as a chemical integrant and aerosol propellant. Official targets set at that time suggested that domestic DME production capacity would increase to 4.4 Mt in 2008, 7.8 Mt in 2009 and 14.8 Mt in 2010. In fact, while production capacity has increased significantly, making China the first large-scale DME producer, it has been at a rather slower rate than the original projections (*see* Table 5) reflecting government caution because of the lack of a definitive cost and performance basis to assess the market viability.

Table 5 DME production capacity in China (OrbiChem, 2009)

Year	Annual production capacity, Mt
2006	0.8
2007	2.5
2008	4.9
2009	6.8 (estimate)
2010	8.0 (estimate.)
2015	14.2 (estimate)

The rise in production capacity was achieved by the introduction of a large number of relatively small plants that lack the necessary economies of scale, with annual outputs mostly in the range 50–200 kt. The standard process comprises methanol dehydration, which is a mature technology and easy to construct. Indeed, if the producer only builds a single DME unit without an associated methanol production unit, the construction cycle of the project can be as short as six months (CBI China, 2008). This will require the owner to obtain methanol from independent sources but, as noted previously, there is a very significant surplus methanol production capacity in China. However, this approach lacks the upstream integration that would occur if the methanol production took place alongside the dehydration process, with the coal being available for this from a nearby mine. Such an approach avoids unnecessary transportation of methanol. DME can also be manufactured directly from synthesis gas produced by the gasification of coal, with overseas companies such as JFE Holdings, Haldor Topsoe and Lurgi offering this technology. Although it is a more efficient process, it is not yet established in China.

Several Chinese companies have been developing plans to construct and prove large-scale (1 Mt/y) DME production units, either by using domestic technologies or through joint ventures with foreign companies. At present, the largest intended project is a joint venture by the China Coal Energy Company Limited, Sinopec, Shanghai Shenneng Group and the Inner Mongolia Manshi Coal group. This consists of a coalmine, linked to a 4.2 Mt annual capacity methanol plant integrated with a 3 Mt DME plant, and supportive facilities including a thermal power plant (China Coal Resource, 2007). The plant, which is located in Erdos, Inner Mongolia with the products to be transported to Jingtanggang by pipeline, was scheduled to be operational by the end of 2010 (Dow Jones, 2008). However, information on progress to date is not forthcoming.

While the potential output has expanded, the necessary markets to utilise the DME have not been correspondingly developed. Thus, from 2007, the expectation was that blending DME with LPG represented a strong near-term option. DME can be blended with LPG and used for domestic cooking and heating, especially as blends containing up to 25% volume DME generally require no modifications to equipment. The Ministry of Architecture released a standard for DME for Downturn and Rural Fuel Gas, which provided official support for the use of DME in energy applications. However, this market for DME was well below the national production capacity. For 2010, on the basis of, say, 25 Mt LPG being used for residential and rural heating/cooking, and all of that LPG being blended with DME to give an 80:20 mix, the maximum demand for DME would be 5 Mt. In practice, consumption of LPG and DME is uneven regionally. LPG supply sources are largely concentrated in South China, with consumption of DME primarily in East and South China, where there is growing competition from natural gas via the west to east pipeline. As such, annual Chinese DME demand is likely to be lower at 3–4 Mt and while this is a reasonable-scale market for blending with LPG, it is far less than existing production capacity.

The other major potential opportunity for DME is its use as a transport fuel, primarily as a substitute for diesel, although this is a longer-term objective. There is a rapidly growing vehicle population and local refiners' unwillingness to boost output due to the high cost of imported crude, combined with caps on domestic gasoline and diesel prices, result in sporadic fuel crises (Dow Jones, 2008). In particular, diesel supplies tend to be very tight since China's diesel consumption is twice that of gasoline/petrol.

Engines capable of running on DME have been under development in Japan, China and Europe (Huang and Taupy, 2008). In Shanghai, DME-fuelled buses have been in operation since 2007 and if this is deemed an acceptable approach then the potential national market would be some 100 Mt. However, before such a transfer from diesel to DME could take place, there would be a need to establish national standards and policies for DME use as a diesel substitute. This would need to be followed by the development of a national infrastructure, appropriate production systems with pipelines to the regions where the fuel would be mostly used, and regional fuel distribution networks (for example, filling stations). The investment requirements would be enormous and there is little evidence of such an approach getting under way. Thus, while China has the coal resources to rapidly grow its DME output, it seems at best that the use of DME as a transportation fuel may not be possible for several years and then it is likely to take only a small slice of the fuel market share held by the oil companies.

However, for both market opportunities there remain two problems, namely transportation from producer to end user, and the price that can be realised compared to alternatives. DME is in gas form at ambient temperature and atmospheric pressure, so it needs to be transported in pressurised containers. At present, this is done using road tankers since the use of marine and rail transportation is excluded in the absence of regulations. Consequently, most DME is used relatively locally, with output mainly concentrated in Hebei, Henan, Shandong and Guangdong Provinces. The majority of producers are not operating integrated units, as the methanol is being brought in from other locations. However, if they are built, the larger plants will be integrated with the coal resources in the remote north-western China and this will create significant transportation logistic problems to get the DME to southern and eastern China.

As with so many coal-to-chemicals and coal-to-oil projects, the prospects look attractive at high oil prices and provided demand and supply are in line with one another. However, the surge in production has coincided with a downturn in the oil price and only a limited market (for LPG blending) being established. In early 2009, the price of LPG was 3200–3400 RMB/t while the price achievable for DME was very similar at 3100–3300 RMB/t even though the cost of production was over 4000 RMB/t. If production capacity rises, with market development proceeding slowly, price battles are likely to become ever more severe and the situation will not be sustainable.

4.6 Coal-to-ethylene glycol

In terms of supply and demand, the Chinese ethylene glycol market appears to have significant potential. From 2001 to 2009, demand for ethylene glycol in China showed an average annual growth rate of 17.4%, which could not be matched by domestic supplies, as shown in Table 6.

At present, China is at an early stage of investments for coal-to-ethylene glycol projects although the large gap between supply and demand has led to some industrial pilot activities, in line with the requirements of China's petroleum and chemical industry stimulus programme. The lead activity is the GEM (Gold Coal) Chemical CTMEG project in Tongliao, Inner Mongolia, which is based on a process part developed by the Chinese Academy of Sciences. The annual capacity is 150 kt of

Table 6 Comparison demand and domestic supply for ethylene glycol in China (168report, 2010)

Year	Domestic supply, Mt	Import, Mt	National demand, Mt	Self-sufficiency ratio, %
2001	0.8	1.6	2.4	33.5
2002	0.9	2.1	3.0	28.9
2003	1.0	2.5	3.5	27.3
2004	1.0	3.4	4.3	21.4
2005	1.1	4.0	5.1	21.4
2006	1.6	4.1	5.6	27.7
2007	1.8	4.8	6.6	26.9
2008	2.0	5.2	7.0	26.1
2009	2.9	5.8	8.9	32.9

ethylene glycol and 100 kt of oxalic acid. Operations began late in 2009 since when the products have met the specification. Following some design and equipment modifications, the plant is expected to reach design capacity by October 2010 (AsiaChem, 2010c). Other similar size projects are at the design and feasibility stage, with a potential total investment of some RMB 25 billion (168report, 2010). There are also several complementary process developments under way by other Chinese enterprises and institutes; however, these are all small-scale R&D activities. The relatively slow approach reflects the lack of clarity as to whether using coal as the raw material will be competitive compared to alternatives such as oil and natural gas (Bharat Book Bureau, 2010). Consequently, the technology for this particular product has not yet reached the stage where the very large units, such as for olefins, are being initiated.

5 Key national coal-to-chemicals projects

Following the various policy adjustments, as described above, China is taking forward a suite of coal-to-oil demonstration projects, with others having completed feasibility studies, as summarised in Table 7.

In addition to descriptions of the projects listed in Table 7, information is provided for some of the major coal-to-gas and chemicals plants that are being established. This is not an exhaustive list; rather, it is designed to give some key examples of the major initiatives under way.

Table 7 Overview of key national coal to oil projects in China (Yue, 2010; Market Avenue, 2010b

Company	Process	Licensor	Initial annual product output	Target capacity	Site location	Start-up date
Shenhua	DCL	Shenhua	1 Mt	3.2 Mt	Inner Mongolia	December 2008
Shenhua	ICL	Synfuels China	180 kt	–	Inner Mongolia	December 2009
Yitai	ICL	Synfuels China	160 kt	0.48 Mt	Inner Mongolia	March 2009
Lu'an	ICL	Synfuels China	160 kt	2.6 Mt	Shanxi Lu'an	July 2009
Yankuang	ICL	Yankuang	1 Mt	–	Shaanxi Yulin	Feasibility study complete
Shenhua Ningmei/ Sasol	ICL	Sasol	3 Mt	–	Ningdong Ningxia	Feasibility study complete

5.1 Technology developments by Synfuels China

Synfuels China is a key company which aims to establish investment projects for coal-to-chemicals production, coal-to-oil equipment manufacture and further project development. Its approach is to develop coal-to-oil core technologies and to select and integrate existing technologies into the value chain for best performance. Its rationale is that if you can design and construct a coal-to-oil plant and make it work then not only does this offer direct market opportunities but there will be numerous related chemical engineering prospects, including SNG, methanol plants, and ammonia plants.

Synfuels China was formed in 2006 with the spin-off of the coal-to-oil group from the Institute of Coal Chemistry (ICC) at the Chinese Academy of Sciences (Li, 2010c). This group has a long history (1980-2005) of R&D including testing up to pilot scale of slurry-based Fischer-Tropsch (FT) synthesis. The spin-off included the transfer of ICC personnel, test facilities and IPR into the new company, with various industrial sponsors purchasing equity shares. The total capitalisation is one billion RMB while the current major shareholders include:

Yitai Group	40.00%
Synfuels Staff	32.20%
ICC-CAS	12.94%
Lu'an Group	8.00%
Xuzhou Mining	4.00%
Shenhua Group	2.00%
Linksun	0.86%

The main company and the R&D centre are based in Taiyuan, Shanxi Province, with the subsidiary companies, Synfuels China Engineering Ltd in Beijing and Synfuels China Catalysts Ltd in Anhui Province and Inner Mongolia.

Synfuels China has established and owns three slurry-based FT technologies and, together with its equity partners, has been instrumental in establishing three 160–180 kt/y demonstrations of the High Temperature Slurry FT Process (HTSFT). Subject to satisfactory results being achieved, work will then begin on designing 4 Mt/y (80,000 bbl/d) projects. Synfuels China is also developing an advanced FT synthesis process, which is based on partial hydrogenation of slurry at mild conditions.

5.2 Yitai Energy Corporation two-stage ICL demonstration

The Yitai Coal Company Limited is one of China's top 500 companies, with 13 coal production bases designated by the State Council. Its aim is to achieve a coal production target of 100 Mt/y of coal by 2010.

In 2005, it received permission from the NDRC to establish a 160 kt indirect coal-to-oil facility, Figure 7, which has been undertaken by its subsidiary, the Yitai Coal Liquefaction Co Ltd. The plant has been established at Erdos, Inner Mongolia and the technology was developed by Synfuels China Co Ltd. The total capital investment is estimated at RMB 27 billion. The main products are diesel, naphtha and LPG (Li, 2009). Synfuels China claim that the optimised reactor and process design with high temperature operation will lead to higher energy efficiency, while the extremely high catalyst activity will lead to both much lower catalyst utilisation and significant product selectivity. The plant incorporates a slurry-fed gasifier. Construction began in 2006 and was completed in March 2009, with start-up and first operation later that month. Oil products were produced towards the end of March 2009 (Green Car Congress, 2009a; HighBeam, 2010). However, there were some initial problems, including a fire, which led to a stoppage for modifications. The subsequent start-up was in August 2009, with oil products being produced from mid September 2009. At that time, some 300 t/d of oil products were produced (Li, 2010c), with up to 70% load being regularly achieved. The catalyst showed good activity and stability, with methane selectivity 3% and C5+ up to 93%. The FT reactor operation was stable, with the reaction heat being well recovered in the overall process. Some modifications were identified and undertaken, especially in the tail-gas treatment section.

Figure 7 View of the Yitai coal-to-oil facility (Synfuels China, 2010a)

A further testing period up to the end of June 2010 has included 5640 h of continuous operation with the whole process line maintained at full load. Daily output has comprised 483 t of oil products, including 265 t of light diesel, 51 t of heavy diesel, 148 t of naphtha, and 19 t of LPG (AsiaChem, 2010c). Full evaluation was scheduled for August to October 2010.

Subject to that being successful, the intention is to upgrade the equipment and apply improved technology to increase product output to 480 kt/y. This would include extending the industrial chain by cracking naphtha from the coal-to-oil facility into ethylene, which is a higher value-added product (Sxcoal, 2009b). The longer-term plan is to expand the coal-to-oil base to an annual output of 5 Mt in three stages. However, it is not known if the company will receive NDRC permission to carry out the expansion plans until both the technical and economic cases can be proven (Chinaview, 2009). The cost of product oil from this process is some 50 US$/bbl. However, the company has indicated that through economies of scale, improvement of catalysts and deployment of stepwise liquefaction technologies, it believes that it can reduce production costs for the next generation of ICL plants to approximately 40 US$/bbl crude oil equivalent (Li, 2010c).

As a result of this promising performance, in December 2009, the Yitai Group Co obtained a wholesale licence for its facilities' product oil (Trading Markets, 2010a). This means that, even though the Yital project has not entered into commercial operations, its oil products have met commercial quality standards (Trading Markets, 2010a).

Subsequently, the Yitai Group Co has also arranged an initial public offering of shares on the Hong Kong market, equivalent to at least 15% of its expanded capital, to fund the purchase of RMB 8.45 billion of coal assets from its parent company (Reuters, 2010c).

5.3 Shanxi Lu'an Mining Group large industrial-scale oil and power polygeneration demonstration

In 2006, the Shanxi Lu'an Mining Industry (Group) Co Ltd, one of five major coal companies in central China's Shanxi Province, began the design and construction of a coal liquefaction project with an initial annual capacity of 160 kt (~3200 bbl/d). Known as the Shanxi Lu'an Coal-To-Liquids Demonstration Plant, this project has received support from the Government's Ministry of Science and Technology (MOST) national high-tech (863) programme (Lu'an Group, 2006). It is designated a key programme in the 11th-Five-Year Plan in Shanxi Province for which MOST has provided a grant of RMB 20 million (Upstreamonline, 2008).

The demonstration unit (*see* Figure 8) is located in the Lu'an New Energy and Clean Coal Chemical Base at Changzhi. The ICL technology, provided by Synfuels China (Li, 2010c), includes a mature fixed bed coal gasification system linked to two FT synthesis lines based on cobalt and ferrous catalysts respectively. In addition, there is scope to include a means to reduce CO_2 emissions, methane utilising technology, sewage recycling and ash residue utilisation technology. The plant is located in an ecological-industrial park, in which the intention is that the material and energy flow will ultimately form a closed chain such that full recycling and zero discharge of wastes can be realised. It is intended to integrate a coal mine and preparation plant, a power plant fuelled with some of the preparation residue and the CTL demonstration plant, to minimise resources input and consumption and to maximise energy efficiency.

Figure 8 View of the Shanxi Lu'an coal-to-liquids demonstration plant (Synfuels China, 2010b)

The fuel source is a local high sulphur coal that currently is discarded during mining operations in Changzhi. It is understood that total reserves of this otherwise unusable coal are 12 Gt. The rationale is that if CTL can transform high sulphur coal into fuel oil, it will provide a use for an otherwise difficult-to-utilise feedstock, thereby increasing the availability of workable reserves of coal while also limiting the amount of oil that will need to be imported.

The annual output capacity of this demonstration unit is comparatively modest. However, if successful, the intention would be to scale-up the process, initially to an annual capacity of close to 3 Mt and subsequently to 15 Mt at some point after 2015 (Upstreamonline, 2008).

In addition, Lu'an had proposed two other 3 Mt/y coal-to-oil projects, one in Shanxi and one in Xinjiang, but their approval from the NDRC are dependent on the performance achieved with this demonstration and whether CTL is deemed to meet China's strategic requirements.

The plant was started up in July 2009 and operated near to continuously for some four months, reaching over 70% of full load performance. The quantities of oil products were in line with the predicted annual production rate of 210 kt, while the designated ultra-clean liquid fuels, diesel, naphtha and LPG, were produced at close to the expected proportions. After some modifications to install the polygeneration system, the plant restarted in mid-June 2010 and is expected to maintain its 210 kt annual oil products capacity together with 180 kt and 300 kt of ammonia and urea respectively. Construction of a FT synthesis off-gas based power generation unit is now under construction and scheduled to be complete by the end of 2011.

5.4 Shenhua ICL demonstration

In order to gain first hand experience of ICL operations and performance, the Shenhua Group has built and commissioned a 160 kt/y (~3200 bbl/d) coal liquefaction project that draws syngas as a sidestream from the Shell gasifier unit that forms part of the DCL demonstration unit (*see* Section 5.7). The FT and associated technologies are based on a Synfuels design (Li, 2009). Construction was completed in October 2009 at a cost believed to be RMB 15 billion. This sidestream was run during the 300 hours first period of the DCL plant's operation and during the longer-term trial in late 2009 (Li, 2010c). It has been stated that start-up and operation was successfully completed but no details have been released (AsiaChem, 2010c).

5.5 Shenhua Ningxia Coal Group and Sasol planned ICL demonstration

Shenhua-Ningxia Coal and Sasol have co-operated on a possible ICL demonstration project to be sited in the Nindong chemicals base in Ningxia, which is an industrial area, with a number of plants already operating and many others under construction. The surrounding area also contains massive coal reserves, which would allow the partners to expand the facility in the future (Sasol, 2006).

In October 2008, the two partners appointed Foster Wheeler International, and Wuhan Engineering to conduct the technical and engineering feasibility study, which is understood to have cost some US$140 million (Engineering News, 2008). The study included obtaining all the necessary approvals associated with the construction of the plant.

The study was completed early in 2010, with the planned annual capacity increased to 4.5 Mt (93,000 bbl/d) from the original 4 Mt (80,000 bbl/d). It is also understood that the plant will consume less water than other, equivalent industrial projects. However, the project still needs NDRC approval before it can proceed to the construction stage and to date this is not forthcoming (Nucoal, 2010).

Subject to approval, Sasol would then make an investment decision on what could be a US$10 billion project (Zoom, 2010).

5.6 Yankuang Group planned commercial-scale polygeneration process

In 2006, the Yankuang Group (parent company of Yanzhou coal mining) initiated preparations for a two-phase coal liquefaction project in Yulin, Shaanxi Province that would involve a total investment of RMB 100 billion. The project, based on its own indirect CTL technology, would be expected to yield 10 Mt/y of oil products by 2020.

The first phase would comprise a co-production unit with 200 MWe power and 1 Mt/y of oil products. This represents a reasonable scale-up from its demonstration unit, which has been operational since 2006 and produces 60 MWe and 240 kt/y of methanol (Cai, 2010).

Yankuang Group has completed the design and engineering study for the 1 Mt/y plant, for which the construction time is estimated to be close to three years. However, approval to proceed to the construction phase has not yet been given by the NDRC.

5.7 Shenhua Group DCL demonstration

The Shenhua Group is developing the largest DCL process demonstration project in the world at Erdos in the Inner Mongolia Autonomous Region, via its subsidiary Shenhua Energy Co Ltd.

This project has full approval from the state government, with initial permission to proceed having been given in 2002 while construction started in 2005 (IEA, 2006). In Phase1, three liquefaction process lines will be built to give an initial total annual production capacity of 3.2 Mt oil products (China Daily, 2009b). The site has been designed with the ancillaries and supporting facilities (power, water, coal) all being put in place to support the three production lines. Each line will comprise coal processing, coal-based hydrogen production plant, liquid production and upgrading facilities, solvent recovery plant and catalyst preparation plant together with storage vessels for the various end products. Each line will process about 3.4 Mt of coal to produce 1.06 Mt of oil products. The expected product slate is given in Table 8. Subject to Phase 1 being successful, Phase 2 will increase the total production capacity to some 5.3 Mt of oil products and will require an additional two process lines. These will be located close by but the site will be self-contained with its own ancillaries and supporting facilities. Coal is supplied from a Shenhua mine that is adjacent to the DCL site. There are also declared long-term plans to achieve a product capacity of over 21 Mt by 2020 (Trading Markets, 2010c).

Table 8 Expected product slate from each production line of the Shenhua DCL demonstration unit (Trading Markets, 2010c)

Product	Annual production level, t
LPG	70,000
Naptha	321,000
Diesel	621,000
Liquid Ammonia	12,000
Sulphur	41,000
Phenol	3,000
Total	1068,000

The DCL technology incorporates components from USA, Japan and Germany, which have been integrated in to an overall design by Shenhua. The facility operates using a Shell gasification/hydrogen unit, with the basic design for the coal liquefaction and H-Oil units licensed from Axens. Figure 9 provides a view of the first production line when construction was close to completion. The process is characterised by relatively mild reaction conditions (operating pressure 18 MPa and temperature

Figure 9 View of the Shenhua DCL production line with construction close to completion (Minchener, 2008)

445–455°C) but with a highly effective and inexpensive catalyst that gives a conversion rate of over 90% and oil yields up to 57% on a dry and ash free coal basis. The process can readily treat high sulphur and high reactivity coals. Some attention has been paid to minimising environmental impacts. It requires close to 8 t of fresh water to produce 1 t of oil products and, to provide enough water for the project, groundwater is piped in from 100 km away (China Daily, 2009a). At the same time, all wastewater is treated and recycled. All solid waste is recycled for use in other applications. For example, the patty residue from the process will be used as the feedstock for the local power plant.

The plant will produce about 3.6 Mt of CO_2 each year, to comprise about 3.1 Mt of high purity (capture ready) CO_2 from the hydrogen making process, with the rest coming from heating, flares, and power generation. Thus it would be relatively easy to either utilise or to store over 70% of the CO_2 output from this project. A pre-feasibility study has been undertaken for the possible addition of CO_2 storage at the expansion stage of the project, although this is not yet a firm commitment. The company has announced that it will establish a CO_2 capture and storage facility with an annual capacity of 100 kt, with start-up planned for 2011 (Capture ready, 2010a). The investment cost will be some RMB 210 million while the operational costs are estimated at 300 RMB/tCO_2. It is also examining options to increase the capture capacity to 1 Mt while a third facility capable of capturing 3 Mt is being considered. However, no timetable for these constructions has been set (Capture ready, 2010b)

Trial operations began on 31 December 2008 and lasted for 300 hours, during which time quality diesel, naphtha and oil were produced. Following various improvements, the plant recommenced operations late in 2009 (CCTV.com, 2009) and extended testing has been undertaken, with over 1600 hours achieved during 2010 (IEA, 2010). This included periods of continuous and steady operation during which daily product output was in the range 2000–2800 t. While this is encouraging, it is understood that the overall process design is very complex and that reliability is not yet at an acceptable level. Consequently, there can be knock-on problems arising. For example, if the plant goes off-line suddenly, hot liquid product can cool and form blockages that are difficult to remove. In part, this is the consequence of the design and the lack of optimisation so far (Ma, 2010). Nevertheless Shenhua has obtained a wholesale licence for its DCL product oil (Trading Markets, 2010a).

5.8 Datang coal-to-gas project in Inner Mongolia

The leading project to convert coal to synthetic natural gas is by the China Datang International Power Generation Co, which has received government approval to build a RMB 25.7 billion plant in Chi Feng city, Inner Mongolia. Davy Process Technology is supplying a technology licence, basic engineering design, catalysts and support services for the methanation unit that converts synthesis gas to synthetic natural gas (Davy Process Technology, 2010). The first production line should be completed by the end of 2010 and this will produce 1.3 billion m^3 of gas each year. The total annual production capacity of 4 billion m^3 of gas will be available during 2013. The plant will be linked to a new 359 km gas pipeline to Beijing (Reuters, 2009).

5.9 Datang coal-to-gas project in Liaoning Province

Datang has also received permission for a second major project in Fuxin City, Liaoning Province (Trading Markets, 2010b). This project has very similar parameters to that in Inner Mongolia, with an annual production capacity of 4 billion m^3. Construction has just begun and will be completed in three phases by 2013, while the gas will be transported within the province by a pipeline network. Total investment is some RMB 24.6 billion.

5.10 Huineng coal-to-gas project

The third major project under way is that by the Huineng Coal Chemical Company, which has started construction of a coal-to-natural gas and LNG project with an annual production capacity of 2 billion m^3 of synthetic natural gas and 1 billion m^3 of LNG. This is being built in Yiqi Nalintaohai County, Inner Mongolia, at a total investment of RMB 13.6 billion (China Energy Net, 2010).

5.11 Shenhua-Dow joint venture for coal-to-chemicals complex

The project, to be located in Yushen Coal Chemical Industrial Park, Shaanxi Province, is expected to cost US$10 billion and will be funded by the Shenhua Group, Dow Chemical and the Yulin municipal government. It is scheduled to start operations in 2016. The Shenhua Group and Dow Chemical are working towards a joint venture to establish what, currently, will be the world's largest coal-to-chemicals project. It is expected to comprise 23 production units, auxiliary projects, supporting facilities and storage devices (ICIS, 2010b). These will include a 3.32 Mt/y methanol plant, a 1.22 Mt/y methanol-to-olefins (MTO) unit, a 400 kt/y monoethylene glycol (MEG) plant, a 210 kt/y ethanolamines/ethylenediamines facility, a 340 kt/y polyether polyols unit, a 150 kt/y acrylic acid facility, a 200 kt/y acrylic ester plant, a 200 kt/y chlorinated methane unit, a 510 kt/y ethylene dichloride/vinyl chloride monomer plant and a 500 kt/y PVC plant (China Knowledge, 2009).

At present, Shenhua and Dow are carrying out a feasibility study, which will take up to two years to complete and includes an environmental impact assessment, front-end engineering design, plus analysis of market and product mix, logistics, supply chain, and economics (China Knowledge, 2009). This includes consideration of whether it would be more cost effective either to locate the entire project in Shaanxi Province, where the coal mines are, or to split the project, with the methanol being made inland and the downstream operations being located near the coastal regions where the end users are situated. The companies plan to submit a project application to the Chinese Government once the study is completed (ICIS, 2010b).

5.12 Shenhua Ningxia coal-to-chemicals complex

This subsidiary of the Shenhua Group is developing a major integrated coal production and utilisation site at Ningdong, Ningxia Hui Autonomous Region, North west China. This includes coal production and electricity generation alongside coal-to-chemicals (dimethyl ether, olefin and methanol) production.

The entire project is scheduled for completion in 2020, at which time there is expected to be eight power plants with a capacity of 30 GWe, together with a chemicals annual production capacity of 250 kt of methanol (remaining after the rest is further processed) 1210 kt of dimethyl ether and 220 kt of olefin. There will also be a research and development facility to examine production of new materials. It is expected that all output will be sold on the domestic market. The investment cost has been quoted as RMB 280 billion (China.org, 2008).

The first coal-to-methanol plant, with an annual capacity of 2 Mt, is already in production, Figure 10. By the end of the first phase of construction in 2010, it is expected that the methanol will be further processed to deliver an annual production capacity of, 210 kt of dimethyl ether and 520 kt of olefin. The latter will be produced using the Novolen gaseous phase polypropylene process under licence from ABB-Lummus.

Figure 10 Methanol plant at the Shenhua Group's new coal-chemical complex in Ningdong, Ningxia Hui Autonomous Region (China.org, 2008)

5.13 Shenhua Baotou coal-to-chemicals project

Shenhua Baotou Coal Chemical Co Ltd is a wholly-owned subsidiary of the Shenhua Group (*see* Figure 11), which was established in December 2005 and located in Baotou City, Inner Mongolia Autonomous Region. Its overall project is designed to process 1.8 Mt/y of coal to produce 600 kt methanol (remaining after olefins production), 300 kt/y of polyethylene, and 300 kt/y of polypropylene. Total investment is RMB 16.5 billion, including three small coal-fired power plants together with auxiliary production facilities and public works. Construction is now complete with operation expected in late 2010 (Baotou news, 2009).

Figure 11 View of the Shenhua Baotou coal to chemicals plant (Baotou News, 2009)

This is the first industrial-scale demonstration of a methanol to olefin process, which was developed by the Dalian Institute of Chemistry & Physics. The project uses equipment from international suppliers, GE coal slurry gasification technology, Linde rectisol technology, Davy methanol synthesis technology, DOW polypropylene technology, and Univation polyethylene technology.

5.14 Datang Duolun coal-to-olefins project

The Datang Duolun project in Inner Mongolia is designed for an annual production of about 1.5 Mt methanol, from which 460 kt of polypropylene will be produced together with 130 kt of gasoline and 70 kt of LPG. This also uses the Dow UNIPOL process, for which a successful trial run of the technology unit took place in November 2009. Commissioning of the complete process is scheduled for the end of 2010 (CoalChem, 2010).

6 Issues arising

It is evident that the surge by Chinese industry towards setting up large-scale coal transformation projects has been slowed significantly by the state government, which remains cautious because of their need to ensure the nation's broad strategic requirements can be met (3E, 2008). The issues that impact on such requirements are set out below.

6.1 Government – industry contradictions

The drivers for developing coal-to-oil, gas and chemicals processes are different for the state government and industry. The former is concerned with establishing energy security, while industry and local government see this as a means to make money, at least when oil prices are high. From an energy security perspective, the state government is adopting a multi-approach, which includes importing as much oil as possible in the short term to build up a strategic oil reserve, buying overseas oil and gas resources, establishing import arrangements from a diverse range of sources, while, for the longer term, possibly establishing coal-to-oil, gas and chemicals processes as a means to offset oil and gas use.

In that regard, coal-to-oil and coal-to-gas are likely to be a means towards expediency. For coal-to-chemicals, the local governments are seeking to establish infrastructure projects in return for granting mining rights. Consequently, they continue to push for various projects as part of their plans to increase local GDP, even though the state government remains cautious. This discontinuity between state government strategic thinking and local government's operational intentions has been seen in various coal-based sectors for some time (Minchener, 2010).

6.2 Research, development and demonstration needs

Coal transformation technologies, including various coal-to-chemical variants, have been proven at modest scale. There is research that might usefully be done, for example either on reactor design or in terms of improving catalyst effectiveness to enhance the efficiency of conversion performance. However, the overriding requirement is to obtain performance and economic data from large-scale demonstration projects. This will allow technology developers and suppliers to establish a robust view of the economic sensitivities for a commercial-scale unit such that investors (either private or government) can make decisions on whether to proceed.

In this regard, China is now ahead of the rest of the world with the three reasonable-scale ICL industrial units together with the very large-scale DCL demonstration unit, all of which are operational. These units are providing valuable data, both positive and negative, that will give the developers early warning of issues to be addressed in commercial-scale designs. As such, this gives these project developers first mover advantage should the decision be made to proceed to commercial operations.

6.3 Implications for national coal production

The original Chinese Government plan suggested a very significant increase in coal-to-oil, gas and chemicals production through to 2020. In fact, while there has been significant growth in certain coal-to-chemicals production routes, with large plants now coming into operation, the utilisation of much of the existing capacity has been well below maximum. At the same time, coal-to-oil projects, which are less established than most of the various coal-to-chemicals process routes, have proceeded less rapidly than expected originally, as a result of reinforcement to the government's policies.

There has been a recent market assessment study, which has been undertaken by the China Coal Information Institute (CCII) and Centric Austria International, to examine the prospects both for conserving oil and substituting it via clean coal technologies. This included modelling the introduction of a range of coal transformation products, which was defined to include coal based methanol, dimethyl ether, methanol to olefin/methanol to propylene, and coal liquefaction. The underlying assumption was that the various large-scale demonstration trials under way are technically successful, after which, between 2011 and 2015, the government will unveil incentive policies and proactive capacity expansion plans. However, this is by no means certain to happen since the analysis says nothing about whether such a massive investment would be appropriate, when compared to alternative approaches.

The study considered a range of scenarios, based primarily on the speed at which industry might establish large-scale units, should the government give permission for this to proceed. It predicted for a reference scenario that China's industries are most likely to be able to deliver about 38 Mt and 84 Mt of coal-to-oil based products annually by 2015 and 2020, respectively (CCTI, 2009). This is equivalent to 16% and 30% of China's expected level of crude oil production. There is a wide range in these predictions and for 2020 these are 46 Mt (18.8%) to 137 Mt (40.5%) for low to high growth scenarios. However, since China's domestic oil production will meet less than 50% of China's needs, then at best China could offset between 15% and 20% of total demand at that time. These predictions assume that the production capacity of China's coal liquefaction plants would reach 12 Mt by 2015 and 33 Mt by 2020, which would appear to be optimistic, given progress to date.

On the basis of the demonstration and large-scale pilot project results achieved so far, it takes 3.5 t of coal to produce 1 t of oil under the direct process and 4.0 t under the indirect process. Thus for the 2020 reference scenario outlined above, the CCTI suggest that China's clean coal transformation industry could consume up to 300 Mt of coal and emit some 350 Mt of CO_2 to achieve the designated level of products (Aden and others, 2009).

Even for a country where the economy is dominated by coal this is a massive increase in production levels. In line with the government's plan for seven coal transformation bases, such coal would need to be produced in North-Western China. This could well mean a need for an upturn in coal production in the Xinjiang Uygur Autonomous Region where there are enormous coal reserves, supportive local policies but also a fragile eco-system. Because of the concerns arising from additional coal mining, the alternative approach might be to link underground coal gasification (UCG), coupled to FT synthesis. However, this energy extraction technique is not yet proven although large-scale trials are under way elsewhere (Coal Authority, 2010).

6.4 Infrastructure considerations

At present, there is a wholly inadequate rail system in North-Western China. Consequently, unless production plants are integrated with coal mines or UCG projects, there could be limitations on the reliable supply of coal for chemicals production. At present, China is investing a large amount of money in improving its infrastructure. For example, between 2001 and 2005 more was spent on roads, railways and fixed assets than during the previous 50 years (ICIS, 2008). From 2006 to 2010, it is expected that some US$200 billion will be spent on the railways, four times more than for the period 2001 to 2005. However, if the costs of establishing the supporting infrastructure have to be factored in to the production costs for industry, this will reduce the margins that can be made on the final products.

With regard to the introduction of coal based oil products into the Chinese transportation fuel market, there is a further issue. While Shenhua and Yitai have received approval for refined oil distribution arising from their coal-to-oil products (EntranceChina, 2009), it seems unlikely that such companies can ever produce enough synthetic fuel to justify their own retail networks. This suggests that their CTL products will probably only sell in the regional market unless deals can be agreed with the large and vertically-integrated oil companies, such as CNPC and Sinopec, which control the transportation fuel markets. It is likely that such companies would need to be encouraged by the state government to open up their retail system to Shenhua and others in due course (Harvard University, 2010).

6.5 Environmental implications

For all coal transformation processes, there are potential environmental issues (Irwin and others, 2007). The first impact of using CTL technologies on a significant scale would be an increase in the amount of coal needed. If this should be achieved by an increase in conventional mining, the environmental standards are established including remediation requirements. Should this be achieved through UCG, then the environmental standards are not yet established, although guidance would be obtained from the large-scale trials.

The government preference is for coal transformation plants to be integrated with an upstream coal mine. If the output is primarily liquid products, then these would be transported either to a refinery or to the end users. Subject to the necessary infrastructure investment, pipeline or rail tanker transport over long distances would replace the transport of coal. If some of the products should be used for power generation in the industrially-developed regions of China, then this approach would replace the construction of power lines to take what would otherwise be produced at a minemouth power plant. This could provide some environmental advantages.

For direct coal liquefaction plants, the exact nature of the by-products and effective methods for their upgrading, treatment and safe disposal will depend both on the coal used, and the exact processing conditions. The practical considerations of effluent treatment have yet to be fully proven due to the absence of commercial plants.

For indirect coal liquefaction plants, the first operation is that of gasification, for which there is considerable accumulated experience and the procedures currently used will remain appropriate. After this, the purification and subsequent processing of the syngas can result in unwanted by-products such as:

- gases from distillation and hydrocracking – NOx, CO, VOCs, SO_2, CO_2, PM_{10};
- water-based effluents with hydrocarbons, salt, calcium, acetic acid;
- solid residues associated with the catalysts and adsorbents used, including both the FT catalyst and that used for subsequent hydrocracking. There may also be some of the catalyst used for converting mercaptans into H_2S. Many of the catalysts are of sufficient value to justify recovery and reuse.

Where such plants are deployed, there will be a need to establish procedures that are adequate to meet local regulations. That said, in each case Sasol has established rigorous procedures for meeting the appropriate environmental regulations which would form a sound basis for possible use elsewhere.

In overall terms, coal transformation plants require substantial amounts of water, up to 8 t for each tonne of liquid products (Yue, 2010). Where lignites are the feedstock, these typically contain a large proportion of water and, if this is recovered, it can provide a significant proportion of that needed. Shenhua has included a water recycle unit on their DCL demonstration unit and this reduces the requirement to about 7 t of water for each tonne of oil product output. By way of comparison, the total water consumption for crude oil exploitation and oil refining processes is 6 t for each tonne of oil product. Many of the units are built close to the Yellow River with the expectation that they can draw whatever they need as their projects expand. However, in recent years, the state government has started to control water consumption and there are strict controls on the extraction of water from the Yellow River. If this is correctly enforced, it will certainly limit expansion of the coal transformation sector. Even with the use of techniques to recycle all wastewater to minimise overall needs, this represents a major government concern.

6.6 Carbon intensity concerns

Producing transport fuels and chemicals from coal is a carbon intensive process and will involve a substantial increase in greenhouse gas emissions compared with possible oil based alternatives. However, as the CO_2 will be provided as a concentrated by-product from both coal conversion variants, unlike in oil refineries, it will be readily available for capture and either storage in geological formations or use in some other mitigation process (Yue, 2010). Thus DCL plants will produce a concentrated stream of CO_2 from the hydrogen production unit while ICL plants will produce a similar stream from the processing of the syngas prior to FT synthesis. Also, as DCL operates with a higher energy efficiency than ICL, it will have a lower specific CO_2 output.

Where there is the opportunity for enhanced oil recovery (EOR) through CO_2 injection, then the sale of the CO_2 may provide a significant income stream that could compensate for the CO_2 transport and injection costs. Where that option is not available, CO_2 storage will need to be in a saline aquifer, the additional and non-recoverable costs of which will affect the economics of the overall operation. However, recent studies in the USA indicate that CTL with CCS can achieve a smaller carbon footprint compared to the average emissions profile of petroleum-derived diesel, and that the cost of the addition of CCS to CTL would be relatively inexpensive. Thus a recent report from the National Energy Technology Laboratory (NETL) concluded that a fuel produced from a CTL process integrated with CCS would account for 5–12% less lifecycle greenhouse gas (GHG) emissions compared to the average emissions profile of petroleum-derived diesel, based on the US national average in 2005. It further suggested that such synthetic fuels would be economically competitive with petro-diesel products when the crude oil price is at or above 86 US$/bbl. This is based on a 20% rate of return, in January 2008 dollars, with a carbon price of zero (Green car congress, 2009b). Equally importantly, the NETL report concluded that the addition of CCS to CTL would add only ¢7 per gallon to the required selling price of the diesel product. This study is specific to particular conditions within the USA and is not necessarily directly transferable to the Chinese current situation. However it does provide some encouragement for limiting the carbon intensity of coal transformation processes.

As noted above, Shenhua are proceeding with an integrated CCS industrial-scale project to obtain data relevant to China (Xinhuanet, 2010).

6.7 Investment considerations

This is the major issue. The overall investment for a commercial-scale CTL plant is massive while the factors that determine the return on that investment cannot be predicted with confidence over the lifetime of the plant. In China, on an energy-equivalent basis, coal is less than a quarter of the price of crude oil. However, despite that, depending on the location, the capital costs of making chemicals out of coal are much higher than those of traditional processes based on oil and natural gas. Thus, coal-based chemical plants require a big, sustained advantage in feedstock costs to be competitive with oil and gas.

There is a limited amount of public information on the costs of coal-to-oil plants in China. Lu'an

Group have stated that the investment cost for its indirect coal-to-oil demonstration plant with an annual capacity of 160 kt is some RMB 1.9 billion , while for a commercial plant with an annual capacity of 5.2 Mt the cost would be RMB 40–50 billion (Li, 2010c). The Yital ICL demonstration plant is understood to have a similar investment cost (RMB 2.0 billion) for a very similar product output while the Shenhua DCL plant, with a current annual capacity of 1 Mt, is reputed to have an investment cost of RMB 24.5 billion although this includes some equipment applicable to its planned scale-up to 3 Mt capacity (Market Avenue, 2010b). The estimates for commercial-scale plants are at this stage very provisional, due to the lack of historic data worldwide.

Since CTL, by whichever route, is capital-intensive, it benefits substantially from economies of scale. Most studies on process economics have assumed that a full-scale commercial plant would produce 50,000–100,000 bbl/d of liquid products (DTI, 1999), which is equivalent to some 2.5–5.0 Mt/y. On such a basis, independent analysts have suggested that production costs in China should be in the range 27–35 US$/bbl of oil, rising to 45–50 US$/bbl once distribution costs and taxes are included. This assumes that the coal mining costs are below 10 US$/t, and currently the average cost of mining a tonne of coal in China in the large mining complexes in North-Western China is about 8 US$/t. However, this is within a wide range, dependent on local circumstances. Thus, under such conditions, when crude oil prices are above 50 US$/bbl, the process should be nominally profitable. However, when oil is below about 35 US$/bbl, the CTL plants would lose money (Chemical and Engineering News, 2008).

To put this in perspective, for most of the time since the Shenhua Group started their DCL project, oil prices have risen while production costs of coal have remained relatively constant, although the price at which the coal could be sold for other applications has risen significantly. Thus:

- in January 1998, the National Council provided Shenhua with a grant of RMB 10.8 billion for CTL development when the international oil price was 12 US$/bbl;
- in late 2001, Shenhua completed the original feasibility study of the direct CTL project at which time the oil price was about 23 US$/bbl;
- the construction of the Shenhua DCL demonstration plant started in 2004 when the oil price was 37 US$/bbl; at the end of 2008 the Shenhua DCL plant was started up, just prior to which the oil price had been 147 US$/bbl;
- the plant has continued its operational programme during 2010 when the oil price has been in the range 60–70 US$/bbl.

The Shenhua DCL project is supported by the Chinese Government and that provides a level of confidence that the company will be underwritten if the oil:coal price ratio gets out of the range whereby the project would be deemed financially acceptable. The company has stated that the CTL plant needs an oil price of 40 US$/bbl or more to be safe from financial risks. However, it has also stated that crude prices would need to remain above 60 US$/bbl in the long term (China Daily, 2009b). As yet, Shenhua has not provided public information on the economics of their CTL unit, either for the initial scale of operation or for the full-scale commercial plant.

The costs for an ICL process will be similar but higher than for a DCL process since the former has a lower conversion efficiency, with an estimate for such a plant to produce synthetic crude oil being about 50 US$/bbl. Should larger production scales and better integrated technology be introduced, there will be efficiency and conversion improvements. It is generally believed that this will result in the coal requirements reducing and the cost of the synthetic crude oil should fall closer to 40 US$/bbl (Li, 2010c).

For the coal-to-chemicals plants, the same principles apply. However, since these are based on indirect conversion processes, there is the option to establish product flexibility. For example, one route would be coal-to-methanol, to DME and then to olefins, namely ethylene and propylene, which are the major building blocks of today's chemical industry. This offers the prospect of a number of products, the output of which can be adjusted depending on market needs. Even then, as China is finding at present, there can be competition from gas-fed petrochemical plants recently built in the Middle East, which are very competitive compared to China's coal-based plants.

As such, given the uncertainties in the coal based production costs and the future price projections for oil and oil-based products as well as international competition from gas-based production processes, the economics of coal-to-oil and chemicals projects in China will most likely look high risk. It is also important to recognise that the technical maturity of the various processes under consideration vary and this too will need to be taken into account by the government that is seeking to manage risk by addressing logistics, financing and environmental concerns when considering these very large investments.

6.8 Alternative investment scenarios

While there may be merit in making the investments necessary to establish coal transformation process at commercial scale, alternative approaches need to be considered, which not only assess the sustainability of resource and environment, together with energy security and climate change, but also economic efficiency and social welfare (Ma and others, 2009). As has been described previously, China has a major programme of investments, collaborative projects and international agreements, which are designed to diversify oil and gas supply sources and to reduce the threat to supplies. This is clearly the key part of its security of supply strategy, as evidenced by the sheer scale of operations. In addition, rather than commit to coal transformation activities, there is a need to consider whether it would be more effective to invest in, say, building efficient urban transport systems, raising the fuel efficiency of all of China's vehicles including agricultural ones, switching to electric vehicles, or even just having specific funds available to pay for imports when demand increases and prices rise (Andrews-Speed, 2007).

It would appear that the state government is grappling with this issue, as evidenced by their refusal to allow industry to proceed with the next stage of coal transformation development and very large-scale deployment, until at least the first wave of projects has been comprehensively assessed and evaluated.

6.9 International co-operation

There has been considerable co-operation with overseas organisations, both for coal-to-oil and coal-to-chemicals applications, including joint projects between industrial companies, licensing and other commercial arrangements, joint studies and R&D. Figure 12 shows examples of the international links that have been established on a global basis for coal-to-oil applications in recent years, many of which have included Chinese input.

Although OECD direct investments have to date been limited, there has been considerable co-operation between Chinese industry and international technology suppliers. While China is determined to establish its own intellectual property, as in other energy sectors (Minchener, 2010), there has been considerable licensing of key technologies for the various applications from such suppliers.

Thus international companies with CTL know-how have been attracted to potentially promising business opportunities (DECHEMA, 2010). For example, in 2006, Shell signed an agreement with Shenhua Ningxia Coal Industry Co to undertake a feasibility study on a coal-to-liquids project. The plant, which was expected to convert coal into oil products, was estimated to cost US$5–6 billion, according to Shell, and would have used Shell's indirect coal liquefaction technology, to yield 3 Mt of oil a year (~70,000 bbl/d). However, following the global economic down-turn, Shell declined to

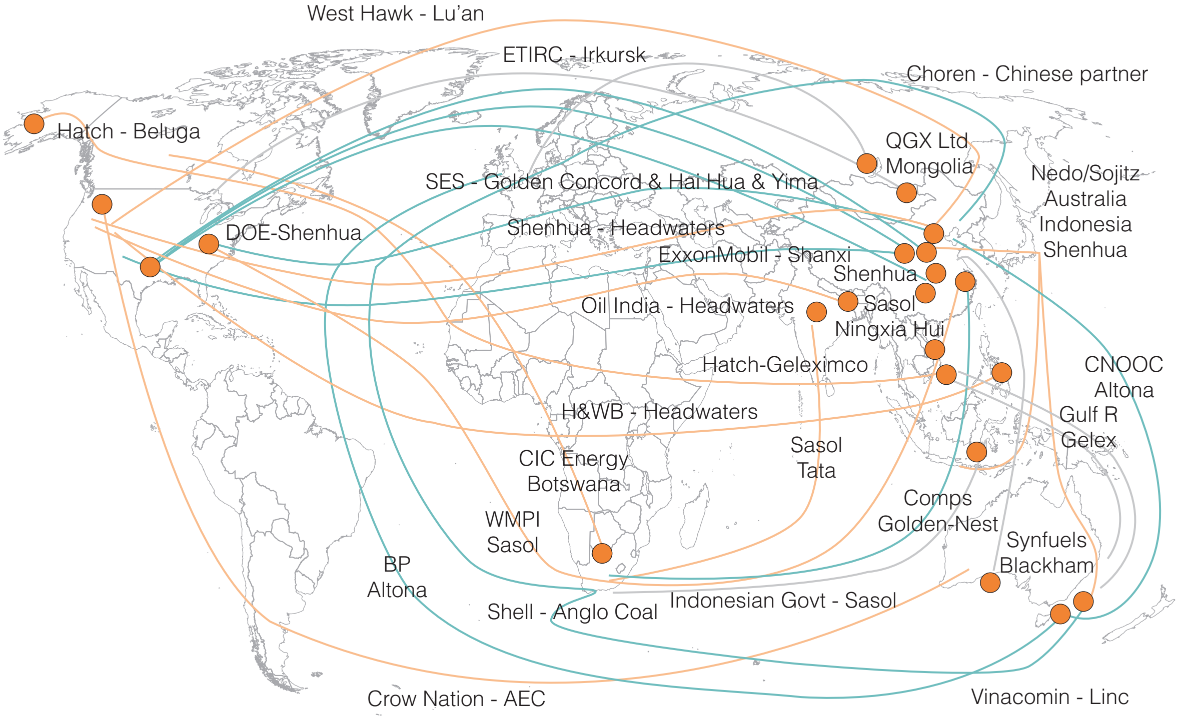

Figure 12 Examples of international co-operation for coal to oil applications (Périneau 2009)

proceed (Businessgreen, 2009b), although since then Shell has signed an agreement with Shenhua to continue co-operation on ICL, which will include the possible application of CCS to their technology.

Sasol has also been co-operating with Shenhua since 2006 when both companies signed two agreements to study the feasibility of setting up of two coal-to-liquids plants in North West China using Sasol's FT technology. One was an 80,000 bbl/d CTL project in Shaanxi Province while the other was for an 80,000 bbl/d coal-to-liquid project in Ningxia Hui autonomous region (Sasol, 2006). However, the Shaanxi Province prospect was subsequently shelved following the NDRC restrictions announced in 2008 and although the Ningxia Hui option has reached the point where both companies have presented a case to the NDRC for proceeding to the construction phase, there appear to be some problems.

There is also evidence of Chinese CTL expertise being exploited outside of the country. Thus the Australian energy company Blackham Resources Limited signed an agreement with Synfuels China Co Ltd regarding the establishment of a CTL FT Diesel Facility in the Esperance Region of Western Australia based on the latter's technology. Under the terms of a non-binding Memorandum of Understanding, Blackham and Synfuels China have agreed to conduct various technical and project related evaluation activities, with the intention to signing a formal agreement with respect to the application of Synfuels China technology in Australia. This would give Synfuels China first option to negotiate to undertake the whole project design for Blackham's intended CTL FT Diesel Facility. If this should be successful, Blackham and Synfuels China would seek to establish a feasible commercial co-operation model to promote the prompt industrialisation of Synfuels China technology in Australia (Synfuels China, 2009).

In another link with Australia, the China National Offshore Oil Corporation (CNOOC), China's largest offshore oil and gas producer, intends to invest in a coal-to-liquids project in Southern Australia. It will work with Altona Energy to jointly develop the Arckaringa project, including the development of an opencast coal mine, coal-to-liquid processing and power generation. CNOOC will hold a 51% stake in the project while Altona Energy will hold the remaining 49% (Caixin, 2010).

With regard to coal-to-chemicals co-operation, there has been considerable interaction between Chinese companies and international technology suppliers. Many of the suppliers have set up joint venture arrangements and have established manufacturing plants in China. Major gasification providers, such as Shell and GE, have been licensing their technology and forming joint ventures, including local manufacturing arrangements, as part of the process to increase market penetration for their equipment within coal-to-chemicals complexes. Companies such as Lurgi, UOP and Davy Process Technology are licensing key components for the various large-scale projects being established. Potentially the biggest co-operation might be that between Shenhua and Dow, as described in Chapter 5.

7 Future prospects

The next five years will be pivotal in determining the extent of China's coal-to-oil, gas and chemicals deployment. In that period, the various large-scale trials and demonstrations for the five key technologies will be undertaken and should provide sufficient data from continuous operation to allow a realistic assessment of the technical and economic options to be undertaken such that the basis, or otherwise, for commercial-scale plants can be established. The first to achieve that will be the coal-to-oil projects, probably during 2011. The three coal-to-olefins trials will commence during 2011 and will thus provide the next stage of the technology assessments. These will most likely be followed by the results from the coal-to-synthetic natural gas projects. For DME, only one very large project has received construction permission, in part because the issue here is less technically related and more to do with market determination and infrastructure. For coal-to-ethylene glycol, this is currently at the large-scale R&D stage although plans for scale-up are being prepared.

Should China decide to pursue the deployment of coal transformation processes, it has the means to undertake the heavy engineering necessary to establish these very large coal transformation production units. While it has drawn on international technology suppliers for many of the key components, through licences and joint ventures, increasingly Chinese companies are establishing their own intellectual property, with the prospect of reducing overall costs that should make the technology more competitive.

However, it is also evident that the Chinese Government is grappling with the same conflicting issues that the USA, Europe and Japan had to address during the oil price rises of the 1970s and 1980s, namely how to reconcile energy security with volatile prices that can make massive investments in coal transformation projects very uncertain. For China, the sheer scale of its still rapidly growing energy economy, especially the transport sector, will make this an even more difficult problem to resolve.

While the key companies taking forward coal transformation development projects towards commercial deployment are all strongly supportive in public, all note the need for strong government policy support in order to underpin the robust introduction of this capital intensive industry. It is also notable that the government directives refer to a steady approach to building up the coal transformation sector, in contrast, say, to its plans for wind energy and to some extent nuclear power. Thus while the companies are making their plans for a major deployment of commercial-scale coal-to-oil, gas and chemicals, it is not at all clear that the NDRC will decide to progress all such technologies until a comprehensive case is made to justify the investment. That said, it seems likely that some processes may be taken forward to commercial scale although the capacity level may be limited.

For coal-to-oil technologies, the various demonstration and industrial-scale projects have yet to be fully technically successful and the overall economic case is not yet proven, given the resource concerns, environmental and carbon intensity issues. As such, any scale-up will most likely be slow and careful, with deployment likely to be much slower than was expected when the 11th Five-Year Plan was being formulated. It is possible that as a means towards expediency, the nearer-term plans of Shenhua, Yitai, Lu'an and perhaps Yangkuang will be realised. It also seems likely that any expansion will be conditional on ensuring that steps are taken to further improve environmental protection and the conservation of both energy and resources In all cases, the issue of carbon intensity will need to be addressed. However, while this might establish some 15–20 Mt capacity by about 2020, the level may well not rise significantly beyond that, at least in the foreseeable future. Indeed, for all the concerns set out above, it seems inconceivable that CTL can ever be more than a relatively small part of the overall process to diversify sources of supply.

For coal-to-synthetic gas, the technology is reasonably straightforward and the end product can readily be transported by pipeline for which there is scope to link in with either existing or planned systems for bringing natural gas overland from west to east of China. Therefore, should the three big demonstration projects prove successful, it is likely that bigger units will be established, if only as a stopgap to supplement the supplies of natural gas that are being built up via exploitation of domestic fields and through international collaboration. The big unknown is how the carbon intensity of such projects would be treated. Should CCS need to be introduced, the CO_2 is concentrated as a result of the methanation process and so is easily available for capture. However, the costs to transport and store the CO_2 would still be significant although, if the CO_2 can be used for a nearby EOR application, that could make the financial impact of CCS close to cost neutral.

With regard to coal-to-chemicals, there is a risk that there are production systems being put in place while the market for the product has not been established. For example, for methanol production, current production capacity far outstrips demand and so there is a need for a much more balanced approach to be established, which includes its use as a primary material for downstream higher value products.

One such product is DME. The very large-scale production has yet to be proven and the economic case yet to be made. However, already there is significant capacity available. What is lacking is the establishment of a market for the product. This might include its introduction as a substitute fuel for LPG and as a diesel substitute in the transport sector. In both cases, there is a need for a regulatory framework and standards plus the establishment and implementation of a comprehensive plan for infrastructure development. Without this, supply capacity is already in excess of demand, and so further significant take-up will not take place.

Another option is gasoline from methanol, which is being trialled at reasonable scale. However, it is a rather low efficiency process, requiring 2.5 t of methanol to produce 1 t of gasoline/petrol. Consequently, if the government strongly pushes the blending of methanol with gasoline then this will be more attractive approach for use of methanol than converting it into gasoline. Consequently, the future for this process is uncertain.

It is a similar situation with coal-to-olefins, via methanol. There has been a rush to build a significant number of relatively small-scale units but until the large-scale demonstration units are established, it is impossible to ascertain if this is a technically and economically viable way forward. Such an evaluation will need to take into account the competition from gas based low cost production processes from overseas.

When all of these coal transformation options are considered, it is clear that the recent strategy of developing and utilising indigenous energy sources and reducing dependence on energy imports is no longer a wholly viable way forward, as evidenced by the shift to diversify sources of international supply of oil and natural gas. For the longer term, the future of all these coal transformation projects will depend on what policies and regulations the state government puts in place. While these will need to address efficiencies of production processes, the government will also need to consider whether a better investment could be made to achieve the same impact (for example energy efficiency). This is part of a much bigger question, namely how China deals with the increasing challenges of balancing economy, energy and environment, as part of its aim to establish sustainability of its long-term development while, at the same time, addressing shorter-term issues such as balancing supply and demand.

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