Challenges and opportunities for coal gasification in developing countries

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Abstract

Coal gasification for chemicals, gaseous and liquid fuels production can fulfil an important strategic need in those developing countries where coal is the primary fuel source and oil and gas energy security is an issue. At the same time, the establishment of major projects in such countries can be problematical for a number of technical and economic reasons, although it is encouraging that some projects appear to be moving forward. There are two developing countries where coal conversion projects to produce chemicals, gaseous and liquid fuels have been taken forward strongly. The first is South Africa, which established the world's only commercial-scale coal-to-liquids and coal-to-chemicals facilities at Secunda and Sasolburg respectively. The other is China, where there is a major gasification-based coal conversion development and deployment programme that is set to become a significant, large-scale commercial element in the nation's energy development plans. This will provide further major opportunities for the deployment of large-scale coal gasification technologies, various syngas conversion units and catalysts for the subsequent production of the required products. The role of China is likely to be critical in the dissemination of such technologies to other developing countries as it can not only provide the technical expertise but also financially underpin such projects, including the associated infrastructure needs.

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Acronyms and abbreviations

bbl/d	barrels per day
cv	calorific value
°C	degrees centigrade
kg	kilogramme
kJ/kg	kilojoule per kilogramme
km	kilometre
kt	thousand tonnes
kW	kilowatt
kWh	kilowatt hour
m	metre
m^3	cubic metre
m^3/h	cubic metres per hour
ppm	parts per million
%	percentage
t	tonne
wt	weight
y	year

BOO	build, own and operate
CAS	Chinese Academy of Sciences
CBM	coal bed methane
CCT	clean coal technology
CCS	carbon capture and storage
CCUS	carbon capture, utilisation and storage
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	dimethyl ether
ECBM	enhanced coal bed methane
EPC	engineering, procurement and construction
FT	Fischer-Tropsch
FYP	Five-Year Plan
GDP	gross domestic product
GJ	gigajoule
Gt	gigatonne (1 billion tonnes)
GWe	gigawatt electric
H_2	hydrogen
H_2S	hydrogen sulphide
ICL	indirect coal liquefaction
IGCC	integrated gasification combined cycle
IEA	International Energy Agency
LNG	liquefied natural gas
LPG	liquefied petroleum gas
MJ	megajoule
Mt	million tonnes

MEG	monoethylene glycol
MTG	methanol-to-gasoline
MTO	methanol-to-olefins
MTP	methanol-to-propylene
MWe	megawatt electric
NDRC	National Development and Reform Commission
NEA	National Energy Administration
N_2	nitrogen
NOx	nitrogen oxides ($NO + NO_2$)
O_2	oxygen
OECD	Organisation of Economic Cooperation & Development
PE	polyethylene
$PM_{2.5}$	particulate matter under 2.5 microns in diameter
PP	polypropylene
R&D	research & development
RD&D	research, development & demonstration
RMB	Reminbi
SADC	Southern African Development Community
SNG	synthetic natural gas
SO_2	sulphur dioxide
UCG	underground coal gasification
USA	United States of America
US DOE	United States Department of Energy
US$	United Sates dollars

Contents

1 Introduction

This study provides an analysis of the challenges and opportunities for the deployment of coal gasification-based fuels and chemical production in developing economies, including reference to underground coal gasification (UCG) where appropriate. It has identified those countries that would benefit most from the introduction of coal gasification technologies, while also identifying the major barriers that must be overcome to ensure significant technology introduction and deployment.

This global assessment has been complemented by an overview of the major coal gasification-based programme that is taking place in China. Although still classed as a developing country, on the basis of various per capita indicators, in absolute terms it has the second largest economy in the world and has shown a very rapid industrialisation, especially over the last decade. This transformation has included the introduction and subsequent development of various coal-based technologies. At the same time, there has been an ongoing establishment of supportive policies backed by a legal and regulatory system to ensure that the growing coal utilisation sector is aligned with the national energy and environmental targets (Minchener, 2010, 2011a,b, 2012a).

Thus an update has been provided on the Chinese Government's approach to developing the gasification-based coal-to-fuels and -chemicals sector. This includes the recent introduction of performance standards in terms of coal and water use per unit of output. These need to be met for new projects to gain government approval, in line with the energy efficiency and carbon intensity targets that have been included within the 12th Five-Year Plan. There is a review of the geographical focus that is becoming established for some products, the redirection of the processes towards the production of those chemicals of greater strategic importance to China, the establishment of synthetic natural gas (SNG) technologies, and the ongoing debate about the size of the coal-to-liquids (CTL) industry that might be developed.

There is a description of the various modern coal gasification technologies that are being used in China, together with comment on the increasing scale of operation and the greater focus on domestically developed options compared to the use of imported technologies. This is presented on a vendor-by-vendor basis, including a technology description and comment on the various approaches being used to develop market share.

Finally, this study also considers the scope for development partners and early gasification adopters from China to engage with other countries in the region in order to advance technology introduction and subsequent scale-up.

2 Coal gasification

Gasification is a process by which coal can be converted into syngas ($CO + H_2$), that can then be used to produce a range of chemicals, either directly or via intermediates, such as methanol. Typically, 1 kg of bituminous coal can be converted into 1.5–1.7 m^3 of syngas.

The coal chemical industry product chain can be extensive. Traditional coal chemical industries include the production of ammonia, coke and calcium carbide. At the same time, especially in China, there is a significant new coal chemical industry being established based around modern gasifier systems, for the production of fertilisers, hydrogen, petrochemical substitutes such as ethylene glycol, olefins and SNG, together with transport fuels, as shown in Figure 1.

In terms of feedstock flexibility, several gasification plant designs have been developed to utilise various grades of coal in addition to waste and biomass. In particular, these modern gasifier systems provide a means to monetise large, low-quality, coal reserves, especially lignite which is at the bottom of any coal grading system due to its high moisture and ash contents, and in many cases cannot readily be used for alternative purposes (Petroleum Economist, 2010).

Gasification results in very low gaseous emissions of conventional (non GHG) pollutants, due to the nature of the process operation. It also offers a potentially low marginal cost route for capturing the resulting CO_2 by-product for either geological storage or enhanced oil recovery.

A further potential attraction is that coal gasification to produce fuels and chemical products can help to limit the need for imports of natural gas and oil, thereby offering some level of energy security, especially as coal pricing generally tends to be less volatile than other fossil fuels (Minchener, 2009). Thus the costs of the end products should be reasonably predictable. However, such gasification-based

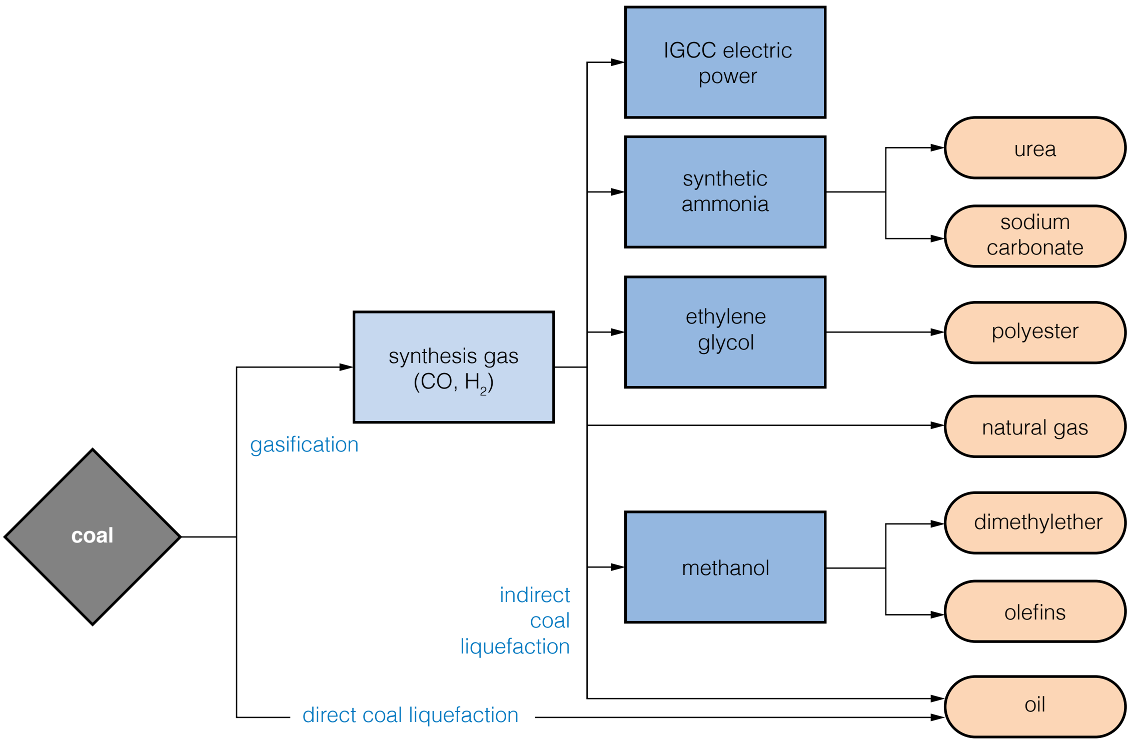

Figure 1 New coal chemical industry supply chain (Seeking Alpha, 2012)

Table 1 Typical coal chemical projects' unit consumption of coal and water and release of CO_2 as a by-product (Seeking Alpha, 2012; ICIS, 2013)

Chinese applications	Standard coal consumption	Water consumption	CO_2 emissions
	tonnes/tonnes		
Indirect coal liquefaction	4.39	13	5.0
Coal-to-olefins	6.68	15-20	5.5
Coal-to-ethylene glycol	2.55	14	2.0
Coal-to-SNG	2.83	6.58	2.5

coal conversion systems require significant upfront capital investment, especially coal-to-oil processes. This can introduce financial uncertainty since the prices of the alternative competing sources of the end products, such as oil and gas, can be very volatile.

In addition, these processes require significant water use, which in certain regions of the world is a growing concern. They can also be large emitters of CO_2. Table 1 indicates the unit consumption of coal and water in the unit production of various key chemical products, and release of CO_2 as a by-product, based on current Chinese experiences.

3 Candidate developing countries for the introduction of gasification technology

3.1 Basis for identification

Any major coal conversion project will require a significant source of coal within the candidate country. Almost invariably, the rights to utilise that coal are held by the government, either directly or via an agency. Consequently, they can determine the more appropriate means to monetise this energy asset.

It is possible to identify some key prerequisites for assessing potential coal conversion projects (IEA, 2006), namely:
- large reserves of low cost gasifiable coal at the proposed location, of the order of 1–2 Gt, to be available to support very large coal-to-chemical projects such as CTL plants of a minimum size of 80,000 bbl/d output capacity;
- stranded coal, due to either its low-quality or location, making it unsuitable to be monetised for alternative applications, such as electricity generation;
- government ability and will to provide enabling support for the very large capital investments, on the grounds of improved energy security through decreased dependence on imported energy, and to shield developers from oil price volatility.

Once it has been determined that the prerequisites have been met, there are additional issues to consider (IEA, 2006), such as:
- fuel resource analysis focusing on coal availability compared to either indigenous supplies or imports of oil and natural gas;
- coal quality analysis and an assessment of the technical and economic issues that might need to be addressed to ensure acceptable utilisation in either combustion or gasification applications;
- for the latter, identification of those gasification products that would most benefit the national economy, both in terms of usage within the country itself and as exports;

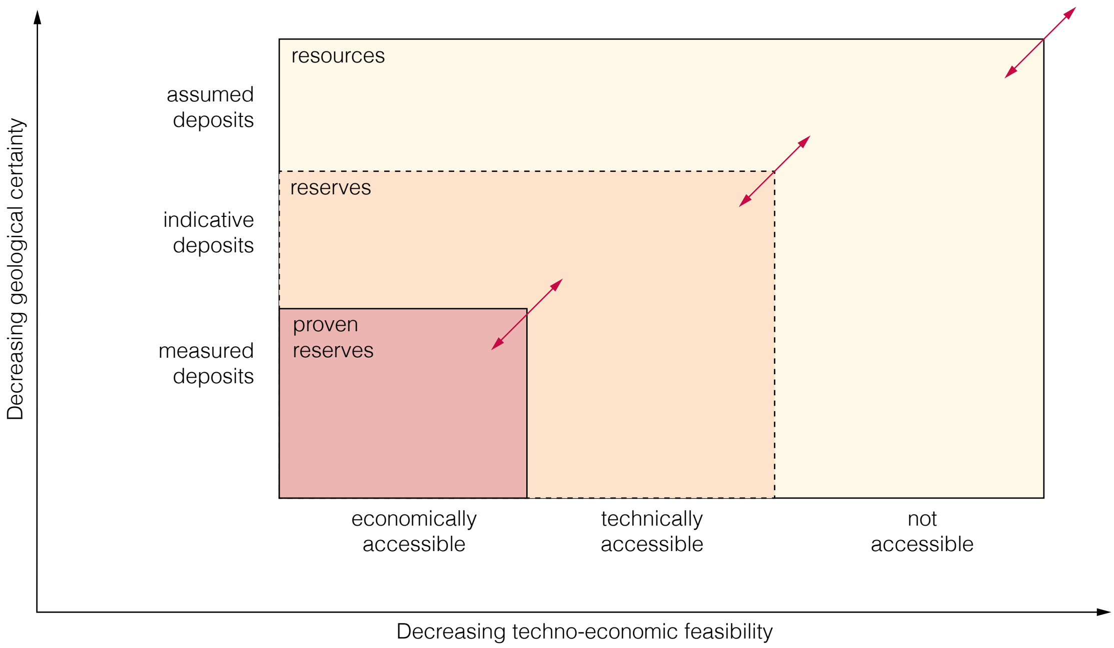

Figure 2 Depiction of resources and reserves (Kavelov and Peteves, 2007)

- extraction of the coal followed by transport either by road or rail to another location for subsequent utilisation. Under this scenario, local infrastructure needs are comparably modest although the environmental impact of the transport options may be unattractive;
- development of a local processing plant, either for power or for, say, chemicals production, which would require infrastructure needs both for the supply of feedstocks and for transporting the end products;
- capacity requirements in terms of the capability of a workforce to support gasification plant construction and operation;
- consideration of possible economic uplift compared to social and environmental concerns that could arise in locations where gasification plant might be established.

In any assessment, it is important to use wherever possible a common terminology to describe the coal assets that might be exploited. Estimations of the amounts of natural resources such as coal that remain to be exploited are defined by two terms, resources and reserves, with the latter being subdivided into proven exploitable reserves and indicative reserves, Figure 2. Thus:

- coal resources are broadly defined as the amount of coal actually present in a deposit, but the quantification is approximate and takes no account of either the technical or economic feasibility of extracting that coal;
- proven exploitable reserves are those that are believed to be economically extractable using current technology and under current market conditions. Such an assessment is expected to take account of a coalfield's geological characteristics, probable seam thickness and quality, as well as the geological discontinuities such as faults and folding all of which affect the practical recoverability of the coal. As such, these reserves should have been thoroughly surveyed and their quantification well defined.
- Indicative reserves are those that have been less comprehensively explored and so are estimated with a lower degree of confidence than the proven reserves. They should be mineable but it is not known how much coal will be economically exploitable.

The size of a proven reserve can change with time, depending on the available technologies for extraction and exploitation and on the current economic conditions. Thus, it will diminish in periods of low market prices for coal and increase in periods of rising prices. It also depends on the market prices of competing fuels. A resource can increase if new deposits are found, as can a proven reserve should deposits be quantified following geological surveys. Also improvements in mining technologies may reduce extraction costs so that uneconomic deposits become viable, converting an indicative reserve into a proven reserve (World Coal Institute, 2005).

Subject to the criteria listed above, this study has broadly identified those developing countries and emerging economies that, in principle, would benefit most from the introduction of various coal-based gasification technologies and conversion processes. In each case, any activities to exploit the available coal assets, which are either being undertaken or are at the planning stage, are included. The findings are presented on a country-by-country basis within each key geographical region.

3.2 Africa

Africa's recoverable (but not necessarily commercially exploitable) coal reserves are estimated to be about 60 Gt although the basis of the definition for reserves is believed to be quite broad (EIA, 2006). Over 99% of such reserves are located within the Southern African Development Community (SADC) region that is shown in Figure 3, with the very great majority being located in South Africa itself. This reflects the extensive development of the coal production sector in that country whereas in most of the other SADC nations there has only been limited exploration and quantification of coal deposits.

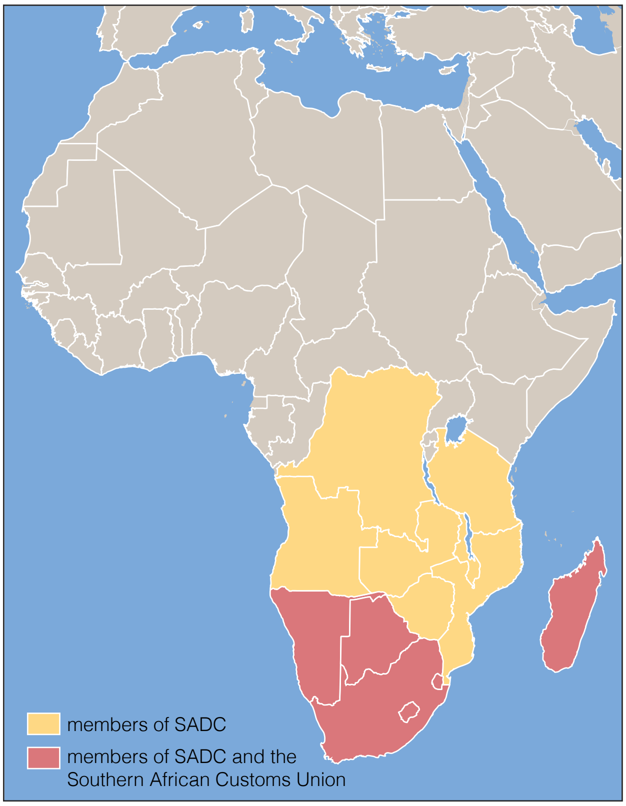

Figure 3 Regional spread of the Southern African Development Community (SADC, 2013)

3.2.1 Botswana

After South Africa, Botswana has greater coal resources than any other country within the SADC region. Estimates vary significantly, with resources put as high as 212 Gt, taking into account all the known coal fields as well as estimates derived from exploration data for coal from other areas. These include the large untapped deposits in the greater Morupule and Mmamabula coal fields of eastern Botswana, other coal fields at which companies have done a lot of work but did not state the resources, and regions where thick coal seams have been and continue to be intercepted during drilling for diamonds and other minerals (All Africa, 2008). The government has suggested that actual recoverable reserves comprise some 3.3 Gt, mostly in the eastern part of the country. Botswana has one operating mine, at Morupule, with an annual output of less than 1 Mt of low quality coal that contains relatively high levels of ash and sulphur (EIA, 2013d). This supplies coal to Botswana's only coal-fired power station, Morupule Thermal Power Station (MBendi, 2007).

The Government of Botswana has stated that it is committed to developing and promoting a wider use of coal to substitute for imported energy and also to replace fuel-wood for domestic and institutional use. It has been developing a National Coal Strategic Roadmap to guide and direct the effective use of Botswana's coal resources. In principle, this approach should support the development of a comprehensive coal processing strategy, which will involve conversion of coal to various products. In practice, the export of coal and various coal conversion products would be problematic, at present, due to the absence of a reasonable transportation infrastructure.

The Government of Botswana is considering the construction of a CTL plant at the Morupule and Mmamabula coal fields (Mitchell Group, 2012; World Bank, 2009). In the latter case, CIC Energy, which holds the rights to the coal deposits, is interested in manufacturing either low sulphur diesel or petrochemicals and has secured an option on coal gasification technology from Shell to be linked to Fischer-Tropsch (FT) conversion technology. Various technical and market studies have been undertaken that identified several downstream product opportunities within the SADC and international markets, while a pre-feasibility study suggested that a multi-product pipeline from the Mmamabula site to the Gauteng area in South Africa would represent a positive investment (Jindal Africa, 2012). It remains to be seen whether the project will actually proceed on a commercial basis.

3.2.2 Mozambique

Mozambique's coal resources are estimated at over 23 Gt with technically recoverable reserves so far quantified at 849 Mt (BGR, 2011), which comprise a mix of thermal (25–30%) and coking (70–75%) hard coal.

Until recently, Mozambique's annual coal production was limited to a few thousand tonnes, which were either sold locally or exported to neighbouring countries. However, about 36 mining companies are currently active in Mozambique's Tete Province, with activities being dominated by Rio Tinto and the Brazilian mining company Vale (Mining Weekly, 2012b). There is an expectation that an export business could be established on a scale similar to that of South Africa, with the major destinations being India and China, especially for coking coal (Platts 2011). However, besides the development of the various mines, this would require massive investment to develop a significant transport infrastructure in the northern two-thirds of the country. Thus the existing railway lines would need to be integrated in order to transport large volumes of coal from a number of locations while the small ports would need to be enlarged to enable large coal ships to enter the harbours (Reuters, 2013). The sheer scale of the infrastructure requirements has led to some projects being put on hold due to problems with getting coal to port, with consequent write-downs of the coal assets by the mining companies. In order to attempt to address this severe limitation, the government has implemented a bid competition for companies to provide the necessary railway and port development, with the winner being required to provide the funds, while also having to transport non-coal cargo and passengers.

Other major challenges include limited access to potable water, sanitation and electricity outside of the main urban areas, as well as low levels of transparency, government bureaucracy and over-regulation, and labour market inflexibility (UK Trade and Investment, 2012).

With regard to the prospects for coal gasification within the country, these are linked to the development of the various coal mining options. There are no lignite deposits and so no possibility of monetising stranded low grade coal assets. The high quality, thermal and coking coal reserves are primarily export grade, after processing, and as such the conversion of these to provide alternative products is not deemed commercially viable. However, the residues from the processing stage could offer an attractive option. These are low grade, higher ash coals, for which there is minimal domestic demand. Consequently, as export grades are produced, these low grade materials would be stockpiled at the mines, which represent an inefficient use of an energy source and a potential environmental risk. However, they could be used as feedstocks for transport fuels production, for which the simplistic rationale is that:

- in principle, the transport fuel supply could be secured inside Mozambique at a known future feedstock price as opposed to using gas as a feedstock which is linked to the oil price;
- such an approach reduces foreign exchange outflows used for fuel purchases, which currently are some 800 US$million/y;
- it avoids using gas for liquid fuel production, which can instead be converted to LNG so generating export revenue for the country.

There are several studies of coal gasification for chemicals and synfuels (CTL) production, which are at the pre-feasibility stage.

Clean Carbon Industries (CCI) is a joint venture company that has been formed by Twin City Venture Capital, Hugh Brown & Associates, local Mozambique shareholders and a team of international engineering specialists. It is working with the Ministry of Energy to undertake a full feasibility study for the development of a CTL plant in the Tete Province (Mining Weekly, 2012c). The aim is to establish a plant that will be capable of converting some 17 Mt/y of low grade coal into 65,000 bbl/d of transport fuel and chemical by-products. The Mozambique government would have first call on about 20,000 bbl/d of the transport fuel, which is slightly in excess of the current national consumption rate. The remaining 45,000 bbl/d could be exported. It is understood that the largest part of the export fraction would be sent to an undisclosed customer in Europe who has signed a preliminary agreement with CCI for an undisclosed amount of clean synfuel for blending with existing fuels (Mining Weekly, 2012d). The intention is to develop a pipeline from Tete to existing port fuel-handling facilities.

The project is believed to be economically viable within certain capital cost limits, subject to a large proportion of the product stream being exported as a synfuel to the existing market in Europe. On this basis, a bankable feasibility study will be undertaken to focus on capital and operating cost estimates, engineering and final execution costs, as well as the existing and growing export and internal markets for clean synfuels. This study is expected to start in March 2013 and take about two years. Should this prove financially acceptable, construction of the plant could start during the first quarter of 2016, with first production planned for 2019.

At the same time, the Brazilian mining group Vale has established a partnership with Portugal's SGC Energia (SGCE) with the intention to set up an industrial plant in the Tete province to convert the lower grade coal, mined at the Vale concession in Moatize, into liquid fuels (American Fuels Coalition, 2011). SGCE has entered into a Master License and Supply Agreement with Thyssen Krupp Uhde under which it will use the PRENFLO® PDQ process for multiple CTL projects plus FT synthesis within SGCE's proprietary XTLH™ design approach. This includes both parties signing a specific License and Supply Agreement for this possible CTL project in Mozambique, which is currently in the preliminary design phase (Thyssen Krupp Uhde, 2011). Should this progress to the implementation phase, Thyssen Krupp Uhde's PRENFLO® PDQ technology will be utilised to process the low grade coal from the Moatize mine. The aim is to produce clean fuels at a nominal design capacity of 9500 bbl/d, for use either domestically or for export to neighbouring countries.

Finally, the Ncondezi Coal Company is looking for opportunities to expand its planned 5 Mt/y export thermal coal operation by finding a market for the lower grade coal included within its assets in the Tete Province. Rather than establish a CTL plant in Mozambique, this includes examining the prospect of exporting such coal to major Asian countries where it could be converted to SNG using the SES U-GAS gasification technology (American Fuels Coalition, 2012a). SES has entered into an agreement with the Ncondezi Coal Company and has analysed the gasification characteristics of this low moisture, high ash (>40wt%), low volatile coal. Laboratory-scale testing showed 99% carbon conversion. Further work is ongoing to examine the economics for such a process within the Asian markets (American Fuels Coalition, 2012d).

However, further huge gas reserves are being discovered in Mozambique's off-shore Rovuma Basin, with current estimates of 5.4–6.2 trillion m^3 and strong indications that further reserves will be established (UK Trade and Investment, 2012). Although these will take more than 10–15 years to be developed and exploited (EIA, 2013g), they may be a major barrier to any initiatives to develop a national CTL programme, with potential impact on plans in neighbouring countries.

3.2.3 South Africa

South Africa is a very significant developing country and a member of the BRICS group of nations. It has an established coal-based economy with appropriate infrastructure both for domestic coal use and for export. In 2009, the Minerals Bureau estimated the total recoverable coal reserves at 33 Gt, Figure 4, with the expectation that production levels could either be maintained or increased with new mines being established during the next decade (Hall, 2011). Domestic coal consumption in 2011 was about 190 Mt, which was equivalent to 70% of the country's total primary energy supply, while exports were some 65 Mt (EIA, 2013b).

South Africa, through Sasol, currently operates the world's only gasification-based commercial CTL facility at Secunda with an output capacity of 160,000 bbl/d of oil equivalent. There is also a major petrochemicals production plant at Sasolburg, which operated using a coal feedstock until 2004 when it switched to natural gas imported from Mozambique (Sasol, 2010). Around 40 Mt/y of low grade coal are converted into liquid fuels, gas, and other products. All the synthetic fuels are used to meet growing domestic demand for petroleum products. Currently about 30% of South Africa's petrol and diesel needs are met through coal conversion (World Coal Institute, 2010).

Figure 4 Coal deposits in South Africa (Hall, 2011)

At the two units in Secunda, which began operation in the early 1980s, pressurised Sasol/Lurgi fixed bed dry bottom gasifiers are used to produce syngas from high ash content, high ash melting point coal in the presence of steam and oxygen (Van Nierop and others, 2000; Alexander's gas and oil connections, 2000). The average syngas production rate is 1.5 million m^3/h, with a typical composition of 58% H_2, 29% CO, 11% CH_4, 1% CO_2 and virtually no sulphur.

After cooling, the various condensates that are removed from the gas provide co-products such as tars, oils and pitches. Other co-products, such as nitrogenous compounds, sulphur and phenolics are recovered as ammonia, sulphur, cresols and phenols respectively, with the pitch being converted into coke in an anode coke plant. The purified syngas is then available for conversion through Sasol's FT technologies (Dry, 2002), which are the Advanced Synthol (SAS) reactors at Secunda and the Sasol Slurry Phase Distillate (SSPD) technologies at Sasolburg, although the latter now use natural gas. These are shown together with the previous reactor vessel designs in Figure 5.

In the SAS reactors at Secunda, the H_2 and CO react under pressure in the presence of a fluidised, iron-based catalyst at moderate temperature to yield a broad spectrum of hydrocarbons in the C_1-C_{20} range (Gibson, 2007). The process is used primarily to produce liquid fuels and gas. The hydrocarbons produced in the reactors are cooled in the plant until most components become liquefied. Differences in boiling points are utilised to yield separate hydrocarbon-rich fractions and methane-rich gas. Some of the methane-rich gas (C_1) is sold as pipeline fuel gas, while the rest is sent to a reforming unit, where it is converted back to syngas and rerouted to the reactors.

The C_2-rich stream is split into ethylene and ethane. The ethane is cracked in a high-temperature furnace yielding ethylene, which is then purified. Propylene from the light hydrocarbon gases is purified and used in the production of polypropylene. Within this stream there are also large quantities

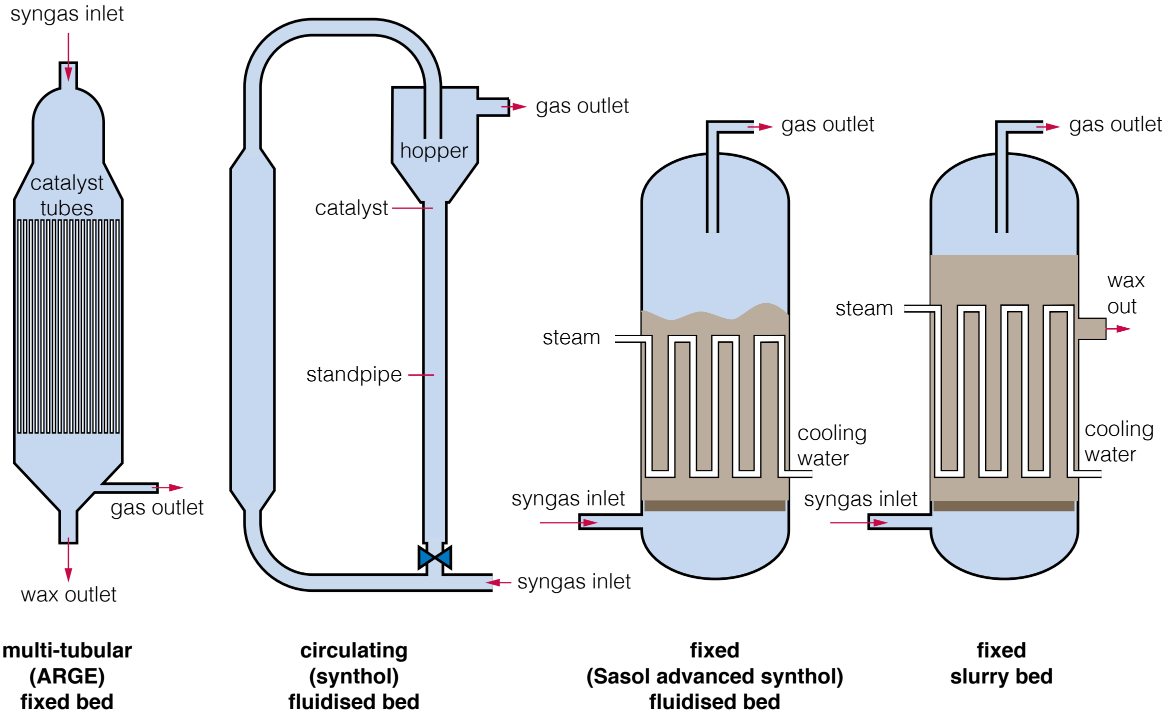

Figure 5 The various types of Fischer-Tropsch reactors (Spath and Dayton, 2003)

of olefins in the C_5 to C_{11} range. The majority of this oil stream is routed to a refinery where liquefied petroleum gas, propane, butane, fuel oil, paraffin, petrol and diesel are produced.

Oxygenates in the aqueous stream from the synthesis process are separated and purified in the chemical work-up plant to produce alcohols, acetic acid and ketones including acetone, methyl ethyl ketone and methyl iso-butyl ketone. These oxygenate chemicals are either recovered for chemical value or are processed to become fuel components. Of the olefins, ethylene, propylene, pentene-1 and hexene-1 are recovered and sold into the polymer industry. Surplus olefins are converted into diesel to maintain a gasoline-diesel ratio to match market demand.

The annual synfuels output from the High Temperature FT plants is about 8 Mt.

At Sasolburg (Sasol 1), from 1955 when it began operation until 2004 the synthesis feed gas was reacted in the SSPD reactors at a lower temperature than is the case in the SAS reactors, primarily producing linear-chained hydrocarbon waxes and various liquid products (Dry, 2002). Apart from hard wax, candle wax and FT waxes, high-quality diesel can also be produced in this process. Residual gas is sold as pipeline gas, while lighter hydrocarbons are hydro-treated to produce pure kerosene or paraffin fractions. Ammonia is also produced and is either sold directly or utilised downstream to produce explosives and fertilisers. It is Sasol's strategy to recover more and more of the higher-value chemical components in its product streams and place them into lucrative chemical markets, thereby maximising their value. The SSPD technology is also the technology favoured by Sasol for the commercial conversion of natural gas to synfuels. It produces a less complex product stream than the SAS technology and products can readily be converted to high quality diesel.

3.2.4 Zimbabwe

There are 24 known coalfields in Zimbabwe, of which ten have some commercial potential, with technically mineable reserves estimated at some 10 Gt (Mining Weekly, 2012a). These comprise thick, shallow seams of high ash content coal. To date, annual coal production is a few million tonnes and while further exploitation is possible, as in so many parts of the SADC region, exploitation would require massive investment both in developing additional mines and a supporting infrastructure.

However, the coal is believed to be suitable for use in gasification processes and there are some possible projects being considered. For example, TA Holdings Limited needs to reduce rapidly rising power costs at its electrolysis plant that produces hydrogen for use in the fertiliser production process at its Sable Chemical Industries company. It has announced plans to introduce its own coal-gasification to hydrogen plant (All Africa, 2010). The project, still at the pre-feasibility stage, could start operation in five years and in principle could cut Sable's electricity consumption from 115 MWe to 30 MWe.

There have also been public statements from the South African-based company Lontoh Coal that it will invest US$9 billion in Zimbabwe over the next five years to build a CTL plant, which will convert 80,000 t/d of thermal coal into 50,000 bbl/d of oil (Fin24, 2012)**.** This is well in excess of Zimbabwe's expected consumption of liquid fuels, which might grow to 20,000 bbl/d by 2018.

3.3 Asia

Asia is the fastest growing economic region in the world and many of the countries are fuelling that growth with fossil fuels, particularly coal. This is reflected in the historical growth patterns for coal use, shown in Figure 6.

3.3.1 China

China completely dominates global coal consumption, Figure 6, and is also leading the world in the

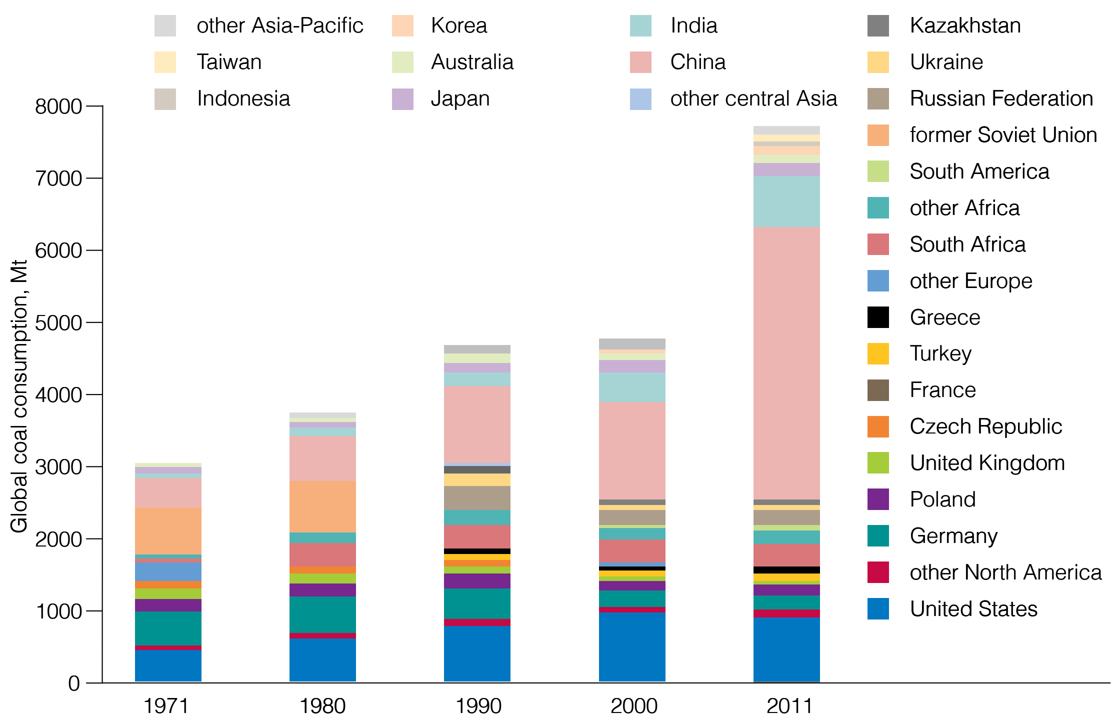

Figure 6 Historical growth patterns in global coal consumption (Baruya, 2012)

use of coal for chemicals production. There are significant lessons to be learned from such experiences, not only from the introduction and subsequent development of technologies but also the establishment of supportive policies backed up by a strong legal and regulatory system to ensure this growing coal sector is aligned with the national energy and environmental targets. Consequently, such an analysis is presented separately in Chapter 4.

3.3.2 India

India is the second largest developing economy after China and to a significant degree is dependent on the use of coal to drive its growth. In principle, it should be seeking to establish coal-to-chemicals and -fuels projects for exactly the same reasons as China. However, in contrast, progress to date is very slow.

Based on data collected by the Indian Geological Service, the inventory of hard coal resources within the depth range 0–1200 m, for seams 0.9 m or greater in thickness, was nearly 248 Gt. An additional 141 Gt has been inferred at deeper levels to a maximum depth of 2400 m (Venkataraman, 2006). In 2010, India had identified 60 Gt of recoverable hard coal reserves, the fifth largest in the world (EIA, 2013f), with more than 60% of this found at depths of less than 300 m. For the most part, these coal reserves are located in eastern India in the states of Jharkhand, Chhattisgarh, Orissa, West Bengal, Andhra Pradesh, Madhya Pradesh, and Maharashtra (*see* Figure 7). As well as hard coal, there is thought to be a total viable reserve of some 35–38 Gt of lignite, almost all of which is in Tamil Nadu and Pondicherry where, depending on the location, individual seam thickness can vary between 2 m and 8 m (Clarke and others, 1997).

India was the third largest producer of coal in 2011 at 576 Mt. However, total coal use was some 649 Mt, including 73 Mt of imports, the latter being required to address both domestic coal quality issues for certain applications (for example, coking), and domestic producers failing to reach national targets. In addition, India's hard coal mines are located far away from the highest demand markets in southern and western India, posing a significant logistical and commercial challenge to coal distributors (EIA, 2013f).

As a means to counter these coal mining and coal quality limitations, it has been estimated that if India adopted UCG technology, it could access the energy within the two thirds of India's coal resources that are considered unmineable using conventional techniques. Conversion of enough of these resources into gas and oil could halve its annual energy import bill of US$110 billion (Reuters, 2012).

The Government has announced that it is seeking co-operation from the South African government to collaborate on UCG technologies (Mining Weekly, 2013a). The Ministry of Coal has identified five lignite and two bituminous coal blocks, with estimated reserves of 950 Mt, which could be appropriate for UCG projects. Until now, coal mining and related activities have been limited to government-owned mining companies, and previous attempts to establish projects such as UCG have been ineffective. In order to change this culture, the government wishes to develop projects in India through joint ventures with private investors, for which amendments are needed to national legislation so that these opportunities can be provided (Mining Weekly, 2013b). However, there are concerns that an ongoing enquiry by the Central Bureau of Investigations, into the lack of transparency and misallocation of coal blocks during the period 2006-09, could significantly delay these UCG options being taken forward.

For coal-to-chemicals options, two projects are proceeding. The country's first coal gasification plant is being built by the private sector company Jindal Steel and Power Ltd (JSPL) in the eastern state of Orissa. It will comprise seven gasifiers to process typical low-quality, high-ash coal to produce 5.7 million m^3/d of syngas. This will be used as a substitute reducing gas for the production of Direct

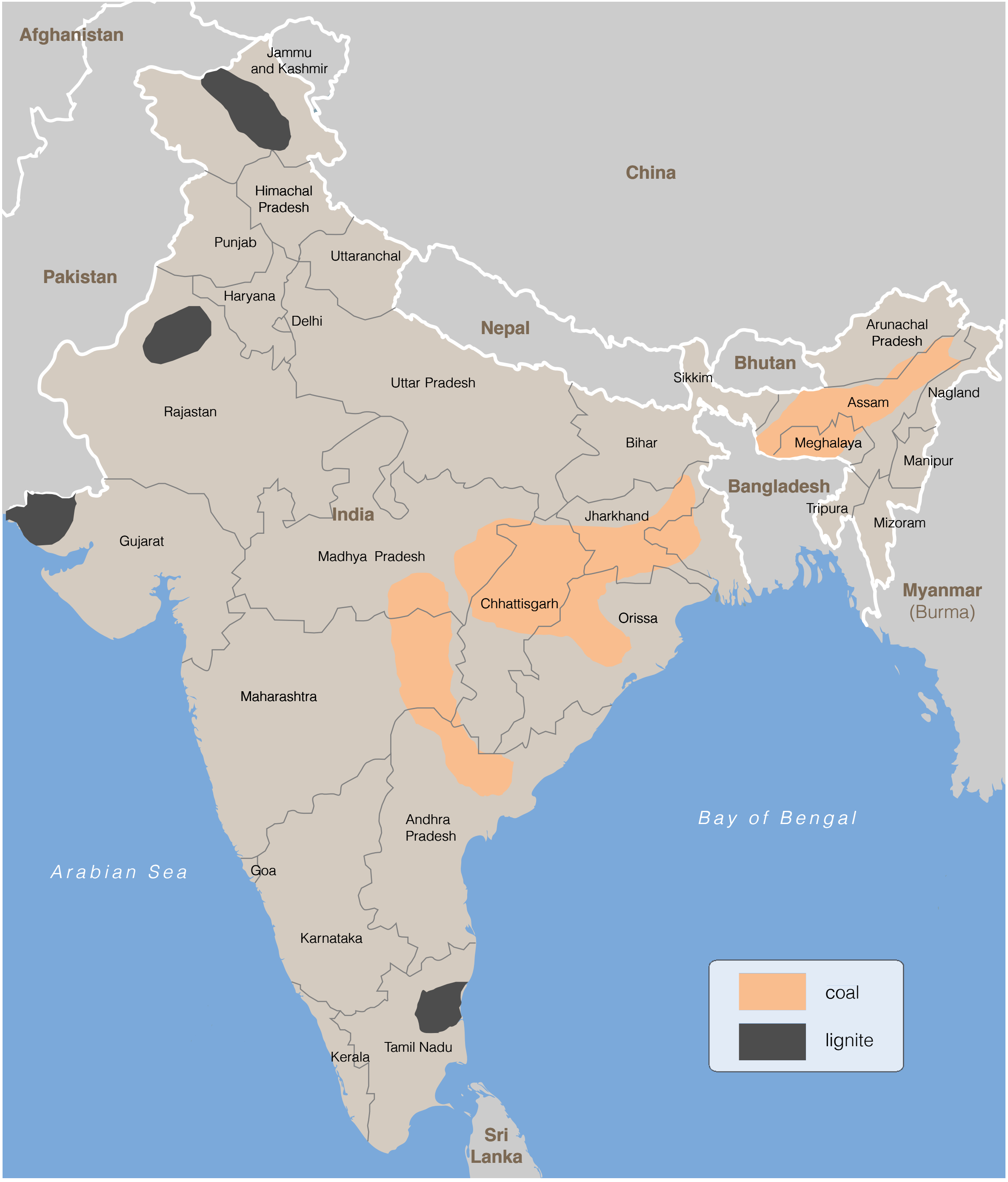

Figure 7 Map of India (Maps of India, 2013)

Reduction Iron in a shaft furnace (Jindal Steel and Power, 2013). JSPL has signed an agreement with the Sasol Lurgi Technology Company of South Africa, to provide the coal gasifiers and associated equipment.

A Joint Venture between Rashtriya Chemicals and Fertilisers Ltd, Coal India Ltd and the Fertiliser Corporation of India Ltd (FCI) has been established in order to refurbish and restart operation of several fertiliser production units at Talcher that were formerly owned by FCI and the Hindustan Fertilizer Corporation Ltd. Tenders have been issued for the supply of coal gasification and gas purification plant on a build own operate (BOO) basis. It is understood that the daily capacity of the coal gasification based ammonia synthesis unit will be 2700 tonnes and that of the urea plant 3850 tonnes (The Economic Times, 2012). It is expected that a BOO-based bid process will be initiated for setting up and operating the urea and ammonia plants in due course.

3.3.3 Indonesia

Indonesia has some 100 Gt of coal resources, of which the proven reserves are either some 5–6 Gt or 21 Gt, according to the EIA and government sources respectively (EIA, 2013a; Gushka, 2011). These reserves, which comprise both bituminous and subbituminous coal, are located primarily in Sumatra and East and South Kalimantan. Some 13% of these reserves comprise high grade coal (cv greater than 25.6 MJ/kg) while the remainder is either medium (cv between 21.4 and 25.6 MJ/kg) or low grade (less than 21.4 MJ/kg) in broadly equal proportions.

Indonesia is a major international coal producer and exporter, particularly as a regional supplier to Asian markets, with some two thirds of coal production coming from East Kalimantan (Gushka, 2011). Most of this production currently comprises the higher grade, higher cv products and the medium grade output, which provide the export material, while some 9% of output is the lower grade coal. Under the government's domestic obligation programme, the larger coal companies in Indonesia must sell approximately 25% of their production domestically. Most of this is used in the domestic power plants, in order to reduce the use of expensive diesel and fuel oil, and comprises a mix of medium and lower grade output. However, this still leaves quantities of low grade coal for which there is no ready market. In 2011, Indonesia produced 353 Mt coal, of which close to 310 Mt were exported to India, China, South Korea, Japan, Taiwan, and other Asian countries. Domestic consumption in the power sector was some 70% of the remainder.

The government is looking at ways to improve utilisation of the low grade coal while also seeking ways to expand overall production of the better grade coals. For example, the public listed coal producer, PT Bukit Asam (PTBA), currently has an annual production of around 17 Mt, which is projected to increase to 50 Mt by 2016. Low-grade coal accounts for between 60% and 70% of its total production and some of this has to be classed as rejects. Consequently, there is interest in gasification for the production of chemicals from coal in order to improve monetisation of its overall output (Jakarta Globe, 2011). There have been a number of proposals, of which the more recent initiatives are outlined below.

PTBA and the state-owned fertiliser company PT Pupuk Sriwijaya Palembang (Pusri) have examined a number of options for converting the low grade coal to syngas for use in fertiliser production (Jakarta Post, 2012). There is also the possibility of syngas conversion to methanol and dimethyl ether (DME). However, while a feasibility study for the planned coal gasification plant, based on coal with a cv below 24 MJ/kg, is under way, there are no details available regarding gasifier type, plant, coal use and end product quantities.

PT Pertamina, a state-owned oil and natural gas company, is also pursuing a coal conversion process with Celanese who are seeking to establish their proprietary TCX process (Celanese, 2012). This is a thermo-chemical process that is designed to convert any hydrocarbon source to syngas for subsequent production of either industrial or fuel ethanol. The aim in this instance is to establish a plant that will convert 4 Mt/y of low grade coal into 1.3 billion litres of ethanol for use as a fuel additive, with all of the end product to be used within Indonesia (Intellasia, 2013). It is expected to take around 30 months to complete the construction of the new facility, from approval of the project by the Indonesian government. The provisional start date for operations is 2016.

There are two possible projects being considered for Sumatra Island, one involving Mitsubishi and the other Reliance Energy (Takahashi, 2013). Both have shown interest in processing the local lignite into synthetic natural gas and various chemicals.

However, for all such prospects, while coal conversion will be encouraged as part of a coal diversification scheme, there is a lack of specific policies and a lack of an enabling environment. At present, Indonesia struggles to attract sufficient investment to implement domestic energy projects because of an inadequate supporting infrastructure and a complex, uncertain regulatory environment, all of which make external investment more difficult (EIA, 2013a).

3.3.4 Mongolia

Mongolia has some 160 Gt of coal resources, comprising both hard coal and lignite with the latter accounting for some 75% of the total (Minchener, 2013). Over 300 coal deposits have been identified, most of which have only recently begun to be defined with modern exploration techniques. About 80 have been explored but not mapped in detail in all cases. To date, over 23 Gt of technically viable reserves have been determined in 15 basins, Figure 8, with about 12 Gt so far having been economically proven. In general, these reserves are shallow, and suitable for opencast extraction, with good mining conditions resulting in production costs of 10–20 US$/t. These comprise over 2 Gt of coking coal and 10 Gt of thermal coal, with the hard coal proportion mostly in the South Gobi region. However, since there has not been a driver to ascertain in detail all the coal quantities available, in overall terms, there is limited information on the future exploitation potential of Mongolian coals, the diversity of qualities, size of deposits and what infrastructure is needed to bring the coals to market (Tserenpurev, 2010).

Mongolia has to import all of its refined oil products from Russia, which is both an expensive and unreliable source. There is also a growing demand for chemical products, which have to be imported from China and Russia. Mongolia, with its abundant, low cost, low grade lignite reserves must be rated a very strong prospect for the introduction of coal-to-chemicals and CTL technologies. The other requirement is water and while Mongolia does have water availability problems this is not in the northern part of the country where the brown coal and lignite resources, which are the better feedstocks for coal conversion, are primarily located.

Consequently, there is a strong interest in gasification within Mongolia, particularly as part of a CTL

Figure 8 Locations of main coal deposits in Mongolia (Tserenpurev, 2010)

scheme as a means to produce synthetic petroleum products. To put this in context, Mongolia's annual petrol and diesel consumption is in excess of 1 Mt and is expected to reach 1.5 Mt by 2015, for which it is currently paying 1000–1100 US$/t for imports from Russia. This is not only expensive but the supplies can be unreliable, which raises significant security of supply issues. Consequently, the Mongolian government has expressed a wish to establish CTL technology. The short-term goal is to establish such a plant with the feedstock being coal extracted from the various large-scale lignite mines that are being established (Mongolia Investment, 2012). The government has specified that a CTL unit should be built and operational in three to four years. However, given the early stage in technology awareness, the infrastructure issues such as transportation of end products to potential users, and the expected cost, this must be considered optimistic.

That said, as part of an intended programme of co-operation on mining and environmental protection, Mongolia and Germany have signed a memorandum of understanding to build an indirect coal liquefaction plant. This was agreed with Thyssen Krupp and its subsidiary Thyssen Krupp Uhde (Bassett, 2012). Various individual partnership agreements have also been agreed between Mongolian industrial companies and German technology providers. These include Mongolian MCS and Petrovis with Siemens, and Tsetsens Mining and Energy with Lurgi (American Fuels Coalition, 2012b). At the same time, Thyssen Krupp Uhde signed a licensing agreement with the Industrial Corporation of Mongolia to provide their proprietary coal gasification technology. The likely companies to establish the technologies, including Industrial Corporation of Mongolia, MAK, Tsetsens Mining and Energy, all own mining rights to very extensive coal deposits.

There have been laboratory-based trials undertaken in Germany to check the likely performance of candidate coals, for which the results are understood to be encouraging. Techno-economic assessments for various prospects have been undertaken, with proposed product outputs of 0.5–1.0 Mt/y (Mongolia Investment, 2012). Information on the economics of these processes is limited. It has been stated that the capital investment for a CTL plant would be some US$ 1–2 billion for a plant that will process 2–6 Mt of coal each year, to produce 0.4–0.8 Mt of petrol and diesel, up to 0.1 Mt of LPG, and 0.02–0.05 Mt of sulphur, with the possibility of generating 200–300 MWe of power. On this basis, given the very low extraction costs for coal, the production costs for one tonne of petrol would be US$ 600–700. However, the level of capital investment required for each project would be the equivalent of some 20% of Mongolia's 2011 annual GDP. Consequently, financial closure on such projects would appear very difficult.

Nevertheless, it is understood that the Mongolian government has agreed to use German technology for a CTL plant. This will be viewed as a strategic project and consequently the government will hold 51% of the equity. However, it is not clear how the overall funding will be raised (Infomongolia, 2013).

In addition to co-operation with Germany, Japan has already proposed to build a coal liquefaction plant based at Tavan Tolgoi in the South Gobi region. Mongolia also agreed a MOU with South Korea on clean coal and energy resource development, with a focus on the production of synthetic oil, gas and unrefined chemical products from low grade coal in Mongolia (Zhushui, 2011). Recently, POSCO, South Korea's leading steelmaker, signed an agreement with MCS to set up a CTL project joint venture company. Subject to government approval, the aim would be to start a CTL business using lignite from the Baganuur mine, with a suggested production output of 0.45 Mt of diesel and 0.10 Mt of dimethyl ether (Global Post, 2013).

For all these possible CTL and SNG plants, the government has pledged to provide financial support for any construction projects, including tax breaks plus ensuring domestic buyers for the products (Mongolia Investment, 2012).

There should also be scope to establish gasification-based coal-to-chemicals units, for which there ought to be ready markets for the products in Russia and possibly China (Seeking Alpha, 2012).

With regard to UCG, many of Mongolia's coal seams are too shallow to be suitable for this technology, but there are enough at deeper levels to make assessment worthwhile. Envidity of Canada made an agreement with Live Energy LLC of Mongolia and its subsidiary, Shine Shivee LLC, to undertake an UCG project to transform low quality coal into domestic fuel (Live Energy, 2012). The intention is to transform underground sources of brown coal, which are within areas of the Shine Ovoo deposit, to syngas via UCG. The gas will then provide the feedstock for a gas-to-liquids transformation using a Japanese process. In August 2011, Envidity announced its commitment to a specific US$1 billion project, with an initial potential output of 1000 bbl/d of synthetic diesel. It was stated that this project would create some 3000 construction and 150 permanent higher salaried jobs for the Mongolian people. Following what would be a commercial prototype demonstration, there were projections for some seven commercial plants in the next 15 years (Wire Service, 2011). However, since that time, there has not been further information as to whether this project will actually move forward.

Meanwhile, Cougar Energy of Australia is also looking at possible UCG sites in Mongolia and China, in conjunction with major mining and exploration companies, although its initial focus appears to be on the latter country (Oilvoice, 2009).

3.3.5 Pakistan

Coal currently provides a minor part (~5%) of Pakistan's energy mix although the national government has plans to increase the proportion to 18% by 2018 and 25% by 2020 in order to increase security of energy supply. Currently coal's contribution for power generation is about 150 MWe, compared to a total power generation capacity of 19,000 MWe.

The only significant coal resources are found in the Sindh region, contained in the Lakhra, Sonda, Thatta, Jherruck and Thar deposits. The latter is said to comprise some 184 Gt of resources, with about 4 Gt of measured reserves that are found at depths between 130 m and 250 m, with the maximum thickness of an individual seam being 23 m (Minchener, 2009). The seams are at depths where, in theory, opencast mining could be applicable. The lignite has a low cv (12.0–13.5 MJ/kg), and is relatively high in sulphur. It could, in principle, be used as fuel for power generation and in cement works.

The quite recent discovery of this lignite deposit in the Thar Desert has led to domestic and foreign development interest in using it to fuel coal-fired plant in that region of Pakistan. However, an ongoing lack of clearly defined strategic plans from the national government in combination with some unrealistic development prospects from the provincial government has meant that progress to date has been very limited, for both the development of the mining and power production projects. Various international companies such as Shenhua of China had shown interest, only to subsequently withdraw from possible schemes on cost grounds, while also citing lack of co-operation at the local level. Others, such as the Sindh Engro Coal Mining Company continue to press for the infrastructure projects necessary to support any development of the coal and power projects, but with little external evidence of success.

The World Bank tried to establish a technical assistance project, only to withdraw, reportedly due to the lack of emphasis on Thar coal resources in the national energy policy and no recognition that such resources would be critical for national energy security. A further reason was the lack of a coherent resettlement programme for local people close to the proposed development site (Examiner 2010).

Thus, this large indigenous coal source remains almost unutilised. It is a low grade fuel and would need to be used close to the mine unless extensive drying and upgrading should be introduced. As well as the usual costs associated with any coal mining project, such as up-front investment costs for mining and the ongoing cost of extraction and storage, there would need to be a massive investment in power plant units and transmission lines plus other industrial units to use lignite close to the point of extraction (Couch, 2004). Nevertheless, various international companies continue to hold talks but it remains to be seen whether these lead to any successful initiatives (Power Engineering International, 2012).

There has been an attempt to establish an UCG project as an alternative approach to power plant projects based on potential coal extraction and direct combustion. The initial phase is intended to be a 50 MW demonstration of the concept, with the syngas to be used either to produce diesel via the FT process or possibly power. In late 2011, this too lacked a bankable business plan and consequently stalled with less than 2% of the funding needed having been committed by the national government (The International News, 2011). Opposition was raised during the first half of 2012 from other vested interest groups, in particular concerning the technical viability (The Express Tribune, 2012). There are understood to be interconnected drinking water aquifers, above, within and below the coal zone, which would make opencast mining extremely difficult. Equally, UCG is not considered viable, in part because the lignite seams are thought to be too shallow, with the soil above them unlikely to provide an adequate gas seal, and because of the risk of water contamination of the aquifers (Daily Times, 2011).

However, in August 2012, the project apparently received close to US$10 million from the government (SciDev Net, 2012), although this is still a small fraction of the likely project costs. The lack of details in terms of technology transfer, and doubts over the credibility of costs claimed for the production of synfuels from Thar lignite, continue to be raised and there are strong calls for an independent feasibility study of the project by an internationally reputed agency to settle the controversy (Oil Price, 2012b).

3.3.6 Vietnam

Vietnam is believed to have significant coal resources, although exploration and surveys are still ongoing (Baruya, 2010). The major deposits are concentrated in the Quang Ninh and the Red River basins, both located in the north of the country. Currently, production is focused on Quang Ninh where close to 4 Gt reserves of anthracite have been identified. Most of the output is exported to Japan for steel making and to China for power production. Production has come from opencast mines although that is now changing as the reserves near the surface become exhausted. For the future, with significant growth in coal power production expected, Vietnam will consume more coal and there is a prospect that imports may be needed to ensure demand can meet supply. Currently, some coal is being imported from Indonesia and Australia although for the future this route may well be more difficult due to competition from India, China and especially Japan (Vinacomin, 2012).

However, whether imports will ultimately be required will depend on the possible contribution of coal from the Red River Coal Basin. It is estimated that this basin has 210 Gt of resources, some 20 times more coal than Quang Ninh, although this remains inconclusive until full surveys are completed (USGS, 2011). Although there appears to be a range of coals, the coal quality is expected to be of lower rank than the Quang Ninh anthracites (Baruya, 2010). According to Vinacomin, the state-owned mining company, initial explorative and analytical data suggest that while some coal is at a few hundred metres depth, the great majority of the coal basin comprises eight coal beds that lie well over a thousand metres underground. Consequently, UCG would appear to be the more promising exploitation route, which would require massive investment and foreign technological expertise.

In May 2009, Vinacomin announced that it planned to develop various projects 'through co-operation and joint ventures with foreign partners in order to create the country's biggest clean energy centre, helping ensure national energy security by 2025'. As the first stage of this initiative, the State Government approved a project to evaluate the coal resources of the Red River basin, which will be implemented from 2012 to 2015, the results from which will form the basis for further detailed quantification (Vietnam net, 2012).

If UCG can be established, there would be scope for the resulting syngas being used for power generation and coal-to-diesel production. Russia's Gazprom is reported as having signed an agreement to supply its UCG technology to Vietnam (West Virginia Coal Association, 2009). More recently, Linc Energy of Australia has entered into a business co-operation contract with Vinacomin and Japan's Marubeni Corporation to undertake a trial project in the Red River Delta region (Linc Energy, 2012). Stage one is designed to confirm that UCG is suitable for producing syngas from coal in the region.

In a parallel gasification development, one coal-to-chemicals project has been established in Vietnam at the Ninh Binh Nitrogenous Fertiliser Plant. In late 2007, Shell licensed its entrained flow coal gasification technology to the Vietnam National Chemical Group (ICIS, 2007). In March 2012, this group commenced operation of its coal-to-fertiliser plant, which is based on the conversion of anthracite to syngas to hydrogen and then to urea (Vietnam Business Forum, 2012).

Total investment for the project was US$667 million and a Chinese contractor, the China Huadian Energy Development Company, is responsible for all activities related to design, technology transfer, supply and installation, commissioning, personnel training and operational support.

When the plant goes into full operation, it will gasify more than 1300 t/d of coal and have an annual urea output of 560,000 tonnes, which will provide 25% of the country's fertiliser demand.

3.4 Eurasia

Eurasia is a massive land area, in which several countries have large coal deposits and also major indigenous oil and gas resources. In contrast to several of the countries considered previously, this tends to mean that there is a much reduced driver to maximise energy extraction from coal.

3.4.1 Kazakhstan

Kazakhstan is rich in fossil energy, including coal resources, which are estimated at 160 Gt, with 31 Gt recoverable reserves comprising both thermal and coking coal (EIA, 2012b). The three primary coal basins are located in Eastern Kazakhstan, where the coal rank varies from low grade subbituminous to anthracite (Eurasian coal portal, 2013).

As part of the government's strategic objective for the economic modernisation of Kazakhstan, there is some interest to establish UCG as a means to use coal for domestic applications in a more environmentally acceptable way (Bank Turan Alem, 2007). However, this initiative appears not to have progressed to any significant degree. With regard to coal gasification, four small units were installed from 2005 onwards to produce 70,000 m^3/h of fuel gas to heat a calcining furnace, based on the independent development of early Lurgi technology (ZVU Engineering, 2013). Subsequently, RWE AG and Samruk, Kazakhstan's state assets management holding company, agreed to look at coal gasification and synthetic gas usage in northern and eastern Kazakhstan as a means to unlock new energy sources in the country (Oil & Gas Journal, 2008). As with UCG, there is no evidence of any outcome from such a study.

3.4.2 Russia

Russia has one of the largest coal resources in the world, this being estimated at 3928 Gt. Proven and strongly indicative reserves are given as 192 Gt, which comprise 47 Gt coking coal, 37 Gt hard steam coal, 7 Gt anthracite and 101 Gt lignite (Crocker and Kovalchuk, 2008). The major deposits are concentrated in Siberia (79.4%) and the Far East Federal District (10.5%), which are reasonably close to China. Following an energy co-operation conference in 2010, China agreed to provide Russia with a US$6 billion loan to finance the development of several large-scale coal mines while Russia agreed to supply China with 475 Mt of coal over the next 25 years (Energy & Capital, 2010).

In addition to securing this coal trade agreement, there is the prospect of a joint-venture development of the Ogodzhinskoye coal deposit in the Amur region of Russia, which borders China. This includes both countries working together to undertake a preliminary feasibility study for the development of a CTL project.

3.4.3 Turkey

Turkey's total coal resources are believed to be at least 12 Gt, with recoverable reserves of ~2.3 Gt. Some 525 Mt are hard coal (anthracite and bituminous coal) while the remainder comprises low grade lignite (EIA, 2013c). The hard coal is mined only in one location, the Zonguldak basin of northwestern Turkey, while around 40% of the lignite is located in the Afsin-Elbistan basin of south-eastern Anatolia.

In 2011, total coal production was close to 80 Mt with just over 1 Mt being hard coal. However, total demand was ~100 Mt, with about 20 Mt of hard coal being imported to meet the national requirements. These import levels have been rising steadily year on year and this trend is expected to continue (Argusmedia, 2012). The local and imported hard coals are used mainly for electric power generation, steelmaking and cement production. About 85% of Turkey's lignite production is also used as a fuel source for electric power production (Eurasiareview, 2012).

Some 75% of Turkish lignite reserves have a cv of 4–9 MJ/kg together with high moisture, high sulphur and high ash contents, and as such are unsuitable for use in conventional power generation. However, should it be mined, it can cost some five to six times less on a thermal basis than the more widely used low ash, higher rank coals that must be imported. This offers a potential driver for its use in local coal-based energy and chemical projects, which are now being considered in Turkey. To date, there are at least two prospects being actively pursued, namely power generation and gas production for use by industry.

Tuten is an independent power projects company that has a development portfolio that includes gas-fired IPPs from 120 to 1200 MWe. On behalf of an unnamed Turkish utility company, it is examining small-scale coal gasification to power project options based on the utilisation of the low grade lignite. It is working with:

- IEG, which is an engineering, procurement, and construction company based in Slovakia with its main focus on turn-key delivery of small and mid-size power plants, up to 300 MWe, operated on various fossil fuels and biomass;
- GE Aero-derivative Gas Turbines, which can modify GE aviation engines to burn natural gas, diesel and/or biofuels for efficient, reliable power production, in the range of 18–100 MWe;
- Synthesis Energy Systems (SES), a global energy and gasification technology company, which has expertise in utilising low grade coals for syngas production.

The consortium has developed a conceptual-level design for 50 MWe and 100 MWe size power generation modules for this type of low grade, low cost fuel. SES has undertaken laboratory-scale testing of three Turkish lignites that are being considered for these clean coal-based power generation projects in Turkey. These tests demonstrated that each coal tested using its proprietary fluidised bed gasification technology achieved single-pass carbon conversions of between 96% and 99.5% (American Fuels Coalition, 2012c).

SES, IEG and GE, with the support of Tuten, have been marketing small-scale, clean coal power generation plants more widely. This type of approach would also be appropriate for other developing regions where low rank coal is readily available and distributed power generation is needed in order to support industry, such as in Southern Africa.

The other prospect is being pursued by Energy Allied International of Texas, USA, which has initiated a preliminary feasibility assessment for building a gasification plant fuelled with Turkish lignite, to produce fuel gas for various industrial applications (Invest in Turkey, 2012). The likely fuel source is the vast lignite reserves in the Aegean province of Manisa and the intention would be to develop the project in partnership with local companies.

There is also a number of gasification-based development projects being taken forward by the state-owned Turkish Coal Enterprises (TKI), which has a majority market share in the production, processing and distribution of lignite (Minchener, 2009). These are being progressed primarily through bilateral aid arrangements, as set out in Table 2 (Tamzok, 2012). These cover both gasification plant developments as well as studies to ascertain the technical and economic feasibility of UCG for Turkey.

Table 2 Listing of various TKI gasification co-operative projects (Tamzok, 2012)

Project	Partner company	Coal specification	Objectives
Feasability study for lignite gasification in Turkey (Financed through US Trade and Development Agency)	Worley Parsons (USA)	Soma Eyenz raw and washed coal (13 MJ/kg and 19 MJ/kg respectively)	Ascertain feasibility for an annual 800 million m^3 coal to SNG capacity power plant
Uhde gasification project	Thyssen Krupp Uhde (Germany)	Soma Eyenz coal (>17 MJ/kg)	Establish multi-product plant to produce an annual 800 million m^3 SNG, 400,000 tonnes ethanol, and 560,000 tonnes urea
UCG feasibility study	Lawrence Livermore National laboratory (USA)	Coal basins of KTI	Determine those basins suitable for UCG and prepare feasibility studies
MicGas coal biotech project	Artech (USA)	Low cv lignites from the Bursa Davutlar basin	Establish a jv company to provide a 10,000 tonnes annual capacity plant, which will subsequently be increased to 100,000 tonnes capacity
UCG project	Linc Energy (Australia)	Trace basin	Feasability study, to be developed further if results are promising
Pilot-scale plasma lignite gasification project	Anadolu Plasma Technology Centre	Low cv lignites	Establish a 5 t/h pilot plant and carry out a lignite screening programme

The projects can be grouped into three categories (Ziypak, 2011):

- Conventional gasification projects, producing liquid fuels and chemicals from low grade lignites and from lignite/biomass mixtures;
- UCG projects, including laboratory studies and site suitability assessments;
- advanced gasification R&D projects, using plasma application, as well as methane production by coal biotechnology.

3.4.4 Ukraine

Ukraine's total coal resources are some 54 Gt, while economically mineable reserves are estimated at 34 Gt, of which 16 Gt are anthracite and bituminous coal while 18 Gt are lignite and subbituminous coal (Euracoal, 2012; EIA, 2013e). Some 6.1 Gt of the hard coal reserves are located in active mines (Euracoal, 2012) and comprise 3.5 Gt steam coal and 2.6 Gt coking coal.

These considerable reserves of coal will remain the main indigenous energy source for the foreseeable future and will underpin the nation's energy security of supply, as well as its economic and political independence. At the same time, the economy is highly dependent on imported natural gas and oil. Consequently, coal gasification is of interest in the Ukraine, both as a means to offset some level of energy imports, and as an alternative power generation option. In particular, given its high degree of dependence on Russia for natural gas supplies from which it imports over two-thirds of its needs, it is estimated that large-scale coal gasification would give Ukraine energy independence and security, and could cut its gas costs by 50% (Petroleum Economist, 2010). In 2008, import prices for natural gas were 250 US$/1000 m^3 while the production costs of coal-to-SNG were estimated at 113 US$/1000 m^3, which suggested an attractive differential. Depending on the coal quality, a gasification plant with an annual capacity to process 1.3 Mt of coal would produce 0.5–0.7 billion m^3 of SNG.

As an early initiative, Ukraine has agreed a deal with China for the design and supply of five coal gasification plants to process brown and bituminous coals, with construction expected to start in June 2013 (American Fuels Coalition, 2012e). The gasification technology, which is licensed from Shell, will be introduced in three regions (Luhansk, Donetsk and Odessa) and China will provide a loan to cover the project's cost.

The deal further includes switching existing power plants from gas to a coal water slurry mix (American Fuels Coalition, 2012h). This is part of the Ukrainian government's strategic plan to reduce its annual dependence on Russian gas imports by about 4 billion m^3 (Oil Price, 2013) and increase domestic coal use, with a projected annual foreign exchange saving of US$ 1.5 billion.

It is understood that China may also assist the Ukraine in biofuel production, with the prospect that ten unprofitable Ukrainian alcohol plants will be turned into ethanol production facilities. Chinese partners will provide equipment, technology, and financing for the project.

There are also tentative plans to establish UCG, with Linc Energy of Australia having signed a deal with DTEK Oil and Gas to jointly evaluate potential projects in the Ukraine (Proactive Investors, 2012). The syngas so produced would be used for electricity production at either CCGT or CHP plants, with the expectation that the production cost would be significantly lower than the price of electricity produced using natural gas imported from Russia.

3.4.5 Uzbekistan

Uzbekistan has over 5 Gt of coal resources, of which 3 Gt are listed as reserves, with over 70% of that being lignite. Annual production in 2010 was 3.5 Mt, which comprised 3.3 Mt lignite and 0.2 Mt hard coal (BGR, 2011; MBendi, 2011).

Table 3 Syngas composition range, vol/% (Eioba, 2008)						
CO_2	CO	O_2	H_2	CH_4	CmHn	N_2
20–22	4.0–7.0	0.5–0.3	22.0–22.4	2.2–3.0	0.2–0.3	44.4–50.6

Uzbekistan has the world's longest operational UCG site at Angren, which produces up to 0.51 billion m^3 of syngas per year for use in the Angren thermal power station, from the part of the local lignite deposit that is not suitable for either underground or opencast mining due to technical and economic reasons (Eioba, 2008)

It is an air blown process, where the air at 3 bar pressure is forced into the coal seam through the air blow holes arranged in parallel rows along the gas generator gasification front. The gas at a temperature of 150–350°C, produced in the underground gas generators, is passed through a system of gas conduits to the station area where it is cooled and dedusted in scrubbers. The latter items are provided with an independent water circulation system including cold and hot water pumps, settlers, and cooling towers. The scrubber cycle wastewater is cleaned in a dephenolising plant and then discharged into the sewerage system. The cooled and dedusted gas is fed to the Angren thermal power station through a 2 m diameter gas conduit.

The lignite has a cv of 12–13.5 MJ/kg, and is found at a depth of 130–300 m, while the seam thickness can vary from 0.2 to 15 m. The proportion of coal lost due to combustion underground is some 5–15% while the gas yield per kg of coal is 3.0–3.4 m^3, this having a heating value of 3.4–4.2 MJ/m^3. The gas composition range is given in Table 3.

3.5 South America

The one country that broadly matches the criteria listed above is Brazil.

3.5.1 Brazil

There are extensive fossil fuel resources and reserves in Brazil, of which oil is exploited to meet current internal demand, much of the natural gas is exported, while coal is hardly used (EIA, 2012a). Brazil has between 6 and 7 Gt of proven hard coal and lignite reserves, mostly in the south of the country, with annual production close to 10 Mt out of a total consumption of some 20 Mt. The domestic coal has high ash and sulphur contents, which limit its use to power generation (Power, 2012). The other major need is for coking coal, which the country's steel making industry has to import, mainly from the USA and Australia.

For the future through to 2030, there will be rapid economic growth, with a corresponding increase in domestic energy consumption (BP, 2011). With regard to fossil fuels, crude oil supply will be in excess of demand, due to exploitation of major new deposits, and so significant exports will be expected. Natural gas production has grown slowly in recent years, mainly due to a lack of domestic transportation capacity and low domestic prices. While there has been some expectation that its use in the power sector would increase as greater quantities become available from the new deposits, this is now seen as less likely since power production from wind energy appears to be less expensive in the Brazilian context (Minchener, 2012b). Growth in overall coal demand is expected to be modest, with limited opportunities in the power generation sector due to the low domestic coal quality. Total annual demand might reach 30–35 Mt by 2030, with imports, currently about 13 Mt, continuing to increase in proportion as demand for coking coal continues to rise.

At the same time, the Brazil Coal Association is attempting to improve the position for domestic coal utilisation by examining alternative market prospects. There has been some consideration of the development of a clean coal technology roadmap to:

- promote further diversification in the Brazilian energy matrix;
- optimise the use of Brazilian mineral resources;
- increase low carbon technologies R&D in Brazil.

The intention would be to undertake strategic economic, social and environmental assessments for CCT implementation in Brazil, including the following options that can address the current problems with lignite combustion:

- Coal gasification;
- UCG;
- CTL;
- CBM;
- ECBM;
- Coal combustion;
- CCS.

This would be complemented with the development of a draft regulatory framework to shape CCT deployment together with an action plan for CCT R&D covering pilot and demonstration projects in Brazil (Faim Martins, 2009). Consequently, while gasification of coal is not undertaken in Brazil at present, in principle, it could be in the future depending on the economic and environmental viability, particularly in the south of the country to replace imported natural gas (Zancan, 2010). However, to date, it is understood that no such initiatives are being established.

4 China's strategy for coal-to-chemicals

China is a country that completely fulfils the criteria for implementing coal-to-chemicals, gaseous and liquid fuels technologies, with a coal dominated economy and significant concerns about oil and gas energy security.

4.1 Background

China has very large reserves of coal, but only limited domestic supplies of oil and gas, which are far from able to meet current and projected future demand. For example, in 2010, China's annual crude oil demand was about 450 Mt, of which some 200 Mt were provided from domestic sources and the remainder via imports. For 2030, the expectation is that total demand may be some 800 Mt, with domestic demand at best managing 200–220 Mt. In effect, this means that almost every unit of additional demand will have to be provided through oil imports. This will be as imports of crude oil rather than refined products, as China has expanded its refining sector and will continue to do so for the next ten years and beyond (Wu, 2012). There is a similar situation for natural gas, with likely demand for 2030 being 550 billion m^3, of which domestic supplies can provide some 200 billion m^3, excluding unconventional sources.

The main elements of China's energy security policy (Wu, 2012) are to:

- enhance domestic oil and gas exploration activities and maximise oil and gas production;
- increase investments in oil and gas infrastructures and establish more options for introducing imports;
- diversify the sources of oil and gas imports, increasing the share of oil and gas imports from Russia, Central Asia, and Latin America;
- establish strategic petroleum reserves;
- strengthen the overseas investments by state oil companies;
- establish a system for comprehensive energy security.

Within this system for comprehensive energy security, as a means to promote domestic innovation and improved resource use, the Chinese central government has sought to determine the technical and economic viability of using gasification-based coal conversion to produce both synthetic oil and gas, and to manufacture various chemical products (Minchener 2011a). However, with concerns about water use, and the recognition that in a global market the outputs from certain coal conversion technologies are commercially vulnerable to imported alternatives, the implementation plan has been a cautious one.

The initial approach was to encourage various coal-to-chemical projects to be established, for the production of syngas as a building block to produce ammonia, fertiliser, hydrogen and methanol (Minchener, 2011a, b). This has led to a large number of units of varying sizes being built with the coal gasification stage comprising a mix of imported and domestic technologies (Minchener, 2011b). The market opportunities have generally been good, except for coal-to-methanol applications where a mature technology was quickly established and consequently supply rapidly surpassed demand. This has led to some 50% of plants either operating at low capacities or not at all (CHEM99, 2011).

With regard to alternative products such as the development of more complex coal-to-chemicals and coal-to-synfuels, the central government tightly controlled possible projects. This was due in part to high capital investment requirements and uncertainty with forward oil prices suggesting potentially unattractive economic returns. For example, for coal-to-liquids (CTL), one large-scale demonstration of the direct coal liquefaction (DCL) process by the Shenhua Group was given approval and three smaller-scale indirect, gasification-based (ICL) technologies by Shenhua, Yitai and Lu'an were allowed. At the same time, several large-scale demonstrations of the relatively complex coal-to-olefins (CTO) process and several large coal-to-SNG projects were initiated, while coal-to-monoethylene glycol (MEG) was tested at much smaller scale. There were also some coal-based polygeneration projects taken forward (Minchener, 2011a). These technology development and deployment programmes are described below.

4.2 Initiatives within the 12th Five-Year Plan (2011-15)

As projects have been established, these have been assessed and their technical and economic viability determined, taking into account market needs, capital investment, relative prices of coal and end products, and the geographical location of the production units compared to the regions where the end users are located. This work continues, taking into account the recent national energy intensity reduction targets (Xinhuanet, 2012).

In contrast to the cautious attitude of the central government, provincial governments see coal conversion as a means to ensure local jobs and tax revenue. They have published plans for large-scale coal conversion projects and high provincial coal conversion targets, particularly in the coal rich regions of Xinjiang, Ningxia, Shaanxi, Shanxi, Inner Mongolia, Guizhou and Yunnan, Figure 9. Some provinces have made coal conversion a condition for obtaining mining rights. These targets are both much higher than those of the central government and unrealistic when the National Development & Reform Commission (NDRC) deliberations on market viability are considered.

In April 2011, the NDRC issued new rules. First, it centralised approval of all coal conversion projects, stripping provincial and local governments of such power. It then aligned the development targets for the coal-to-chemicals sector with the energy and carbon intensity issues to be addressed during the 12th FYP (ICIS, 2011a).

With regard to energy conversion efficiency, it introduced minimum plant size requirements for manufacturing chemicals and fuels from coal, below which approval would not be given. The minimum annual plant capacity requirement for a CTO plant must be 0.5 Mt; for coal-to-methanol, coal-to-methyl tertiary butyl ether and CTL, all are set at 1 Mt; while for coal-to-SNG the annual minimum must be 2 billion m^3 (SZW Group, 2011). For a coal-to-MEG plant, this must at least have a 0.2 Mt/y capacity (ICIS, 2011a) once the technology is deemed to have progressed beyond the pilot development stage.

Another key issue is water availability. The national policies prohibit using residential and agricultural water for coal conversion projects, restrict SNG, CTO and CTL projects in regions with water scarcity, and prohibit coal conversion in regions where water consumption has reached quotas. Policies also prohibit coal conversion in regions where industrial impact exceeds environmental tolerance, and require the rejection of projects that fail to meet environmental standards on emissions and wastewater treatment. Finally, on location selection, policies limit coal conversion in regions that import coal, while promoting coal conversion in regions with sufficient water and indigenous coal resources (China Greentech Initiative, 2012). At the same time, China's National Energy Administration has released new policy guidelines for the coal industry aimed at curbing development in the north-eastern and central regions, while accelerating output and demand in the west of the country (UK FCO, 2013).

There is also an expectation that the NDRC will apply tighter environmental protection limits in the same way that is has for coal-fired power plants (Minchener, 2012a) in order to reduce ambient $PM_{2.5}$ levels in or close to Chinese city locations.

For CO_2 emissions reduction, the NDRC has advised that, for all new units, approval to proceed will

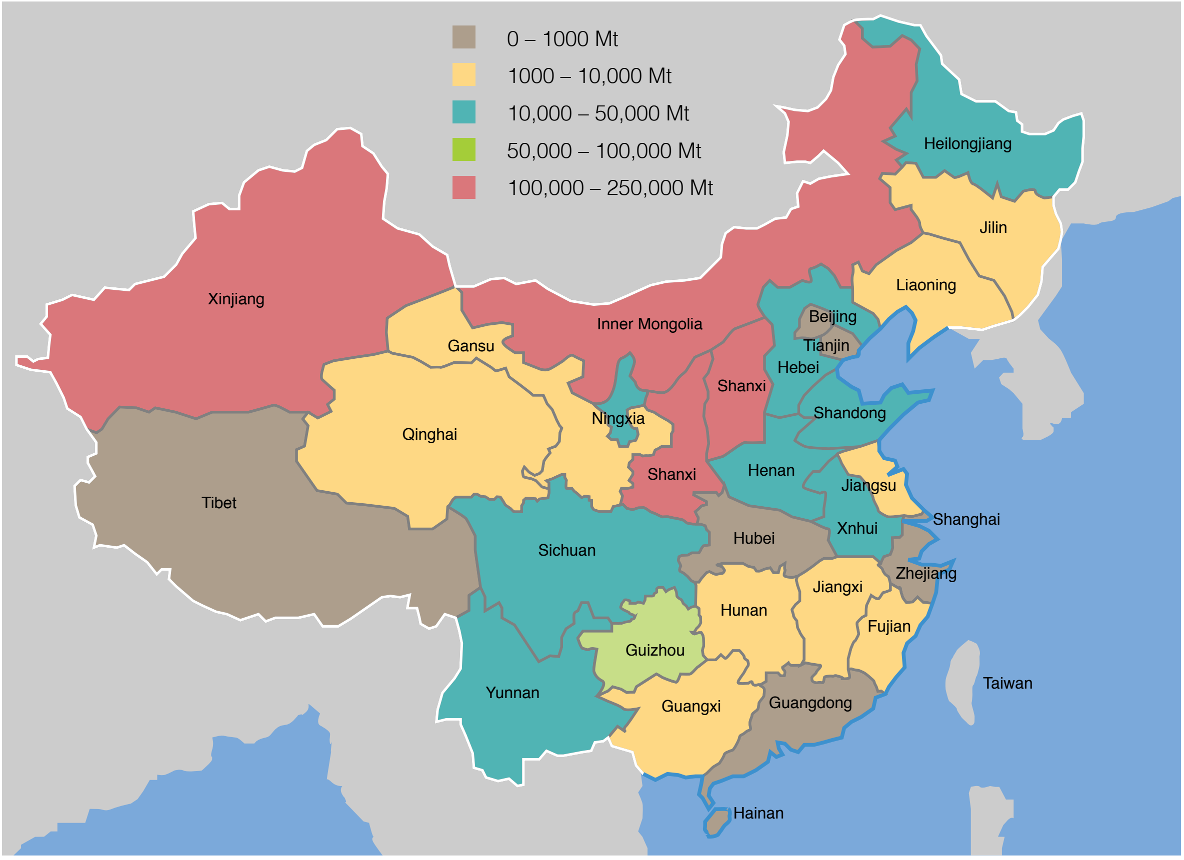

Figure 9 Map of China indicating the geographical distribution of coal resources (Wikimedia, 2013)

require the owners to show how CO_2 capture technology could be applied in due course, in effect a form of CO_2 capture-ready requirement.

Within this framework, against a national background of high oil prices and tight energy supply, the intention during the 12th FYP period is to further establish a modern coal chemical industry, to include the upgrade of those demonstration projects that offer the higher energy conversion efficiency, a suitable geographical location with both adequate suitable coal supplies and sufficient water availability, as well as offering prospects for extending the industrial chain to promote local economic and social development. This will include a focus on the construction of projects for clean production, utilisation, processing and conversion of low-calorific-value coal (Inside China, 2012).

In February 2012, the Ministry of Industry & Information Technology published the Petrochemical & Chemical Industry overall 12th Five-Year Plan, together with specific plans for the olefin and fertiliser industries (Asiachem, 2013d). This set out the need to actively promote advanced coal gasification and coal-based polygeneration processes; to further establish Chinese intellectual property rights; and to further improve the utilisation ratio of lower rank coal and other poor quality mineral species. It suggested that coal/methanol to olefins should achieve at least 20% market penetration, displacing traditional naphtha-based conversion processes, while the proportion of nitro-fertiliser capacity using advanced gasification processes should reach 30% together with the development of 450 kt/y ammonia and 800 kt/y urea (or higher capacity) process units.

In March 2012, the NDRC published the Coal Industry 12-5 Developing Programme. This specifies that new coal-to-chemicals projects will be based in those areas of Inner Mongolia, Xinjiang, Shaanxi, Shanxi, Yunnan, and Guizhou Provinces that have both adequate quantities of suitable coal and water supplies necessary to support process upgrading projects for CTL, coal-to-SNG, CTO, coal-to-MEG, and other novel coal chemicals processes.

Further, in May 2013, the NDRC published the Climate [2013] Document No 849, which has been sent to all provincial, autonomous region, special zone, municipal and city governments, as well as to a wide range of ministries and commissions, and to all State-Owned Key Enterprises and all related Industry Associations. Its purpose is to promote Carbon Capture, Utilisation and Storage (CCUS) Pilot and Demonstration projects throughout the thermal power, coal chemical, cement and steel industries (NDRC, 2013). This is a powerful document and calls on the recipients to:

- develop pilot and demonstration projects for the full CCUS technology chain;
- develop CCUS demonstration projects and base;
- explore and establish financial incentive mechanisms;
- strengthen strategy and planning for CCUS development;
- promote CCUS standards and regulation;
- strengthen capacity building and international collaboration.

This indicates that CO_2 capture projects will be encouraged in the coal chemical industry, together with the oil and gas industries, with the intention to guide those industries to consider CCUS projects in their medium- and long-term development plans (Asiachem, 2013g). To put this in context for the coal-to-SNG sector, an annual gas production capacity of 40 billion m^3 would result in the release of 180 Mt of CO_2. Since China has begun trials to assess the impact of a carbon tax in various industrial sectors, there would appear to be a powerful driver to apply CCUS in this sector within a medium- and long-term timeframe.

4.3 Coal conversion market considerations

As part of its plan to limit further coal-based industrial development in the eastern provinces, primarily on environmental grounds, the Chinese government is attempting to shift new development towards the western provinces where there are large coal reserves. Currently, coal availability in China is good, with prices falling while oil and gas prices remain high. This has encouraged various Chinese companies to set up gasification-based projects in the western regions to convert coal into higher-value derivatives. Most of these coal projects are from energy companies that either have mining rights or other access to the coal reserves, thus ensuring adequate feedstock supplies (Sxcoal, 2013). In particular, the Xinjiang Autonomous Region is a focus for many such projects, due to its very large, easily accessible coal reserves, while the end products are more readily transportable than raw coal. As noted previously, the central government has a relatively cautious approach to additional coal conversion projects, while the provincial governments have included far larger numbers in their own development plans. However, on behalf of the central government, it is the NDRC that has the last word on approvals and their policies will dictate how fast the coal-conversion industry is developed. This central-provincial discrepancy is reflected in the projects overview set out below, with some approvals likely to have been given prior to the NDRC tightening of the assessment process. There also remains a major uncertainty regarding water availability, since these plants are all water intensive and there are shortages in some western China areas.

The remainder of this section comprises a review of the development drivers, possible market sizes through to 2020 and achievements for the development and deployment of the key coal conversion technologies. It is important to recognise that the Chinese coal-to-chemicals sector is fast moving, with a considerable number of projects being proposed and declared publicly to be proceeding. However, although the sector is growing rapidly, many of the proposed projects will not ultimately proceed to the implementation stage for a wide range of reasons. Consequently, this review has been limited to projects that are understood to be formally approved by the NDRC. Even so, while every effort has been taken to verify the information presented below, there may be errors and omissions. Consequently, any interpretation of the data should be made with caution.

4.3.1 Coal-to-methanol

Methanol is a prime chemical output that can be produced from coal, petroleum and natural gas using a mature conversion process, Figure 10, and which has a number of direct applications while also being used as a building block in the manufacture of most of the coal-based petrochemical substitutes that are described below.

During the 11th FYP period, the drive was to rapidly and significantly increase coal-to-methanol production in order to avoid using higher cost petroleum and natural gas as the primary feedstocks. In overall terms, the expectation was that methanol use would rise rapidly, with likely products including:

- formaldehyde, agricultural and pharmaceutical chemicals;
- a blend component with gasoline/petrol;
- dimethyl ether (DME) as a substitute for diesel and LPG;
- a means to produce substitutes for petro-chemical industrial products.

The NDRC projections were that total methanol use would increase from some 7 Mt in 2005 to 25 Mt by 2010 and 65 Mt by 2020, with domestic producers being able to supply all of China's needs. However, while demand has increased broadly in line with projections, Chinese production capacity had soared to levels well in excess of government targets (Minchener 2011a). It is understood that in 2011 there were over 180 methanol companies, most of them with an annual production capacity of less than 0.2 Mt. At the same time, there has been a rise in imports, which indicates a lack of competitiveness in some regions of China (Allbusiness, 2009). The lower cost producers, which use natural gas as the starting material, are in Malaysia, Saudi Arabia, Indonesia, Oman, Egypt and New Zealand.

As part of its 2011 announcements of the need for an orderly development of the coal chemical industry, the NDRC stipulated that there would be a cap on annual coal-to-methanol production capacity of 50 Mt by 2015 (Yang and Jackson, 2012). Current methanol production capacity is around 40–45 Mt, and most plants are either operating at well below annual capacity or are standing idle due to the over-expansion of the industry (The Oil Drum, 2012). Although it is understood that this cap is not yet legally binding, the NDRC can control matters through its projects approval process.

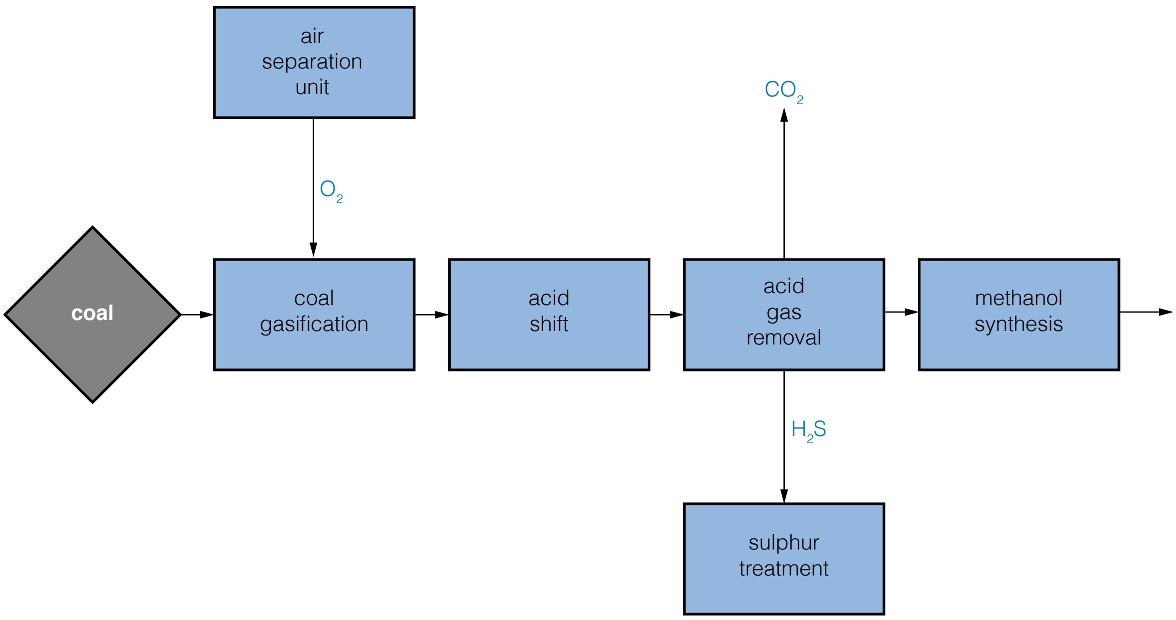

Figure 10 Coal-to-methanol block diagram (Davy, 2013)

The country's annual methanol consumption for non-traditional sectors, which include DME and blending with petrol, currently stands at about 10 Mt, about a third of China's total methanol consumption (ICIS, 2012e). In terms of new markets for methanol, its use for methanol-to-olefins (MTO) and methanol-to-propylene (MTP) offer better prospects, as described below.

4.3.2 Coal-to-SNG

Gas consumption has been increasing rapidly, due to demand from industry and a government intention to increase usage in the residential and utility sectors. It has risen from 25 billion m^3 in 2000 to 130 billion m^3 in 2011, with imports becoming increasingly important from 2007 onwards (Oil Price, 2012a). In 2012, China's annual consumption of natural gas is believed to have reached 150 billion m^3, with close to 44 billion m^3 either imported via pipelines (20.5 billion m^3) or as LNG (23.5 billion m^3) (Asiachem, 2012b; UK FCO, 2013).

The Chinese government has set an ambitious goal of increasing the share of natural gas in the national energy mix from its current 4% to 10% by 2020. Government projections suggest that the annual gas demand will reach 350–400 billion m^3 by 2020 and ~550 billion m^3 by 2030. These levels will have to be met by a combination of domestic natural gas production, imports by pipelines and as LNG, plus the introduction of the alternative unconventional domestic sources such as CBM, shale gas, and coal-to-SNG. It is possible that in 2020 a combination of pipeline imports (at ~80 billion m^3), domestic production (at ~200 billion m^3) and unconventional gas sources (at 70 billion m^3) with LNG (as the balance) will meet Chinese demand. However, there are considerable doubts that CBM and shale gas can provide significant proportions of the suggested targets, due to the lack of established extraction techniques, especially for the latter as the viability of shale gas is far from proven in the Chinese context. There is also the need for major transport infrastructures to be established from relatively remote locations.

According to the National Energy Administration in its 12th FYP Shale Gas Development Plan, the national target is to reach 6.5 billion m^3 shale gas output by 2015, and strive for 60–100 billion m^3 output by 2020. To put this in perspective, this would require at least 20,000 shale gas wells to be drilled by 2020, at a total investment of more than RMB 800 billion (Asiachem, 2013a). This is widely seen as unrealistic, not least by the Chinese companies that are expected to be involved in the shale gas production programme, as the first tranche of shale gas projects being developed can best be described as speculative demonstrations (Asiachem, 2013d).

Consequently, SNG could have a key role in meeting national demand, at least in the period to 2020 (Platts, 2012). Subsequently, should it be found that China can achieve large-scale exploitation of relatively low cost shale gas, this could have a significant impact on the natural gas industry, with possible falls in the import quantities of pipeline gas and LNG, as well as coal-to-SNG requirements. The associated quantities of ethane and propane in the shale gas would also be a suitable feedstock for olefin production.

The process scheme for coal-to-SNG production is relatively straight forward, as set out in Figure 11 although it has yet to be proven at commercial scale in China. In its development plan for the natural gas industry during the 12th FYP period (2011-15), the central government's target is a national SNG production level in the range 15–18 billion m^3. Originally, the intention was to establish four demonstration plants to allow the developers to gain technology awareness and, indeed, market experience. However, this approach appears to have been overtaken, with a major deployment programme under way prior to the first four projects becoming operational, including plants with significantly greater capacities than those included in the original plan.

Some 14 coal gasification projects in China are understood to be either under construction or at the design/planning stage through to 2016, with a total potential annual SNG output of just over

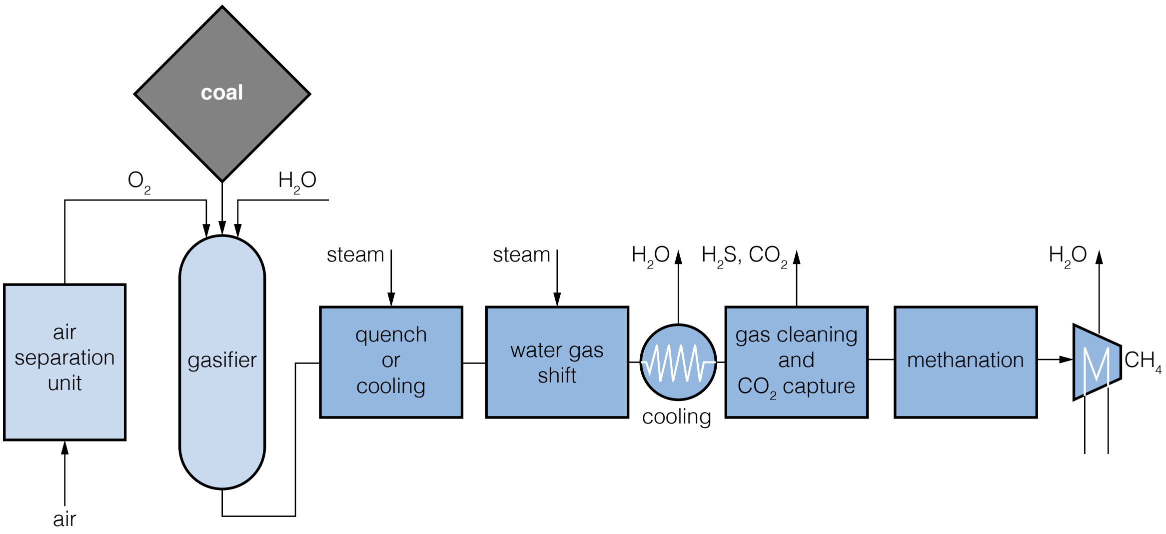

Figure 11 Coal-to-methane process schematic (Lei and others, 2009)

Table 4 Coal-to-SNG projects for construction in China through 2016 (Platts, 2012; Chemical Engineering, 2012)

Owner	Location	Annual output capacity, billion m^3		Schedule for first phase operations
		First phase	Target	
Guanghui	Xinjiang	–	0.5	2012
Qinghua	Yili, Xinjiang	1.4	5.5	2012
Datang	Inner Mongolia	1.4	4.0	2012
Xinwen	Yili, Xinjiang	2.0	10.0	2013
Huineng	Ordos, Inner Mongolia	-	2.0	2013
Huaneng	Zhundong, Xinjiang	4.0	6.0	2013
Guodian	Ulanhot, Inner Mongolia	2.0	10.0	2014
Shenhua	Ordos, Inner Mongolia	–	2.0	2015
Sinopec	Xinjiang	–	8.0	2015
Guanghui	Fuwen, Xinjiang	4.0	4.0	2015
CPIC	Yili, Xinjiang	2.0	6.0	2015
CNOOC	Shanxi	4.0	6-15	2015
Hongshengqi	Gansu	–	4.0	2015
Datang	Fuxin, Liaoning	–	4.0	2016

21 billion m^3 pipeline quality gas by that time, Table 4. Should these plants then be scaled up to reach their target capacities, they could be supplying 89–96 billion m^3/y, although the timelines for these subsequent expansions have yet to be defined. The first plant in operation was the Guanghui Energy unit in Xinjiang, with an annual capacity of 0.5 billion m^3, which commenced production in December 2012 (Interfax, 2012). As yet, performance data have not been made available.

For these initial projects, the expectation is that a major use for SNG will be for heating and cooking in households in the densely-populated cities of the eastern provinces. Infrastructure is being put in place to facilitate this.

It is understood that these projects all have at least pre-approval from the NDRC, which gives them permission to undertake the preparation works for the project prior to actual construction (Asiachem, 2013g).

Table 4 also indicates that the majority of project owners are from the coal and power sectors, which reflects these organisations' continued diversification towards becoming integrated energy companies. At the same time, the big Chinese state oil and gas companies are diversifying into fossil and renewable energy applications. This includes coal-to-SNG projects and the strategic establishment of the pipelines to transport the output from Xinjiang, Inner Mongolia and Shanxi Province to the demand centres in the eastern provinces (China Gas Maps, 2013).

Sinopec announced that it intended to establish six coal-to-chemical bases in Inner Mongolia, Xinjiang, Henan, Guizhou, Anhui and Ningxia provinces during China's 12th FYP. It is also taking forward plans to establish the largest single coal-to-syngas project in China, Table 4, with an expected annual gas production capacity of 8 billion m^3 when fully operational, which will be equivalent to 7.5% of China's 2012 natural gas production (UK FCO, 2013). This is being undertaken by its specialist coal-to-chemical subsidiary, Sinopec Great Wall Energy Chemical Co Ltd, based in Beijing (American Fuels Coalition, 2012g). It is also providing the investment for the construction of two pipelines from the western part of the country with a total annual transmission capacity of 30 billion m^3. One will link Xinjiang with 13 provinces and municipalities, including Gansu, Ningxia, Shaanxi, Shandong, Jiangxi, Zhejiang, Guangdong and Fujian, Figure 9. The other will also start in Xinjiang and pass through seven major areas, including Henan, Anhui, Tianjin, Jiangsu and Beijing (Platts, 2012).

These will complement the West-East pipelines that were built by the National Petroleum Corporation (CNPC) to take the Central Asian natural gas imports and Xinjiang's own production to China's eastern provinces. The first, which started operation in 2003, has an annual capacity of 12 billion m^3 and runs from Xinjiang to Shanghai. The second, with an annual capacity of 30 billion m^3, transports gas from Turkmenistan to Shenzhen in Guangdong Province and is already believed to be operating close to capacity. CNPC is also building a third pipeline, with an annual capacity of 30 billion m^3. Commercial operations are targeted to begin in 2015. This will link with the Central Asia-China gas pipeline Network, starting at the Kazakhstan-Xinjiang border and will pass through ten provinces. It is understood that this could provide additional capacity for SNG, which will be needed if the target production levels of the projects in this part of China are to be achieved (Energy China Forum, 2013).

The China National Offshore Oil Company (CNOOC) also has an interest in upstream coal gasification-based SNG production and in transportation (World Fuels, 2013). It has plans to build several coal-to-SNG plants in Inner Mongolia and Shanxi Province, together with a 30 billion m^3/y pipeline to take SNG from Inner Mongolia and Shanxi Province through to Shandong Province and the Tianjin municipality (China Daily, 2010).

Based on the projects under construction, by 2016, it will be possible to determine if coal-based SNG can provide a technically and economically viable pipeline quality gas and so make a significant contribution to China's overall gas utilisation targets for 2020 and beyond. In terms of increasing capacity, there are numerous other projects in preparation although all would need NDRC approval if they are to proceed. For example, according to the Xinjiang 12th Five-Year Plan, this province has incorporated 20 SNG projects into its development targets, the total output capacity of which would be close to 80 billion m^3. While many of these projects will not proceed as far as the approval stage for 2015 operation, it is possible that they could reduce China's demand for additional gas imports beyond the currently secured LNG contracts by 2020 (Platts, 2012).

4.3.3 Coal-to-olefins

Domestic demand for olefins and polyolefins has increased steadily, and from 2005 to 2010 China's utilisation of these materials grew by 14% and 10% per annum, to reach 27.8 Mt and 30.0 Mt respectively. This has led to a growing need for imports (Deloitte, 2012). For example, propylene imports in 2012 reached 2.2 Mt and are forecast to reach 2.6 Mt in 2013 (Asiachem, 2013f). China's propylene is used mainly in the production of polypropylene (PP), acrylonitrile (ACN), oxo-alcohols, propylene oxide (PO), acrylic acid (AA) and phenol/acetone (Ph/Ac). PP is the dominant derivative of propylene, accounting for more than 70% of China's consumption.

The central government's aim during the 12th FYP is to improve self-sufficiency in ethylene from 48% in 2010 to 64% in 2015, while the target for propylene is an increase from 63% to 77%. Given the shortage of domestic propylene supply, several investors have launched propylene projects, which incorporate the CTO process (Asiachem, 2013f). This involves firstly gasifying coal into syngas, which is then turned into methanol, and then to olefins (ethylene and propylene) via dimethyl ether and finally to polyethylene (PE) and polypropylene (PP), Figure 12. There is also a separate propylene-only process, based on methanol-to-propylene (MTP). The end products are plastic pellets, which, when transported by rail, offer greater national economic and energy value per railcar-load than coal. From a producer perspective, the process is attractive as it offers significant added value by converting coal priced at ~100 US$/t into a product that sells for well over 1000 $/t (ICIS, 2012c).

However, as with SNG, environmental concerns have been raised over the sustainability of the industry due to high levels of CO_2 emissions and heavy water consumption in Western China where in some regions water is in short supply. That said, there is scope to recover and recycle water from the overall process in the stage where methanol is converted into dimethyl ether.

In the period 2012 to 2015, sixteen coal-to-methanol-to-olefins (MTO) and methanol-to-propylene (MTP) projects are due to come on stream, with a total annual production capacity of about 10 Mt. The leading projects are listed in Table 5, and comprise four commercial prototype demonstration units, which have commenced operation and have produced commercial grade products. At full

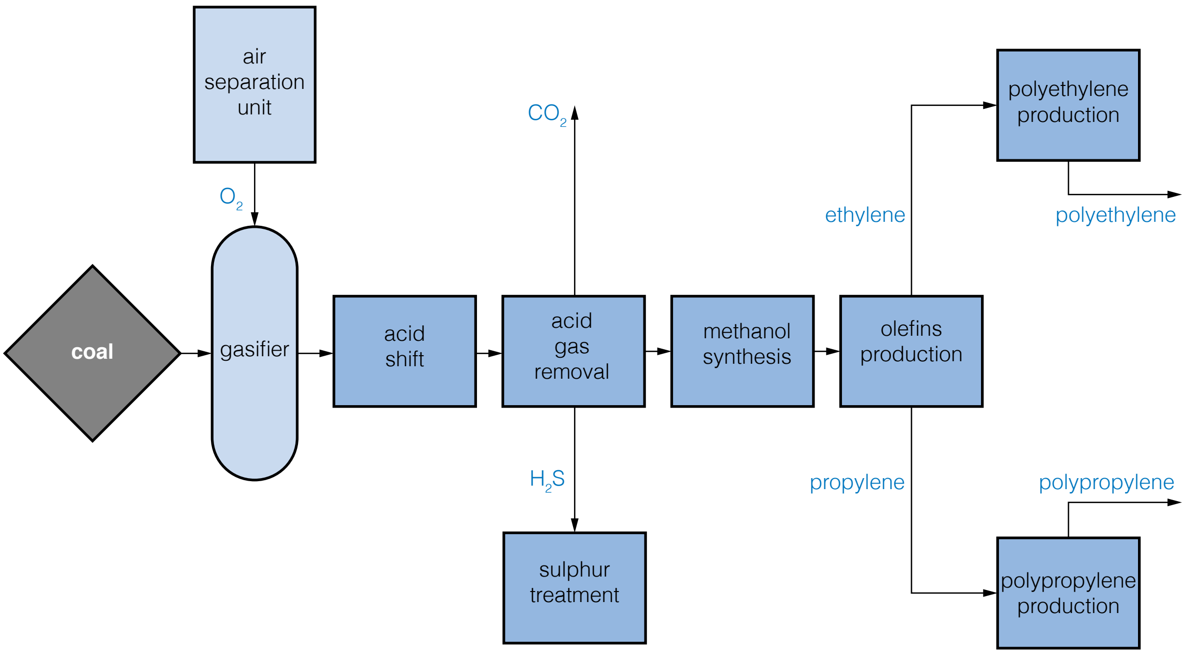

Figure 12 Coal-to-olefins process (Davy, 2013)

Table 5 Initial commercial prototype demonstration coal to olefins projects (ICIS, 2012d)

Project	Location	Type	Annual production capacity	Operational status
Datang International	Inner Mongolia	MTP	Integrated coal to methanol (1.68 Mt) to polypropylene (460,000 tonnes)	Generally at 50–60% capacity
Shenhua Group	Baotoi, Inner Mongolia	MTO	Integrated coal to methanol (1.8 Mt) to olefin (600,000 tonnes)	Stable, but rate not reported
Shenhua Ningxia Coal Industry Group	Ningxia	MTP	Integrated coal to methanol (1.67 Mt) to polypropylene (500,000 tonnes)	Generally at 70–80% capacity
Sinopec Zhongyuan Petrochemical	Puyang, Henan Province	MTO	200,000 tonnes*	Stable, but rate not reported

* This unit processes 600,000 tonnes of methanol, which is supplied from a nearby coal to methanol unit

output, these four projects would have a combined capacity of 1.76 Mt/y. However, market conditions have not been attractive due to the global economic slowdown and so none of them has operated at full capacity (Sxcoal, 2013). Also, the product quality is at the lower end of the market range. Further development work is needed to introduce more highly efficient catalysts and to ensure operational stability, in order to be able to penetrate the higher value end-use markets (ICIS, 2012d).

Even so, in the period January-October 2012, the Shenhua Baotou CTO project sold 460 kt of polyolefin products, nearly 90 kt of higher hydrocarbons and 10 kt of sulphur, while the Shenhua Ningxia CTO project realised sales of 405 kt of polypropylene, 178 kt of mixed aromatics, and 66 kt of LPG. Both projects are understood to be making operational profits on such sales (Asiachem, 2013d).

The NDRC needs to ensure that these and the other CTO projects can be upgraded to achieve higher energy and environmental standards (Asiachem, 2012c) and this has led to the following project requirements of:

- a minimum energy conversion efficiency of 40%;
- a maximum coal consumption per tonne olefins of 5.7 tonnes coal equivalent (tce);
- a maximum water consumption per tce conversion of 3 tonnes.

The expectation is that for many projects this will require better optimisation of the coal gasification processes and MTO technologies, together with the optimisation of the process engineering design, including air-cooled and water management technologies.

Details of the subsequent twelve projects are given in Table 6. Production capacity in each case is equal or greater than that of the first four projects. However, whether these will actually start up on the dates shown will depend on the markets improving. If all the planned projects listed in Table 6 proceed to schedule, by late 2015 this would represent an increase in national CTO production annual capacity of some 6.2 Mt and would require an additional 24 Mt methanol to be produced either as part of an integrated CTO process or as a feedstock that is produced and then supplied to the MTO/MTP site.

The rationale for this latter approach is that a MTO project based on outsourced methanol will need a lower capital investment than the entire process flow of a CTO project. It is also easier to obtain NDRC approval as MTO production, either based on outsourced or self-supplied methanol, is seen as a benefit to the nation in that it uses some of the surplus methanol production capacity within the country, thereby contributing to employment and the comprehensive utilisation of resources (Asiachem, 2013d).

Table 6 Early stage coal-to-methanol-to -olefins projects in China (ICIS, 2012c; ICIS, 2012d)

Company	Location	Type	Annual product capacity, 000 t		Possible start-up date
			Ethylene	Propylene	
Ningo Heyuan (Skyford Chemicals)	Zhenhai, Zhejiang Province	MTP*	200	400	End 2012
Zhejiang Xingxing New Energy	Zhejiang Province	MTO	600	Pending	
Wison Clean Energy	Jiangsu Province	MTO	135	160	2013
Zhengda New Material Ltd.	Changzhou	MTO	500	500	End 2013
Pucheng Clean Energy	Shaanxi Province	MTO	300	400	2014
Ningxia Coal Industry	Shaanxi Province	MTP	500	2014	
Shanxi Coking Co.	Shanxi Province	MTO	300	300	End 2014
Shaanxi Shenmu Chemicals	Shaanxi Province	MTO	300	300	2014
Jiutai Energy (Zhungeer)	Inner Mongolia	MTO	300	300	2014
Sinochem Yiye Energy Invest	Shaanxi Province	MTO	800	2014	
Shaanxi Yanchang	Shaanxi Province	MTO	600	2014	
Xinjiang Guanghui Chemicals	Xinjiang	MTO	1000	2015	

* Will use methanol produced at another site

Either way, there are doubts that China has sufficient engineering and procurement contractors in China for this scale up of coal-to-olefins capacity, given the enormous number of large-scale coal conversion sector construction projects that are planned (ICIS, 2012d).

A further 5 Mt/y of CTO capacity is under development but not yet at the stage of seeking approval to proceed. The majority of all such projects would be located in China's north western regions, where the coal is especially suitable for coal conversion applications. Although this means the growing industry is located a long way from the major olefin derivative consumption markets in southern and eastern China, the logistics of transporting the products to the coastal regions are improving as the rail links continue to be developed (ICIS, 2012d).

4.3.4 Coal-to-monoethylene glycol

Monoethylene glycol (MEG) is an important raw material for industrial applications, especially the manufacture of polyester resins, as well as films and fibres, and for the production of antifreezes, coolants, deicers and solvents. Since 2001, there has been very significant demand for MEG, reaching

10.1 Mt by the end of 2010, of which only 2.8 Mt were produced domestically (Research in China, 2010). It can be produced from various process off-gases but there is also a significant driver to develop a coal-based production process.

In contrast to the other coal-to-chemical processes listed above, which were developed outside of China, this coal-to-MEG technology was developed in China by the Fujian Institute of Research on the Structure of Matter, which is part of the Chinese Academy of Sciences (IHS, 2012). In summary, this involves initial preparation of dimethyl oxalate via oxidation of carbon monoxide (derived from the gasification of coal) by reaction with methyl nitrite, followed by hydrogenolysis of the dimethyl oxalate to give MEG. In the last step, methanol is liberated and recycled to make additional methyl nitrite through the reaction of nitric oxide and oxygen. As a result, the only feedstocks consumed are syngas and oxygen (ICIS, 2012b). Figure 13 provides a schematic of the process scheme.

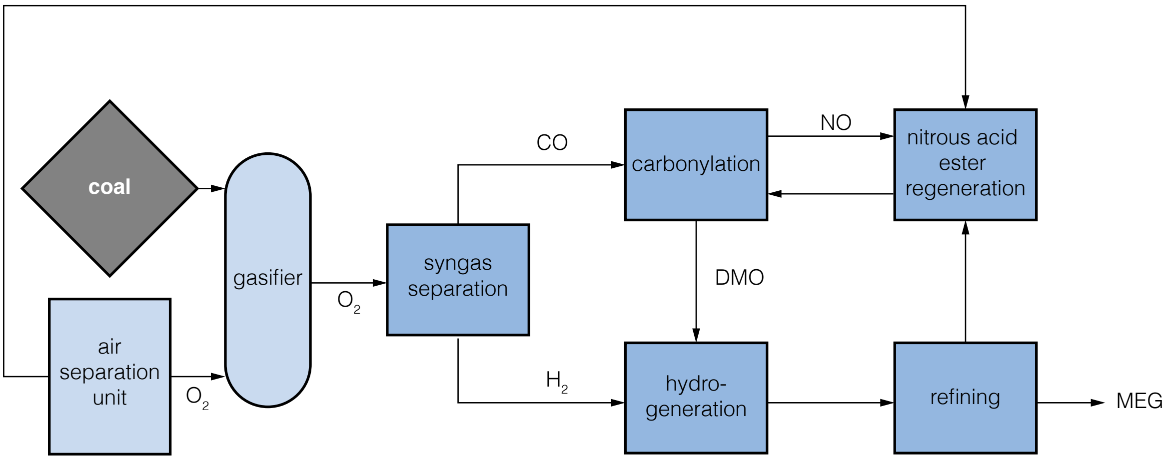

Figure 13 Flow scheme of the syngas to oxalate hydrogenation ethylene glycol process (Asiachem 2013b)

Table 7 China's coal to MEG projects for 2013 (Asiachem, 2013e; ICIS 2011b, 2012b)

Company	Location	Capacity, kt	Schedule for starting operation
Tongliao GEM Phase 1	Tongliao, Inner Mongolia	200	2009
Yonglin Chemical	Xinxiang, Henan Province	200	2012
Hualu Hengsheng	Dezhou, Shandong Province	50	2012
Xinjiang Tianye	Shihezi, Xinjiang	50	2012
Yonglin Chemical	Puyang, Henan Province	200	2013
Yonglin Chemical	Anyang, Henan Province	200	2013
Yonglin Chemical	Luoyang, Henan Province	200	2013
Yonglin Chemical	Shangqiu, Henan Province	200	2013
Huaihua Phase 1	Huainan, Anhui Province	100	2013
Sinopec	Zhijiang, Hubei Province	200	2013
Berun Su'nite Phase 1	Xilinguole, Inner Mongolia	100	2013
Hebi Baoma Phase 1	Hebei, Henan Province	50	2013

This technology is at a less advanced stage of development compared to coal-to-SNG and CTO processes, and the focus is on establishing large-scale pilot applications and commercial prototype demonstrations (Asiachem 2013a). The NDRC has noted in its 'Coal Deep Processing Demonstration Projects Planning' document that the demonstrations should each comprise a single facility with an annual capacity of at least 200,000 tonnes (Asiachem 2013b).

The projects that are already operational and those expected to come on stream this year are listed in Table 7. If these twelve plants operate to specification, they could comprise a total annual product capacity of 1.75 Mt. However, the economic viability of the process is not yet proven and there are technical issues to be resolved, including maintaining stable operation at high load factors while ensuring that polyester-grade quality MEG products can be produced (Asiachem, 2013c).

As an example, six plants based on the Fujian Institute technology, each of 200,000 tonnes annual capacity, are being developed jointly by the Henan Coal Chemical Group Co Ltd and Tongliao GEM Chemical Co Ltd, who set up the Henan Yongjin Chemical Ltd (HYCL) to undertake such projects. The first demonstration plant, with an annual capacity of 200 kt, was started up by Tongliao GEM in 2009. This project experienced considerable problems. There have been quality issues due to catalyst adsorption and coking when the operating rate was raised (ICIS, 2011b). Following modifications, the company has managed to achieve 85% of its design capacity with some 90% of the output meeting the premium product standard (Asiachem, 2013e). In 2010, HYCL started construction of the further five projects. Of these, the project in Xinxiang, Henan Province began trial operations in March 2012, and in October 2012 succeeded in producing MEG product that conforms to the national premium grade specification. The Puyang plant was started up August 2012, while the Anyang plant commenced operations in December 2012, both ahead of schedule. The remaining plants are scheduled to come on stream in China before the end of 2013.

The other technology development of interest is to establish an integrated gasification-based coal-to-MEG to polyester process. This would require linking the coal-to-MEG process with a coal-to-aromatics process that would provide purified terephthalic acid, in order to produce polyester directly. As yet the coal-to-terephthalic acid process is still at an early stage of development. A 10,000 t/y pilot unit, owned by the Huadian Yuheng Coal Chemical Company and located in the North Shaanxi Energy Chemical Base, has been built and is being commissioned (Asiachem 2013c). This is based on a fluidised bed methanol-to-aromatics technique developed by Tsinghua University.

4.3.5 Coal-to-liquids

Transport fuels (gasoline/petrol, diesel and jet fuel) are currently derived 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 approaches to providing liquid fuels from coal (Couch, 2008).

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 that comprises a process-derived recyclable oil, Figure 14. The hydrogen/carbon ratio is increased by adding gaseous H_2 to the slurry of coal and coal-derived liquids, together with catalysts 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%.

The indirect coal liquefaction route (ICL) is a high temperature, high pressure process that first

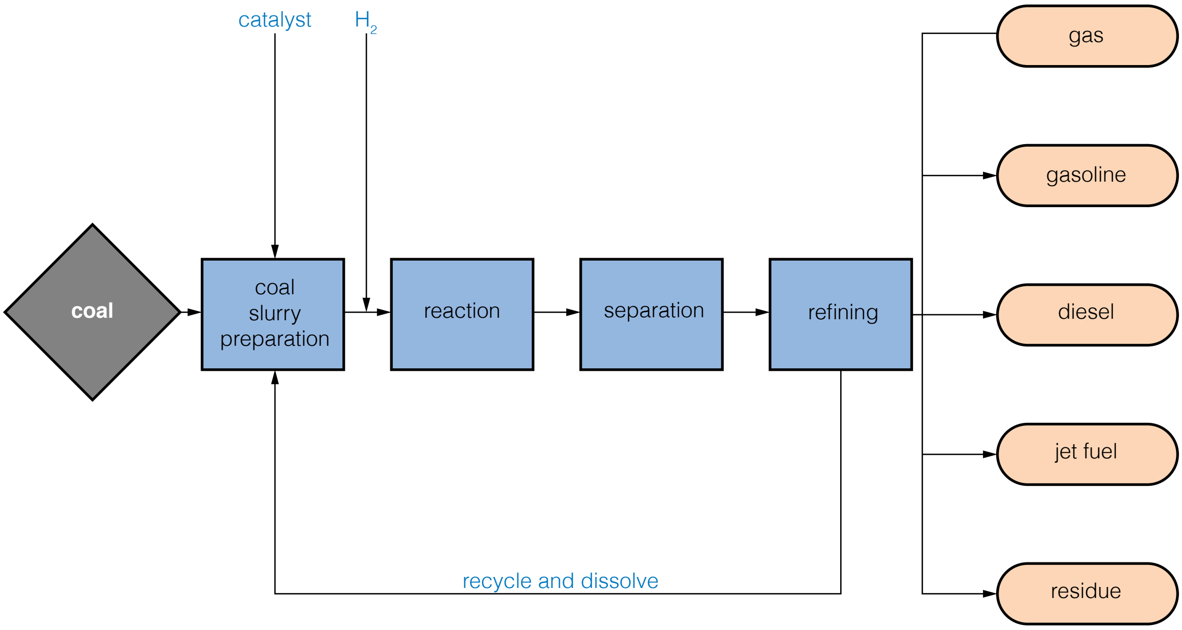

Figure 14 Simple flow scheme for the direct coal liquefaction process (Deutsche Bank, 2007)

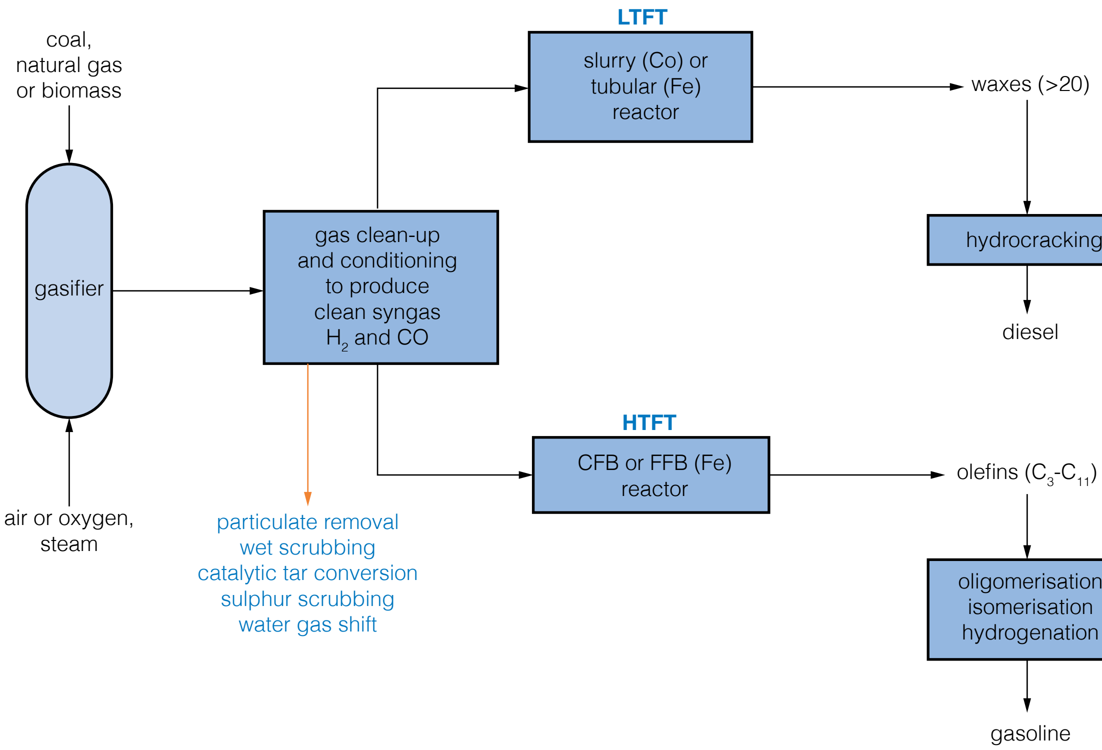

Figure 15 Flow diagram of the two generic routes to synthetic transport fuels using Fischer-Tropsch synthesis (Spath and Dayton, 2003)

requires the gasification of coal to produce a syngas, which can be converted to liquid fuels via either the FT process or the Mobil process (Radtke and others, 2006). In the FT process, which is the more common, the syngas is cleaned of impurities and then 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 the FT synthesis stage, the choice of making either petrol or diesel is determined by the choice of operating temperature and choice of catalyst, Figure 15. In the Mobil process, the syngas can be converted to methanol, which is then converted to petroleum products via a dehydration sequence (AAAS, 2009).

Although more complex, 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.

The four demonstration projects in China that were constructed and begun operation during the 11th FYP period are summarised in Table 8. In 2012, the performance data that were released suggested that some of the earlier operational problems had been resolved. In particular, after numerous periods of below specification operation and subsequent equipment modifications, the Shenhua DCL process achieved long-term stable operation and commercial grade products, although this required some departure from the original process specification. That said, it made a cumulative operating profit of 480 million RMB (US$ 80 million) on turnover of 4.58 billion RMB. The Yitai CTL Company produced over 160 kt of various oil and chemical products in 2012, reached design capacity for the first time since initial start-up, and achieved an unit consumption per tonne of oil of 3.64 tonnes of coal and 820 kWh of electricity. All the other performance indices were better than the design specification (Asiachem, 2013d).

On the basis of the results from these four plants, and recognising the enormous difference in scale of operation between the DCL and ICL processes, an outline economic assessment has been made. This has considered the impact of the input coal price on the production cost of the crude oil from both processes. Results are given in Table 9. These figures indicate the lower production costs of the DCL process compared to ICL and suggest that both techniques should remain competitive when coal prices are no greater than 125 US$/t (~750 RMB/tonne). As an alternative, the use of methanol as a feedstock for the methanol-to-gasoline (MTG) process remains in contention although the economics are understood to be less attractive.

These companies and others have plans to expand production and it is understood that preparations are under way to scale up the technology (Research in China, 2011). Thus, In December 2012, Shenhua Group started construction of the other two production lines for its DCL project, for which

Table 8 Summary of national coal to oil projects established in China during the 11th FYP period (Yue, 2010; Market Avenue, 2010)

Company	Location	Process	Licensor	Initial annual product output, Mt	Target capacity	Start-up date
Shenhua	Inner Mongolia	DCL	Shenhua	1.0	3.2	December 2008
Yitai	Inner Mongolia	ICL	Synfuels China	0.16	0.48	March 2009
Lu'an	Lu'an Shanxi Province	ICL polygeneration	Synfuels China	0.16	2.6	July 2009
Shenhua	Inner Mongolia	ICL	Synfuels China	0.18	–	December 2009

Table 9 Indicative coal price sensitivities on oil production costs for CTL technologies (Research in China, 2011)

Input coal price, US$/t	Crude oil production costs, US$/barrel	
	ICL	DCL
15	35-45	25-30
125	80-90	49-59
155	110-120	65-75

the overall investment is given as 24 billion RMB, with start-up scheduled for late 2016. The Lu'an Group has received preliminary approval from the NDRC for its polygeneration demonstration phase, based around a 1.8 Mt/y coal-based synthetic fuel unit. It is now undertaking the front end design study. Shenhua Ningxia Coal has longstanding plans to establish a 4 Mt/y ICL unit and has started site work, with preparations under way for the construction of the power plant that forms part of the overall project. This suggests that government approval has been given to take things forward. There is also the general expectation within the industry that development of the large-scale Energy & Chemical Bases (Ningdong in Ningxia, Shanghaimiao in Ordos, Inner Mongolia) will be further progressed (Asiachem, 2012a).

There is some interest in co-processing technology, which is a variant on direct liquefaction processes that includes the simultaneous upgrading of coal and a non-coal-derived liquid hydrocarbon. The latter serves as the slurry and transport medium for the coal. It is usually a low value high boiling point material, such as bitumen, an ultra-heavy crude oil, a distillation residue or tar from crude oil processing. The overall aim 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 (DTI, 1999).

In April 2012, the Yanchang Petroleum Group started construction of a co-processing demonstration project in Yulin, Shaanxi Province. On an annual basis, this is designed to convert 225 kt of raw coal (dry-basis), 225 kt of residue oil and 77.5 kt of natural gas, to produce 262.4 kt of diesel fuel, 77.7 kt of gasoline and 45 kt of LPG. The driver is to utilise residue oil, with the natural gas being included as a relatively low cost feed for hydrogen generation, thereby reducing overall capital investment (Asiachem, 2013d).

4.3.6 Other development prospects for the Chinese coal chemical industry

These comprise the coal-to-aromatics and coal-to-ethanol sectors, where development is at an early stage and as such information is more limited than for the major sectors described above.

Coal (methanol)-to-aromatic chemicals

Such chemicals include benzene, toluene and xylene (BTX), of which some 45% is used to manufacture para-xylene that is used for the production of purified terephthalic acid (PTA). The latter chemical is used to produce polyester (*see* Section 4.3.4 *above*).

Coal-based aromatics production can be either via a one-step syngas to aromatics route or a syngas to methanol to aromatics (MTA) process (Asiachem, 2013d). The former approach results in a mixed output of benzene, toluene and xylenes, of which only part of the latter component is suitable for polyester production. In contrast, the methanol to aromatics route is deemed more promising. Chinese developers include Tsinghua University, ICC-CAS/Sedin Engineering, Beijing University of Chemical Technology, and Sinopec Shanghai Research Institute of Petrochemical Technology. The latter company has developed a methanol/toluene methylation process, which produces only xylenes, thereby improving the para-xylene yield.

Initial economic studies suggest that the Chinese MTA processes can realise nearly 100% of methanol conversion, 60~70% of single pass total aromatic yield and over 80% of selectivity to BTX light aromatics. On the basis of a 1900 RMB/t methanol price, the combined aromatics (BTX) net cost will be 5578 RMB /t after allowing for income from by-products such as LPG. On this basis, the cost of para-xylene has been estimated at 7000 RMB/t (tax excluded). In 2012, the para-xylene average spot price in East China was some 11,500 RMB/t, suggesting that this technique could be economically viable should the technical aspects of the process be proven.

Coal (syngas)-to-ethanol

There is a potentially significant industrial demand for ethanol, for which several biological and chemical production methods are available, as shown in Figure 16. Of these, the first generation bio-ethanol route, based on the use of food crops (for instance, cereals) is not considered sustainable, and so the emphasis has shifted to second generation cellulose bio-processes and to other options including the conversion of coal-based syngas.

The options include the conversion of acetic acid either by direct hydrogenation or esterification/hydrogenation, for which coal-based syngas is being used as the raw material source. There are some fifteen plants in operation with another seven at the development stage, each with

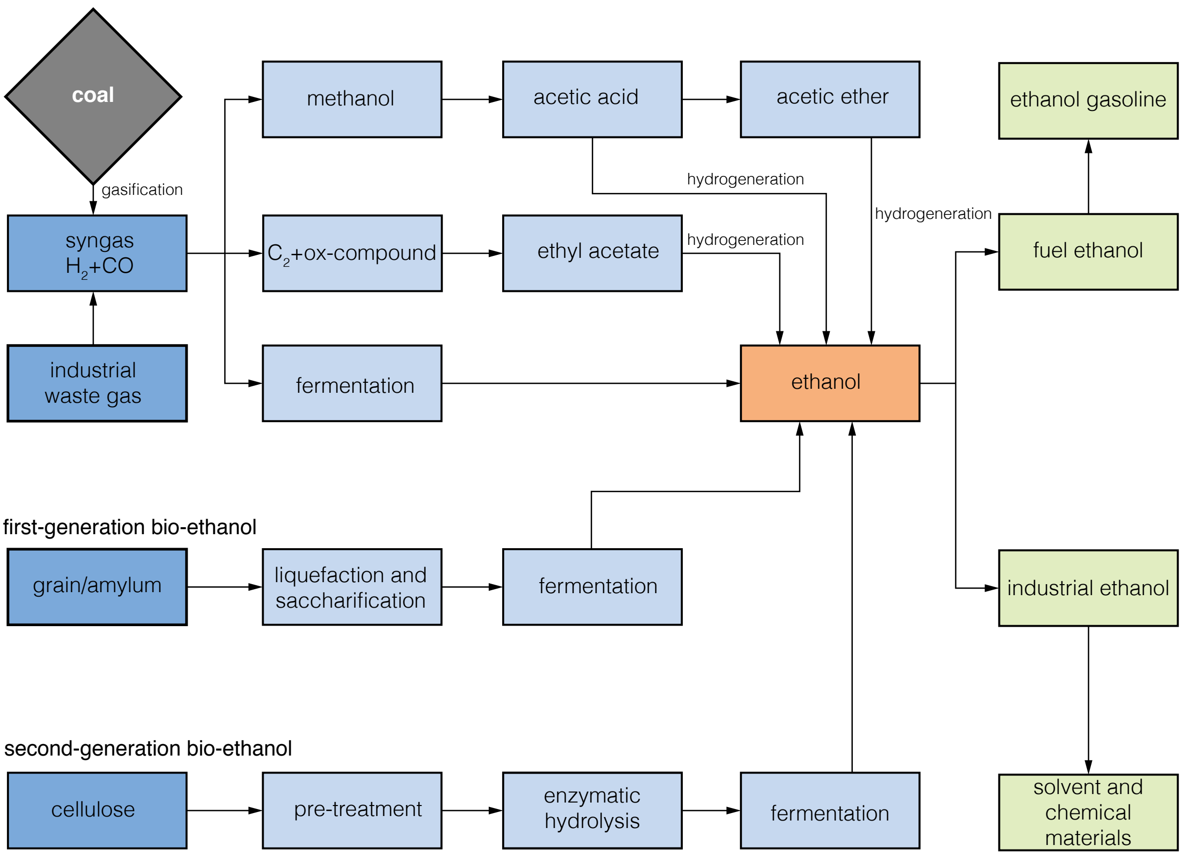

Figure 16 Coal and biomass to ethanol process schemes (Asiachem, 2012e)

product annual output capacities of 150–200 kt. In 2012 although the total operational capacity was 7.6 Mt, output was limited to 4.2 Mt, indicating a significant mismatch between supply and demand. This problem will worsen by 2015 when the total annual capacity will be close to 11 Mt/y (Asiachem, 2012d).

Notwithstanding the mismatch, there is interest in an alternative approach, which is to apply microbe fermentation to a coal-based syngas. A pilot trial is under way at the Shanghai Baosteel LanzaTech New Energy Co Ltd at a very small annual capacity of 300 tonnes, which uses offgas from a steel plant as its feedstock. The basic concept has been shown to be technically feasible and the intention is to scale up operations in order to improve stability and to gather economic data such that the commercial potential can be determined. This approach should be able to use any clean syngas that contains CO and H_2.

Finally, the SOPO Group is carrying out trials of a syngas-to-ethanol technique that was developed jointly with the CAS Dalian Institute of Chemical Physics and the Wuhan Engineering Company. This uses a silica-base catalyst to convert coal-based syngas and, through the process flow of hydrogenation and separation, obtains a product conforming to both the specifications of premium industrial ethanol and fuel grade ethanol. Annual capacity is up to 10,000 tonnes.

The latter two developments are at the laboratory- and pilot-scale respectively; consequently, neither the technical nor economic viability of the coal-to-ethanol process have been verified by industrial demonstration (Asiachem, 2013d).

From a market perspective, the volume for industrial ethanol is limited and so this industry will only become significant if ethanol can be used as a blend with petrol in the transportation sector. From 2015, there is a possibility of an annual market of some 5 Mt, this being dependent on positive Chinese polices being established. It remains to be seen whether the second generation bio-process or a coal-based production process will take this market share. Even then, the end product is likely to face competition from the use of batteries and natural gas as alternative approaches.

5 Coal gasifier development and deployment within China

In general terms, the manufacture of coal-based chemicals using modern gasification technologies, in conjunction with downstream processing and conversion techniques, can provide products of the same quality and for the same downstream usage as those made from traditional petrochemicals. This has led to coal gasification for non-power applications becoming rapidly established in China (Minchener, 2011a), with large projects being shown to be technically feasible.

5.1 Introduction

The very great majority of the modern coal gasifiers in use in China are entrained flow systems, although there are a few fixed/moving bed and fluidised bed units. Entrained flow gasification technology is favoured as it offers considerable fuel flexibility for the production of syngas. The scale of operation is significant, typically up to 2000 tonnes coal throughput per unit per day while 3000 t/d units are starting to be introduced as the overall scale of the various projects increases (NETL, 2013b).

As has been discussed in a previous report (Minchener, 2011b), the technology for these large gasifiers was first licensed from foreign suppliers with the current market leaders up to the end of 2011 being GE and Shell. These two companies initially supplied units to process either refinery residues or natural gas as feedstocks but subsequently the focus has been on coal. The other technology suppliers from outside China include Siemens and KBR (entrained flow), Lurgi (fixed/moving bed), and SES (fluidised bed), all of which have introduced technologies for coal conversion at a number of sites. In these cases, much of the equipment is typically manufactured in China.

Increasingly, Chinese designed and manufactured alternatives are becoming available and being preferentially selected by Chinese industrial companies. The leading developers include ECUST, TPRI, HT-L and Tsinghua University (entrained flow) and ICC-CAS (fluidised bed). There are other technology variants being marketed for which very limited information is currently available in the public domain, including MCSG and Sedin.

Table 10 provides an overview of the technology status as of the end of April 2013, together with the situation as of end November 2011 for both international and domestic coal gasifiers in China. This indicates the number of projects that are either operational or at the contracted design/development/construction stage. In many cases, there will be several large gasifiers installed at a particular site, which for the more recent projects reflects the NDRC approval criteria of a minimum unit output capacity. This listing does not include more speculative development projects as in such cases these will not have reached the point where approval can be sought from the NDRC and as such there is no guarantee that they will actually proceed.

It is stressed that access to detailed information on the various projects can be hard to obtain and verify, and while every effort has been taken to ensure the accuracy of the information in the tables, there may be errors and omissions. Consequently, any interpretation of the data should be made with caution.

Table 10 indicates that the total number of projects has increased very significantly during the eighteen month period since November 2011, reflecting the growing importance of coal gasification based conversion within the Chinese economy. Further, it shows the increasing introduction of Chinese technology within that time period, with numerous projects having reached the design/construction stage.

Table 10 Status of non-power coal gasification projects in China at the end of April 2013

Technology supplier	Coal gasification projects		
	Operational	Design/Construction	Total
GE	28 (27)	10 (10)	38 (37)
Shell	21 (14)	– (5)	21 (19) *
Siemens	1 (1)	5 (2)	6 (3)
Lurgi variants	7 (3)	5 (3)	12 (6) †
SES (U-Gas)	2 (1)	1 (1)	3 (2)
KBR (TRIG)	– (–)	2 (–)	2 (-)
ECUST	12 (8)	25 (9)	37 (17)
TPRI	1 (-)	4 (3)	5 (3)
HT-L	4 (3)	14 (15)	18 (18)
Tsinghua U	4 (3)	16§ (5)	20 (8)
ICC-CAS	4 (3)	2 (–)	6 (3)
MCSG	12 (12)	2 (–)	14 (12) ‡
Sedin	2 (1)	8 (5)	10 (6) ‡
TOTAL	98 (76)	94 (58)	192 (134)

Data for end November 2011 included in brackets
* Some 25 projects have achieved operational status although 4 have since been closed, allegedly due to problems with the use of high ash deformation temperature coals
† This includes Lurgi FBDB and BGL variants
‡ In 2011, no data could be obtained for these technologies even though subsequently it has been ascertained that there were some operational units and some projects at the design/construction stage.
§ Three projects believed to be suspended for reasons unknown

The remainder of this chapter provides a short description of the coal gasification technologies available in China, on a vendor-by-vendor basis, where such information is in the public domain. The level of detail varies, particularly for several of the Chinese technologies where the information is very limited. This is reflected in the descriptions provided.

5.2 GE Energy

GE Energy acquired its gasification technology from Chevron in 2004, and has units operating commercially worldwide using a wide variety of feedstocks such as natural gas, heavy oil, coal and petcoke. The GE coal gasifier comprises a single-stage, downward-feed, entrained-flow refractory-lined reactor to produce syngas. Coal/water slurry (~ 60% in weight for Chinese applications) is pumped into the top of the gasifier, which together with oxygen is introduced through a single burner, Figure 17. The coal reacts exothermically with the oxygen at high temperature (1200–1480 °C) to form syngas, which contains mostly H_2 and CO, and slag (NETL, 2013b). The latter flows downwards, is quenched and then removed from the bottom of the gasifier via a lock-hopper arrangement. The water leaving the lock-hopper is separated from the slag and sent to a scrubbing unit after which it can be recycled for slurry preparation.

The raw syngas leaving the gasifier can be cooled by a radiant and/or convective heat exchanger and/or by a direct quench system, where water is injected into the hot raw syngas. The selection from

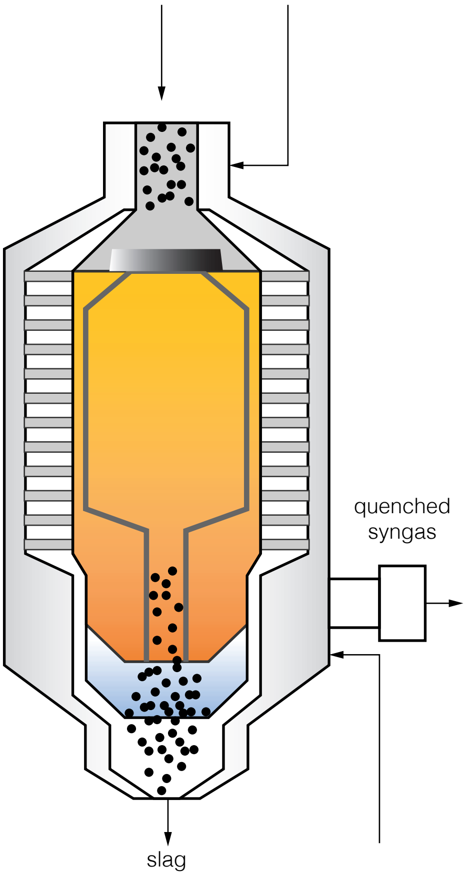

Figure 17 The GE coal gasifier quench mode (NETL, 2013b)

these alternatives is a choice of cost and application. The radiant cooling design uses a soot-tolerant radiant syngas cooler that generates high-pressure steam. Slag is quenched in a water pool located at the bottom of the reactor vessel, and removed through a lock-hopper. The syngas is further cooled after leaving the gasifier by a water scrubber to remove the fine particulate matter, before the gas is sent on to downstream processing. The direct quench system uses an exit gas water quench where hot gas leaving the gasifier is contacted directly with water via a quench ring; it is then immersed in water in the lower portion of the gasifier vessel. The cooled, saturated syngas is then sent to a scrubber for soot and particulate removal. The quench design is less efficient, but also less costly, and it is commonly used when a higher H_2 to CO ratio syngas is required.

GE has been particularly active in China and, as of March 2012, its installed fleet included 75 gasifiers that use solid feed (slurry) and 77 gasifiers that use either gas or liquid feed (NETL 2013b). At the same time, the company has continued to improve the economies of scale as output capacities of the various coal-to-chemical projects continue to rise. Thus, GE has increased the size range of its units to include a gasifer with a coal throughput of ~3000 t/d and syngas production of ~210,000 m^3/h (GE Energy, 2009). Much of the equipment for plants built with GE Energy gasification licence technology can be fabricated locally in China.

It has also formed an industrial coal gasification 50:50 joint venture with the Shenhua Group to combine their respective expertise in industrial gasification technologies and coal-fired power generation (Greencarcongress, 2012). The aim of the GE Shenhua Gasification Technology Company Ltd is to advance the development and deployment of cleaner coal technology solutions in China. It will sell industrial gasification technology licences, conduct research and development to improve cost and performance of commercial-scale gasification and integrated gasification combined cycle (IGCC) solutions, and work to advance the implementation of commercial-scale IGCC.

5.3 Shell

Shell's technology comprises a dry-feed, pressurised, entrained flow, slagging gasifier that can utilise a wide range of solid, liquid and gaseous feedstocks, Figure 18.

The coal-based variant was developed in the 1970s. Coal is pulverised and fed to the gasifier through two sets of horizontally opposed burners using a transport gas (either syngas or nitrogen). Preheated oxygen and steam (as a moderator) are mixed and fed to the injector, where they react with the coal to produce syngas consisting of H_2 and CO with only small amounts of CO_2 and no hydrocarbon liquids or gases. The hot product gases flow upward through a vertical membrane cylindrical wall, shown in

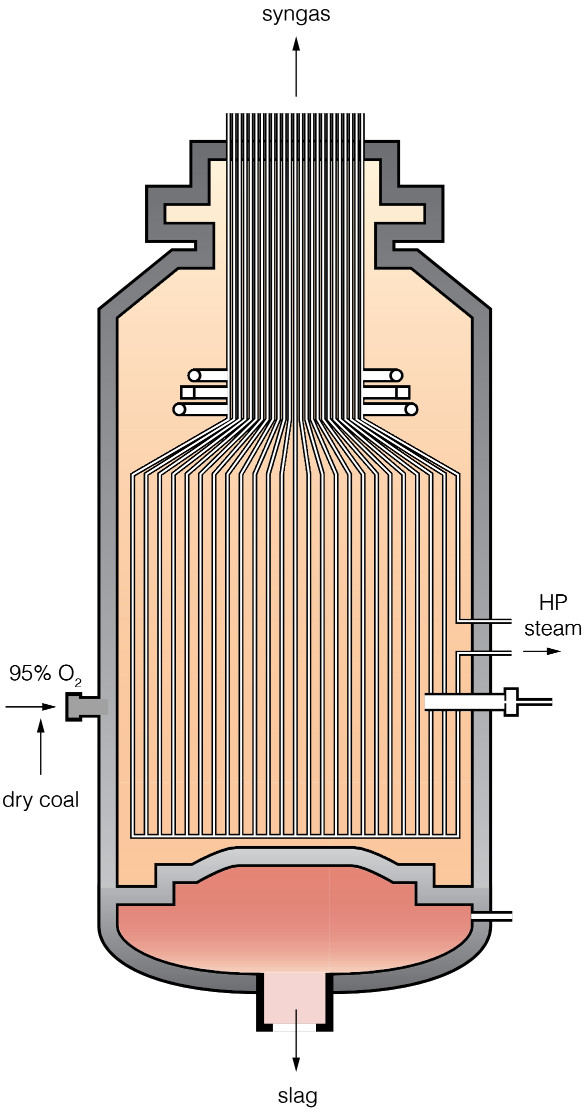

Figure 18 Shell entrained flow gasifier (NETL, 2013b)

Figure 18. Molten ash entrained with the upward-flowing syngas is deposited on the waterwalls and flows downwards, to be removed through the base of the gasifier where it is quenched in a water bath. The raw syngas exits the gasifier in the temperature range 1370–1480°C and is then treated with lower temperature recycled product gas to convert any entrained molten fly slag to a hardened solid material. It then enters the syngas cooler for heat recovery, generating high-pressure superheated steam. The bulk of the fly ash contained in the raw syngas leaving the syngas cooler is removed from the gas using either commercial filter equipment or cyclones. Any remaining fly ash is captured downstream with a wet scrubber.

Some 95% of Shell's coal gasification key equipment is produced in China, through manufacturing agreements with Chinese companies including Dong Fang Boiler Group Co, WuXi Huaguang Boiler Co Ltd and Suzhou Hailu Heavy Industry Co Ltd.

Although Shell has already established a strong presence in China, it has recently begun collaboration with the Wison Group of Shanghai, which is the largest private engineering company in China (The Hydrogen Journal, 2011). This venture is focused on the marketing of its gasification technology and includes the joint development of a hybrid gasification system, combining Shell's design with state-of-the-art bottom-water quench technology. This approach should result in a simplified design at lower cost that should prove suitable for a wider range of coal feedstocks, which could be more competitive in the Chinese market (E&P, 2011). Wison has built the first demonstration plant in partnership with Shell, at its Wison (Nanjing) Clean Energy site, with start-up scheduled for August 2013 (ICIS, 2012a).

5.4 Siemens

The Siemens gasifier is a dry-feed, pressurised, entrained-flow system, with a top-fired burner through which coal and/or other fuels together with oxygen and steam are introduced, as shown in Figure 19.

It can be supplied with either a refractory lining, for low ash feedstocks, or with a gas-tight membrane wall structure in the gasification section of the gasifier. The molten slag formed in the gasifier flows down the reactor chamber into the quench section where it solidifies upon contact with water from a ring of quench nozzles and is removed through a lock-hopper (NETL, 2013b). The gasifier can achieve carbon conversion rates higher than 99% and the technology is well suited for coals from anthracite to lignite, as well as biomass, petcoke, and residual oil.

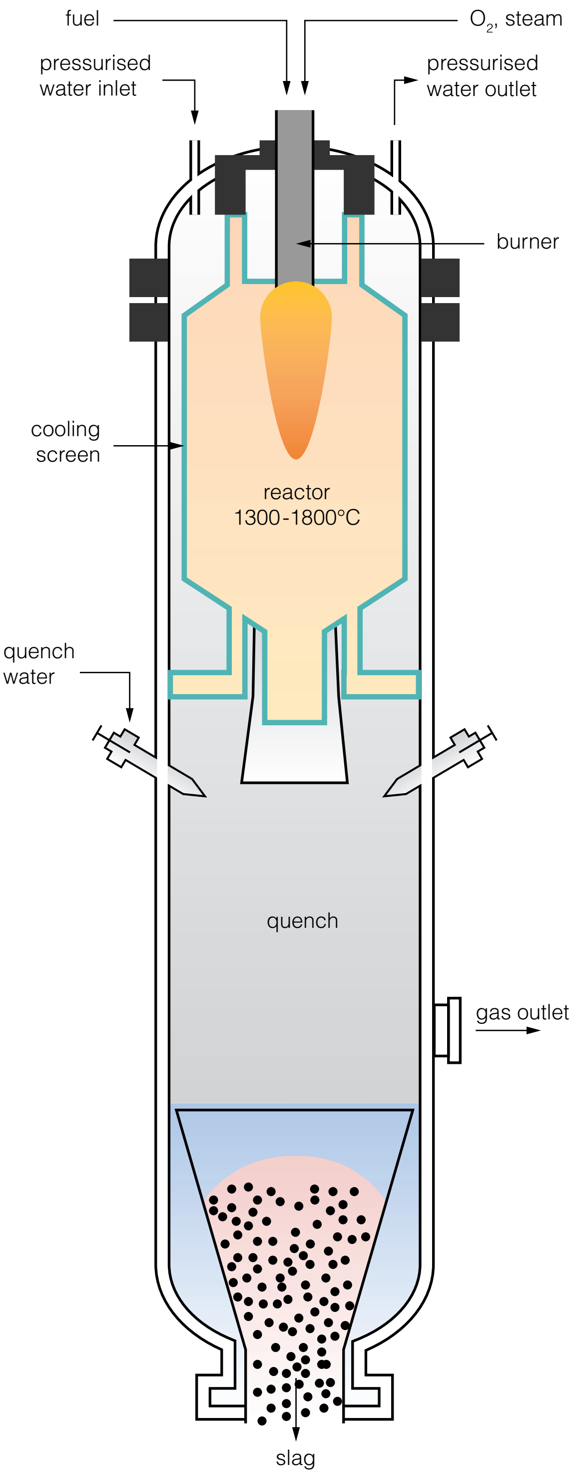

Figure 19 The Siemens gasifier (NETL, 2013b)

Siemens has established close links with the Shenhua Ningxia Coal Group through a joint venture arrangement. The first Siemens project in China (Hannemann and others, 2011), comprising five SFG-500 units, each of 500 MW capacity, began commercial operation in 2011 at the Shenhua Ningxia Coal Industry coal-to-polypropylene project (NCPP1). A further two projects to produce methanol and DME are operational while additional initiatives under development include a second project with the Shenhua Ningxia Coal Group (NCPP2) and a possible coal-to-liquids project that would include 20 SFG-500 units, plus a major coal-to-SNG development with CPI.

5.5 Lurgi variants

The Sasol Lurgi gasification process comprises the reaction of steam and oxygen with lump sized, low or medium caking coals on a rotating grate at pressures of 20 to 30 bar, Figure 20.

In the bottom combustion zone at the grate the coal char is burned with oxygen to provide energy for the gasification reactions. As the coal moves down the reactor, it is heated by the upward-flowing syngas that leaves the gasifier. The heat causes the coal to dry followed by devolatilisation. Some of the devolatilised products escape before reacting and leave the gasifier with the raw syngas. As the devolatilised coal moves down, it is gasified with combustion products from the combustion zone below. In the dry ash mode of operation, excess steam is injected with oxygen to keep the temperature below the ash fusion temperature. A motor driven rotating ash grate is used to remove ash in a 'dry' state and also to support the coal bed (NETL, 2013a).

The countercurrent flow of gasification agent and fuel results in a high thermal efficiency of the reactor to produce a raw gas with heating values of 11 to 12 MJ/m³ (STP). Depending on the feed coal characteristics the product gas contains by volume 25–33% CO_2, 15–21% CO, 35–41% H_2 and 10–13% CH_4. For use as syngas, the methane must be removed. The high methane yield is, however, advantageous if the product is to be SNG (Reimert, 2008).

Since the 1960s, the Lurgi process has been improved through increases in reactor size and components, extension of the feed coal slate to include low rank coals, and the use of air instead of

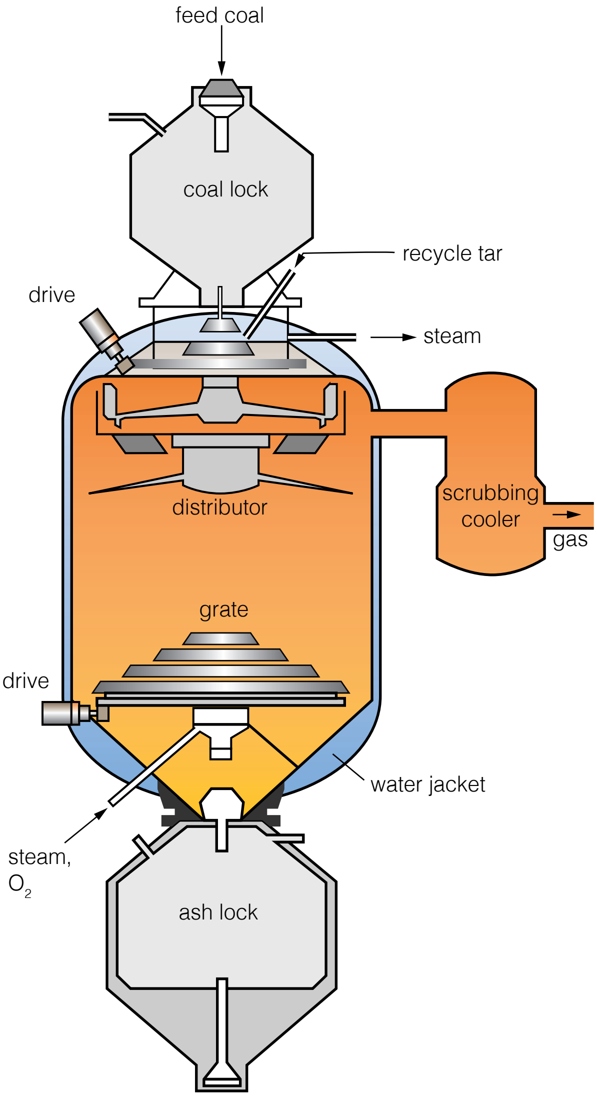

Figure 20 The Lurgi dry bottom pressurised coal gasification process (NETL, 2013a)

oxygen as the gasification agent in order to make the process attractive for use in combined cycle power generation applications. In addition, the design has been demonstrated for operation at up to 100 bar in order to increase the reactor throughput while at the same time increasing the methane content of the raw gas to be better suited for SNG production. This led to the results being used to market a 60 bar gasifier with 120,000 m^3/h syngas output (Higman, 2013).

The British Gas Corporation, in co-operation with Lurgi, developed a new design of the gasifier bottom in order to avoid the problems associated with rotating equipment in the fuel/ash bed, while simultaneously overcoming the limitation set by the ash softening temperature in the gasification zone. This resulted in the BGL slagging gasifier (Kamka and Jochmann, 2005). It is now offered by Enviroterm GmbH and the Chinese owned German company Zemag Zeitz GmbH. The gasifier differs from the standard Lurgi reactor through:

- the replacement of the grate and ash lock by a hearth for liquid slag tapping;
- the introduction of the gasification agent (oxygen and steam) by means of tuyeres instead of through the grate;
- the use of refractory lining in the lower part of the reactor body to reduce heat loss.

It also operates at higher gasification temperatures than the standard Lurgi system and, hence, the CO/CO_2 ratio in the product gas is higher and the methane content correspondingly lower. Typical gas compositions by volume are 2–3% CO_2, 55–60% CO, 25–28% H_2 and 6–9% CH_4. The high temperature provides for a better steam utilisation and, consequently, the amount of water that must be cleaned and processed is much reduced. Coal ash is converted into slag which forms a non-leachable glass on removal. This requires a low slag viscosity, which is obtained by adding fluxing agents, usually limestone or basic blast furnace slag.

To date, the take up of these technology variants in China has been comparatively limited, due in part to perceived coal selectivity and sizing issues.

5.6 SES

Synthesis Energy Systems (SES) has a worldwide exclusive licence for the U-Gas gasification technology, which is a single stage fluidised bed system that can provide a low-to-medium heating value syngas, Figure 21. It is particularly suitable for gasifying low quality fuels, including all ranks

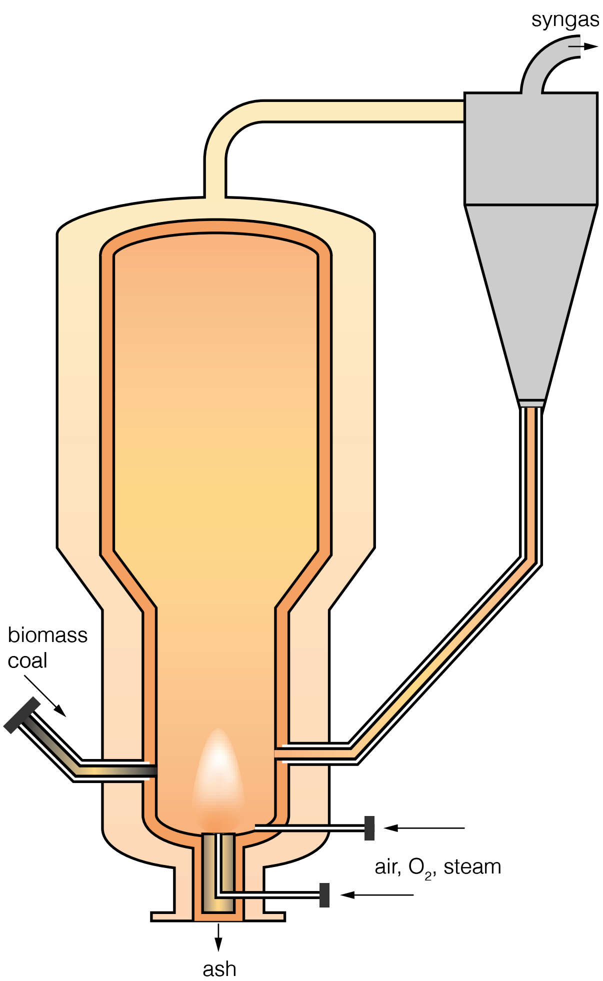

Figure 21 Schematic of the U Gas gasifier
(NETL, 2013c)

of coal, petroleum coke, biomass, and industrial wastes, fed either individually or in combination (NETL, 2013c). Dried and milled fuel is fed via a lock-hopper into the gasifier, which is fluidised by a mixture of steam and air or oxygen. These reactant gases are introduced at the bottom of the gasifier through a distribution grid, and at the ash discharge port in the centre of the distribution grid. The bed is maintained at temperatures from 840°C to 1100°C depending on the softening temperature of the ash within the fuel. At such conditions, the concentration of fuel ash (mineral content) particles within the gasifier increases such that they begin to agglomerate and form larger particles, which are selectively removed from the fluidised bed by gravity. This design allows for 95% or more of the fuel's carbon to be gasified.

SES has applied this technology for two commercially operating coal-to-chemicals projects in China, through joint ventures with local companies (SES, 2012). A third, larger project has recently been announced, which will also be implemented through a joint venture approach.

5.7 KBR TRIG

The Transport Integrated Gasification (TRIG) technology was developed by the Southern Company and KBR Inc, with some financial support from the US Department of Energy, at the Power Systems Development Facility in Wilsonville, Alabama, USA. It is designed to process reactive low rank coals, including those with up to 50% ash and high moisture content, and can be operated with steam and either air or oxygen as the gasification medium. Air-blown operation may be preferable for power generation, while oxygen-blown operation may be better suited for chemicals and fuels production (NETL, 2013c).

The system comprises a circulating gasifier, Figure 22, which consists of a mixing zone, riser, disengager, cyclone, standpipe, loopseal, and J-leg. This is designed to operate at high solids circulation rates and gas velocities, resulting in higher throughput, carbon conversion and efficiency (Greeningofoil.com, 2010). The raw syngas is formed in the riser portion of the unit, from which laden with unreacted solids it passes through a series of cyclones where the solids are removed. The ash material is recirculated through the riser to allow unconverted carbon to be utilised and to provide heat to the reactor. As ash accumulates in the down comer, it is discharged from the unit.

The gasifier operates at moderate temperatures and below the melting point of ash, which may

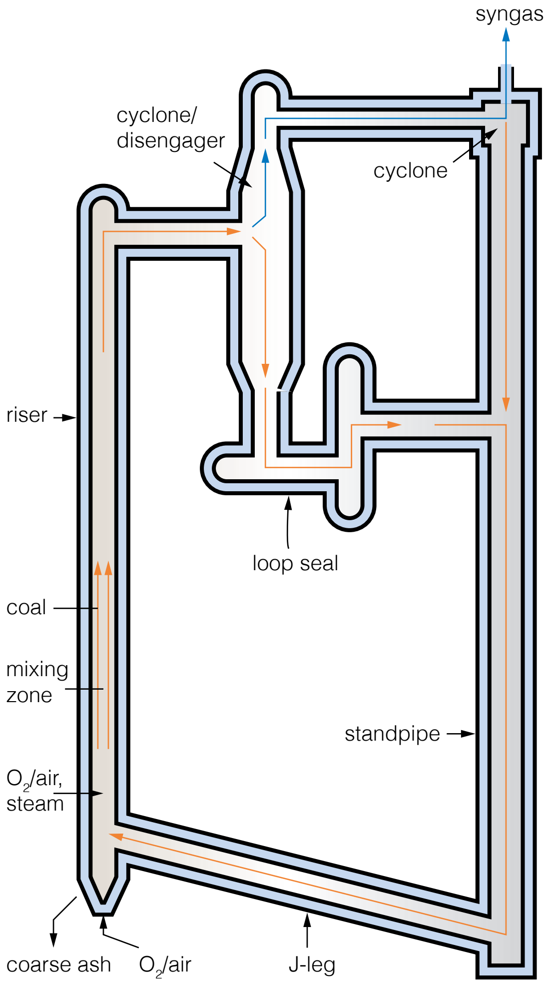

Figure 22 Simplified layout of the TRIG process (Greeningofoil.com, 2010)

increase component reliability and availability. The latter is enhanced by the use of a downstream particulate filter, which eliminates water scrubbing and significantly reduces plant water consumption and effluent discharge.

Typical syngas compositions for a Powder River Basin coal and a North Dakota lignite following gasification in an oxygen blown TRIG unit are shown in Table 11.

Following its development as a 60 t/d unit in the USA, the technology is first being applied as a retrofit to a small 110 MWe power plant operated by Dongguan Tianming Electric Power Company in Guangdong Province, China. The intention is to produce syngas that will be fired, instead of fuel oil, in the existing gas turbine combined cycle plant, with start-up scheduled for 2016. There is also an intention to modify the process so that it can also be used to gasify bituminous coals by increasing the oxygen input to raise reactor temperature and recovering heat within the reactor. It is intended to test this at the 100 t/d scale at the Yanchang Petrochemical Company in Shanxi Province (Zhang, 2013).

Table 11 Typical syngas composition at TRIG gasifier exit for two lower grade coals (KBR, 2008)

	Wyoming PRB	North Dakota Lignite
Gasifier temperature, °C	930	900
CO	39.7	35.6
H_2	28.5	25.6
CO_2	14.3	17.5
CH_4	4.3	6.1
NH_3	0.4	0.4
H_2O	12.6	14.4
N_2	0.09	0.09
Ar	0.08	0.07
H_2S	750 ppmv	2,007 ppmv
HCN	250 ppmv	274 ppmv
COS	40 ppmv	106 ppmv

Gas composition mol% (wet basis)

5.8 ECUST

The Institute of Clean Coal Technology (ICCT) at the East China University of Science and Technology (ECUST), in partnership with the Yankuang Coal Mine Group, has developed and deployed the opposed multi-burner (OMB) gasification technology (Zhou, 2012).

The primary technology variant is an entrained down-flow gasifier with a water-quench and four top-mounted, opposed fired burners that introduce the coal-water slurry with oxygen into the reactor (Figure 23). The slag is removed via a lock-hopper arrangement while other solid particles are removed from the syngas with a combination of jet mixer, cyclone and a water scrubber. The OMB technology can also be applied with a membrane wall while using a dry coal feed system (via N_2 or CO_2). Operating conditions are dependent upon the choice of either dry or wet feed, as well as the required end product, but gasifier temperature and pressures fall in the range of 1300 to 1400°C, and 1 to 3 MPa.

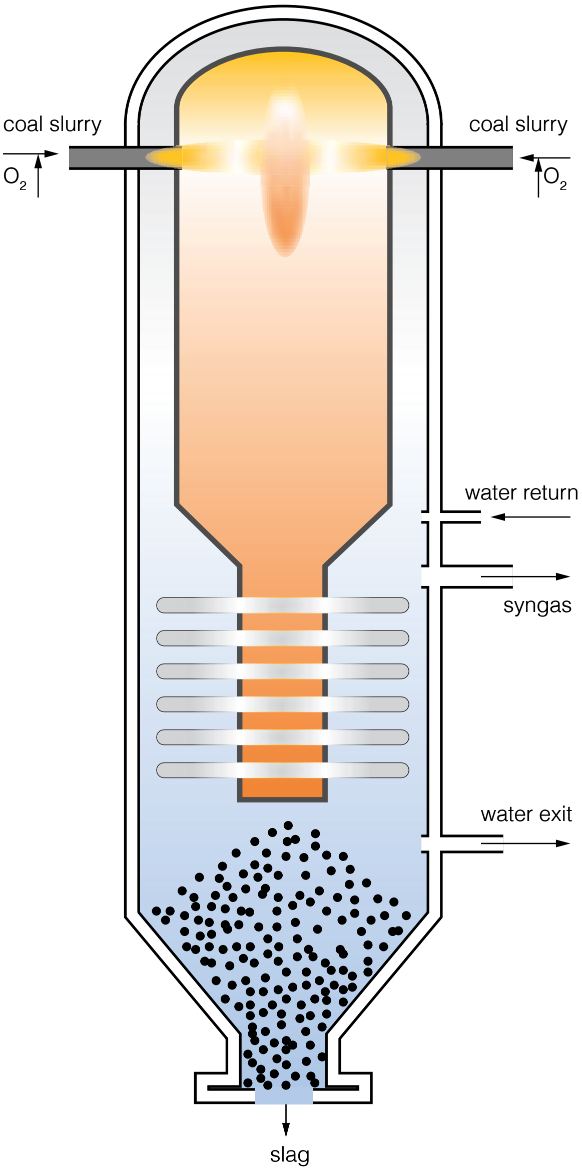

Figure 23 Schematic of the ECUST OMB gasifier (NETL, 2013b)

The development programme included a 22 t/d pilot unit that was located at the Lunan Chemical plant and by 2004 commercial-scale units were being established with the first OMB coal-water slurry commercial-scale gasifier having a coal throughput capacity of 750 t/d (NETL, 2013b) The size of such units has steadily increased, with a 3000 t/d unit now being included for a plant due to be operational in 2015. The majority of the plants produce methanol, while several produce ammonia. There are four plants that produce combinations of products, namely methanol/ammonia/hydrogen, ammonia/methanol (two plants), and methanol/power.

At the end of November 2012, ECUST had licensed its OMB coal water slurry technology to 31 end users, covering 88 gasifier units (ChinaCoalChem, 2012). The total licensed syngas ($CO+H_2$) capacity of the OMB gasifiers was 6.7 million m^3/h. On this basis, ECUST is now ranked third in the global coal gasifier vendors' market. It has also established a collaborative venture with Sinopec.

5.9 TPRI

The Huaneng Clean Energy Research Institute (HCERI) gasification technology, more commonly known as the TPRI gasifier, comprises a two-stage dry-feed, oxygen-blown, water-cooled up-flow

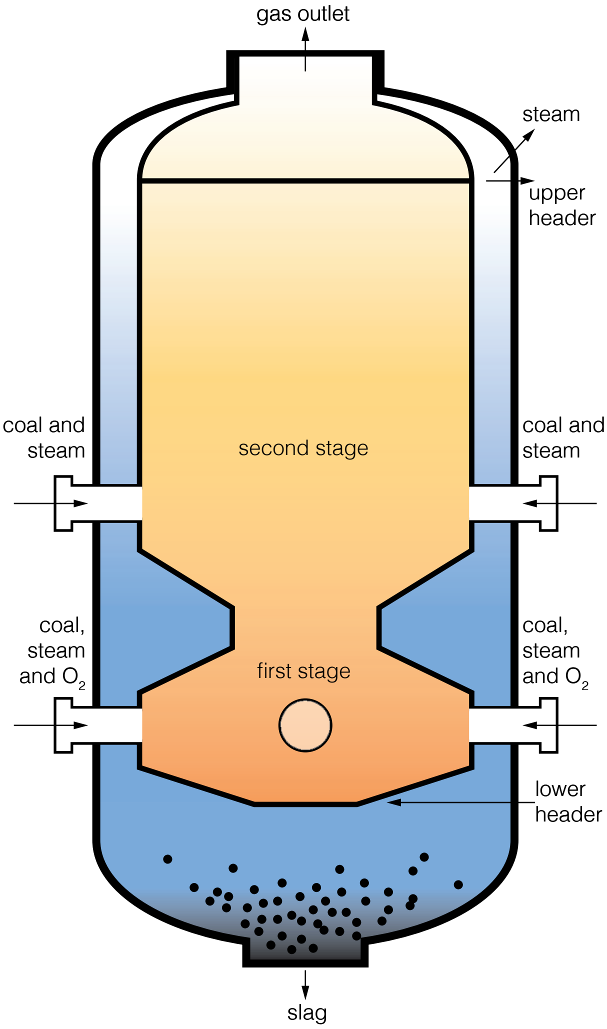

Figure 24 Schematic of the TPRI gasifier (Xu, 2007)

entrained bed reactor with a membrane wall, Figure 24. In the first stage of the gasifier, 80–85% of the coal feed is introduced where it reacts with oxygen and steam, while further steam and the remaining 15–20% of the feed coal are fed into the second stage, which operates at about 1400–1500°C. The temperature of the outlet syngas is decreased to 900°C due to the second stage's endothermic reaction, which helps the slag particles to solidify as well as improving the gasifier's thermal efficiency (NETL, 2013b). It is offered either with a syngas cooler that generates external steam or with a quench system that increases the water content of the fuel gas. The former is more likely to be used in power generation applications while the latter is appropriate for non-power applications where the additional water is used in the syngas conversion processes (Xu, 2007). Feedstocks include bituminous coals, petcoke, and low grade coals with high sulphur content.

As part of the development programme, a 36 t/d pilot plant was established to determine the gasification performance for a range of coal types. The carbon conversion rate was in excess of 98.9% with a cold gas efficiency of >83%. Typical syngas compositions are given in Table 12.

Having determined the gasifer flexibility with various coal types, the focus was then to establish Stage I of the Greengen 250 MWe IGCC project, which includes one 2000 t/d coal gasifer unit that represents a considerable scale-up from the pilot plant. Construction of the project was started in July 2009, and mechanical completion was achieved by the end of 2011. Commissioning began early in 2012 and on 7 December 2012, the plant was handed over for commercial operation in full IGCC mode (Gas Turbine World, 2012). It is understood that operation has not yet been optimised (Liu, 2013).

The gasification technology is also being used in a number of non-power applications. These include three large coal-to-methanol plants and a major coal-to-SNG plant.

Table 12 Variation in syngas composition for various coal types (Xu, 2007)

Gas composition, %	Lignite	Bituminous coal	Anthracite
CO	61.9	62.4	59.9
H_2	27.8	29.4	25.8
CH_4	<0.1	0.3	<0.1
CO_2	3.6	2.8	9.1
H_2S + COS	0.1	0.4	0.1
N_2	6.5	4.9	5.0

5.10 HT-L

The Changzhang Engineering Company, a subsidiary of the Beijing Aerospace WanYuan Coal Chemical Engineering Technology Company, owns the patents for the HT-L pulverised coal pressurised gasification process. This is an entrained flow system that was developed as a spin-off from a military technology programme. Initial gasifer size was 1500 t/d and this has since been scaled up to 2500 t/d. The first unit commenced operation in 2007 and the technology has been subsequently installed at a large number of industrial sites (Zhang, 2013).

5.11 Tsinghua University

Since 2001, Tsinghua University (the Department of Thermal Engineering) has been developing a novel gasification technology. It comprises a staged, downward-feed, entrained-flow reactor. Coal-water slurry, typically with a composition of 60wt% coal, is pumped in to the top of the gasifier through a single warm water-cooled jacket-type burner, Figure 25. The primary oxygen is blown into the reactor through the burner, while the secondary oxygen is introduced from both sides of the reactor. Such a staged oxygen supply reduces the temperatures around the burner and shifts the high temperature zone towards the centre of the reactor. It also makes the axial distribution of oxygen more homogenous and thus the cross-sectional reaction more complete. It also increases the slag temperature at the exit of the reactor, which means that coals with high ash fusion temperature can be used successfully. This increased fuel tolerance is particularly desirable for users who want to utilise low-cost indigenous low-quality coals (Yingde Gas, 2013).

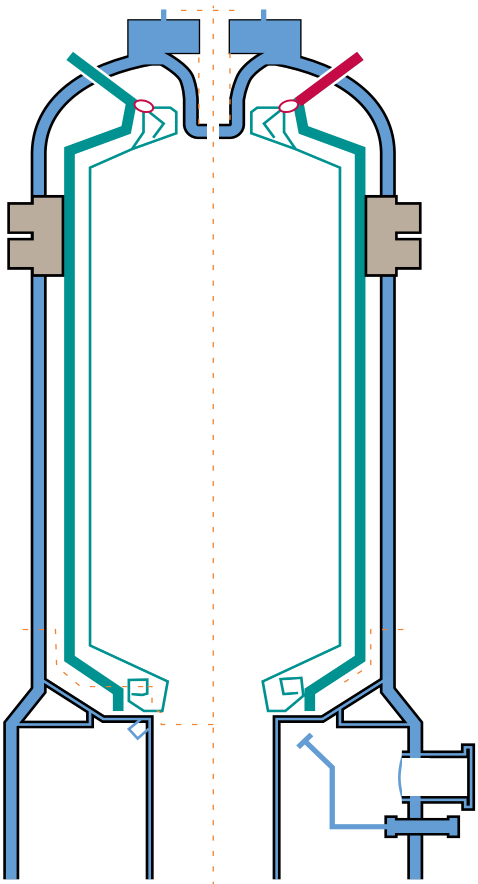

Figure 25 The schematic of the Tsinghua University gasifier (Yingde Gas, 2013)

The original design used a refractory brick lining for the gasifier. However, after six projects, the design was changed to a water-cooled membrane wall. This is designed on the basis of natural circulation and is vertically hung from the top of the reactor and can thus expand downwards when the temperature increases. It can readily accommodate gasification temperatures of 1600°C, while the size of the combustion zone is also increased compared to a refractory-lined gasifier for the same fuel loading. In addition, the sale of steam produced can bring in extra revenue while the costs associated with replacing the worn-out refractory lining can also be eliminated (Zhang, 2013).

The raw syngas carries the slag and ash particles down past the cooling ring, where the water injection reduces the temperature to ~1050°C (lower than the deformation temperature of coal), and into the quenching water pool located at the bottom of the reactor vessel. The cooled and saturated syngas then flows through a venturi washer into a scrubber for soot and particulate removal. After scrubbing, the syngas contains no more that 1 mg/m^3 of particulates and is ready for use after removal of excessive moisture. Typical syngas composition is some 45% CO, 35% H_2, 19% CO_2 and 0.1% CH_4.

The use of a slurry feed improves performance reliability, through stable fuel feeding and the avoidance of dust explosion, equipment wear and leakage. The vertically-hanging membrane wall eliminates complex thermal expansion problems, while the natural circulation ensures that the membrane wall can continue to work safely in emergencies. The system has high coal flexibility as it can operate at very high temperatures, thereby allowing for faster reaction, higher carbon conversion as well as increased tolerance for lower-quality coals with higher ash fusion temperatures. Availability is good and a single gasifier unit can operate for up to 8000 hours per year. Since the ignition and fuel feeding are integrated, it takes only three hours for a cold unit to reach full load, compared to three days typically for refractory-lined entrained flow gasifiers.

The first commercial gasification unit was deployed in Shanxi Province by the Yangmei Fengxi Fertiliser Industry (Group) Co Ltd in August 2011. In April 2012, Tsinghua University established a joint venture with China's biggest industrial gas producer, the Hong Kong-listed Yingde Gases, to market its gasification technology in China and to facilitate further coal gasification research and development. Thereafter, several licensing contracts have been signed and these include two contracts to retrofit the Tsinghua University gasifier at two fertiliser plants in order to replace the existing refractory-lined units, supplied by other vendors, which have encountered various adverse operational issues (Zhang, 2013).

5.12 ICC-CAS

In Shanxi Province, the Institute of Coal Chemistry, Chinese Academy of Sciences (ICC-CAS), in collaboration with the Jincheng Anthracite Mining Group, has developed an ash agglomerating fluidised bed coal gasification system. This comprises a fluidised-bed gasifier, with agglomerated ash separation and discharge, fly ash circulation and waste heat recovery. The ash agglomeration fluidised bed provides the means to gasify large coal particles, while any incompletely converted fine material that is elutriated in the hot fuel gas is carried over into a dense phase pneumatic conveying feed system and can be re-injected. The fuel gas from this stage, which contains small pieces of molten slag, is passed to an intersection segment of the fluidised bed. The high temperature fuel gas is rapidly mixed with the lower temperature large-particle partially carbonised coal in the fluidised bed while the ash slag is selectively discharged out of the gasifier as a solid (Institute of Coal Chemistry, 2008).

It is claimed that this technology is particularly suitable for processing high ash content (>25wt%) coal and coal with a high (>1500ºC) ash fusion temperature while achieving a high level of carbon conversion. In 2006, the ICC researchers carried out trials on a pilot plant at the Shanxi Chenggu Fertiliser Corporation's Ammonia Production Plant using an anthracite feedstock. Coal feed capacity was 60 t/d and the operating temperature was between 1020ºC and 1050ºC. They reported that the carbon conversion level reached 87%, gas yield was up to 1.8 m^3 dry gas/kg coal, with a CO plus H_2 content of up to 66% (Zhang, 2010). In order to improve gasification efficiency and capacity, a Shanxi Coal Gasification Engineering Research Centre has been set up jointly by ICC and the Jincheng Anthracite Mining Group. However, the subsequent take-up of the technology to date has been limited to relatively small plants.

5.13 MCSG

The Institute of Coal Gasification at the Northwest Research Institute of Chemical Industry in Shaanxi Province has a long history of coal gasification development. This includes the Multi-Component Slurry Gasification (MCSG) technology. This process is based on an existing oil gasification technology, with the multicomponent slurry being used to replace heavy oil for the production of syngas. The slurry comprises blends of oil and water with various materials such as coal, petroleum coke, and asphalt. Applications include coal to ammonia, methanol and hydrogen (Northwest Research Institute of Chemical Industry, 2013).

5.14 Sedin

The China Second Design Institute of Chemical Industry (usually referred to as Sedin) is a member of China National Chemical Engineering Group Corporation (Sedin, 2013). It has undertaken a range of chemicals production projects, many of which have been based on using either coke or coke oven gas as feedstocks, and more recently coal (Zhang, 2009). The latter technology is understood to be based on a fixed bed gasifier that is similar to a Lurgi design (Higman, 2013).

6 Export of Chinese technology and expertise

China has established a strong international presence in the global markets for coal mining and coal utilisation technology. To date, a combination of coal mining and coal power plant projects have either been established or are under development in over 23 countries in Africa, Asia, Eurasia, Europe, and North America (Sourcewatch, 2012).

The three major Chinese heavy engineering equipment manufacturers, in Shanghai, Harbin and Dongfang, are world leaders in the production of advanced coal-fired power plant, with production facilities meeting international standards. They are supported by various Chinese industrial engineering procurement and construction companies and can, for example, supply both subcritical and advanced supercritical coal-fired boilers together with other power plant components. They can offer a significant cost advantage compared to OECD suppliers, together with the provision of strong financing arrangements (Minchener, 2010).

These companies and others also supply large-scale coal gasifier units, at present primarily for use within China. However, as it continues to expand its non-power coal-based gasification technology deployment, China would also appear to be well-placed to exploit various gasification subsectors overseas, including coal-to-chemicals and IGCC should its ongoing development programme for the latter option prove successful. That said, while there is an increasing emphasis on the use of domestic designed coal gasification plant, there continues to be a very significant input from foreign technology suppliers for equipment such as large-scale high efficiency air separation units together with downstream syngas processing stages and the associated catalysts. These companies include Air Products, Air Liquide, Davy, Siemens, General Electric, Shell, and the Linde Group. In some cases these include arrangements where foreign companies will undertake build, own and operate (BOO) contracts (FT, 2013).

External exploitation of coal gasification is so far comparatively limited, due to the focus on domestic applications. However, there are some significant activities.

On 31 July 2008, ECUST licensed its technology to Valero Energy in the USA for use in a 2500 t/d petcoke gasifier H_2 production project. This was followed on 26 March 2009 by TPRI, which licensed its two-stage pulverised coal gasification technology to US Future Fuels Technology LLC and its subsidiary, Future Power PA Inc, with its expected application for IGCC projects in the USA and China.

Besides the activities in Vietnam and the Ukraine referred to in Chapter 3, as a further example of China exploiting its financial strength and EPC expertise, the Summit Power Group in the USA has signed an agreement with the Sinopec Engineering Group for the latter to handle the engineering, procurement and construction of the Texas Clean Energy Project, while the Export-Import Bank of China will serve as sole financial lender to the project. The Texas Clean Energy Project will be a large-scale coal gasification plant near Odessa that will capture 90% of its CO_2 for use in EOR in the Permian basin of West Texas. The plant will also produce more than 635 kt of urea each year and will supply 200 MWe to CPS Energy, San Antonio's municipal electric and gas utility. The plant is expected to begin operation by 2017 (American Fuels Coalition, 2012f).

7 Conclusions

7.1 Strategic considerations

For those developing countries that have large coal reserves and either limited or high-cost crude oil and natural gas deposits, gasification-based coal conversion technology offers significant potential for the production of chemicals, gaseous and liquid fuels, at a time when there is increasing global demand for such products. In particular, this approach offers the opportunity to monetise low grade coals, which are cheap and abundant with limited alternative uses available. However, the realisation of that potential is problematic, both for those with very low national GDPs and those that are already showing considerable industrialisation. At this time, take-up of the technology is very limited except in the cases of South Africa and China. That said, there does now appear to be a large number of initiatives being developed, which might suggest a shift in economic sensibilities, although it remains to be seen whether the barriers can be surmounted.

For several developing countries with low per capita GDPs, coal conversion looks particularly attractive in that they are beginning to exploit their large coal resources and international co-operation via bilateral and/or multilateral arrangements is under way, with mining groups and other industrial developers becoming active. However, it is also evident that the gestation period for both mining and coal conversion projects can be very long and their sustainable success will be dependent on the governments having a clear strategic view supported by favourable policies and complementary legal and regulatory frameworks. At the same time, there is little institutional capacity regarding technology deployment and application, as well as minimal industrial infrastructure to get the end products either to locations where they can be used internally or to ensure export opportunities.

In practice, this means these countries will need very significant international financial support to establish such major projects, and to attract international developers to implement them as the overall requirements will be much greater than just the coal-to-chemicals/CTL plant. It is also very important that such actions should be supported with various capacity building activities such that the people of these countries can have a stake in these projects, with the wealth produced being used in part to support education, better healthcare and employment. This offers the prospect of resource exploitation being used to help establish a sustainable approach within such countries.

For those countries that might better be described as industrialising nations, with middle ranking per capita GDPs and which are establishing industrial infrastructures at varying speeds and to varying degrees, some opportunities are being taken forward. However, in many cases the lack of a clear and comprehensive government vision regarding energy resources exploitation, which can be compounded by a lack of effective industrial application by state-owned companies, is hindering progress. This will deter inward investment. In addition, those countries that have large oil and gas reserves will tend to focus any investments on their further exploitation rather than get involved in seemingly more complex coal related projects.

7.2 Candidate countries for coal-to-chemicals, gaseous and liquid fuels projects

This review has suggested that some fifteen developing and industrialising countries, on four continents, have reasonable prospects for establishing gasification-based coal conversion to chemicals, gaseous and liquid fuels projects. However, with a changing and uncertain investment climate, such prospects may not be taken forward.

South Africa is the leading global exponent for gasification-based CTL worldwide, with plans to expand its operations, and is in a strong position to influence developments in the region. Elsewhere in Africa, the more promising developing country is Mozambique where projects for the mining and export of high quality coal are under way although progress is hampered by the lack of viable land transport and shipping infrastructures. Should these problems be solved, the introduction of CTL plants would appear to offer a complementary approach by monetising the mining and coal preparation wastes to produce liquid fuels for which there are both internal and export markets. Botswana and Zimbabwe, while having adequate coal reserves, show less promise, as there are no firm government drivers for such an industrial approach. However, the discovery and intended exploitation of large offshore natural gas deposits, including those close to Mozambique, are likely to make coal conversion investments less attractive.

In Asia, leaving aside China which is a special case that is considered below, the most promising country is Mongolia, which has adequate low grade coal and water supplies, and a clear internal market need for CTL. However, a key issue may be the financial requirements, which would be significant compared to national GDP and would have to cover the transportation infrastructure as well as the actual CTL plants. At present, Mongolia is seen as a risky investment option although these problems relate to coal production for export rather than coal utilisation opportunities. Elsewhere, Vietnam shows promise with one coal-to-chemicals plant under way, while UCG is being considered although developments are at an early stage. Pakistan has a massive low grade coal deposit but the government is showing little coherence regarding its exploitation and consequently, despite considerable international interest initially, there is minimal positive activity. In principle, Indonesia should be a good option for lower grade coal gasification and projects have been proposed. However, the lack of a clear government vision and policies that do not encourage implementation do not make this an attractive investment option. Finally, India should be seeking to establish coal gasification including UCG. However, the lack of positive policies and the use of ineffective state-run industries in the past to try and implement some initiatives have prevented any significant activity being established. There is some evidence that the situation might be changing with a few coal-to-chemicals projects starting to be developed by private companies. However, the enormous potential in India is very far from being realised.

In Eurasia, there are five countries with potential. Of these, in Russia and Kazakhstan, the investment focus is on oil and gas for export opportunities and so coal gasification is not a priority. In the Ukraine, there are very strong prospects for coal-to-SNG as a means to enhance energy security and the first project is being developed, implemented and financially underpinned by China. In Turkey, due to the extensive low grade coal available and the attractiveness of distributed power generation, there is considerable activity, including state-led R&D and several intended industrial projects involving Turkish stakeholders and international vendors. Finally, in Uzbekistan, there is the world's first and long-standing UCG project, which provides syngas for use in a power plant. Despite its technical success, there are no immediate plans to develop such projects further.

In South America, the only country with some potential is Brazil due to its large deposits of low grade coal. However, coal-based projects do not fit readily with the Government's focus on oil, gas and renewable energy options. Consequently, to date, activities have been limited to proposals to develop a clean coal roadmap through to 2030.

7.3 The role of China in the global coal conversion sector

Globally, the country that dominates coal gasification is China. It is a medium level developing country but is also a very large industrialising nation, with fossil energy resources that are dominated by coal. It is also at a stage in its development cycle where there is an increasing need for the use of cleaner energies and their derivatives. Coal conversion via gasification can transform coal into both fuels and chemicals, and offers a means by which it can reduce both its conventional (non-GHG) emissions as well as its reliance on imported oil and natural gas.

At the same time, as well as clean energy use, its national government has a further strategically important sustainability target, namely to cut CO_2 emissions. As part of its national plan to meet both these goals, in recent years, China has increased investment in nuclear power, hydroelectric power, natural gas, solar energy, and wind power (Xinhuanet, 2012). Nevertheless, coal will remain the major energy source for the foreseeable future and, with the development of new technologies, coal gasification could be a significant part of the nation's clean energy initiative.

Initially, from an energy security standpoint, China identified a strategic need to diversify the means to produce petrochemical products and has taken a global lead in establishing gasification technology to use coal as a feedstock for chemicals and fuels production. Its efforts first focused on the production of ammonia for fertiliser production and methanol either as a possible fuel or as an intermediate feedstock for materials such as DME. This initiative continues to be important, and in particular there is a major drive to establish coal-to-SNG processes while it seems probable that the scale-up of various coal-to-oil technologies may move forward. However, equally importantly, there has been a move to apply coal gasification for the production of olefins as a means to establish higher value-added markets for plastics and fibres. Alongside these scale-up and new market activities, there is a continuing assessment of other coal-to-chemicals techniques, with research and development of coal-to-glycol and coal-to-aromatics processes under way.

In order to develop its sustainability agenda, the NDRC has demanded centralised approval for new coal conversion projects and has introduced various constraints regarding water use, energy efficiency and environmental protection, including the capability to be able to address CO_2 emissions in due course. It is also looking to limit possible future vulnerability to lower cost imports for some products. The expectation is that within the 12th FYP it will take further steps to limit any expansion of the lower end coal-to-chemicals processes. At the same time, it will encourage scale up and upgrades of the higher value and more complex processes that provide organic materials, resins, synthetic fibres and monomers.

This will be complemented by the closure of those companies and industries with low production efficiency and high-energy consumption (KPMG, 2012), as part of the plan to meet new and more restrictive standards concerning the consumption of water and energy, and CO_2 emissions,

It is also strategically significant that Chinese companies are investing overseas where acquisitions will give them access to more sophisticated product lines, which can be used to meet their domestic market demand (KPMG, 2012; China Greentech Initiative, 2012).

Consequently, China offers a template for large-scale coal-to-chemicals, gaseous and liquid fuels deployment, for all stages of the industrial development cycle. It has shown what can be achieved from a technical standpoint while demonstrating, as technology familiarisation has been achieved, that there are various routes that can then be followed to ensure acceptable economic performance becomes a key factor. It is evident that in China there will continue to be major opportunities for the deployment of large-scale coal gasification technologies, various syngas conversion units and catalysts for the subsequent production of the required products. There will also be a strong market for the cost-effective deployment of water-saving and wastewater treatment technologies. Such activity will provide a significant stimulus to GDP growth at a time when export opportunities in other sectors may not be as strong as in the previous FYP period.

The Chinese experience continues to demonstrate the importance of the development and strong enforcement of supportive policies and regulations. That said, on a cautionary note, the ongoing disconnection between national plans for the coal conversion industry and the overambitious and unrealistic plans set out by the provincial governments remains a major potential issue. While the central government has put in place various incentives to ensure national compliance, it remains to be seen how these important energy and environment initiatives will proceed during this and the next FYP period. If the provincial governments are not controlled there is a severe risk of output outstripping demand, leading to economic problems as well as posing environmental risks (China Greentech Initiative, 2012).

China is also beginning to seek export opportunities for its own gasification technologies as well as seeking to establish a major engineering, procurement and construction role on overseas projects, where it has in some cases licensed technology from international suppliers. Indeed the role of China is likely to be critical in establishing coal conversion projects in certain developing countries as it can provide the technical expertise and financially underpin such projects, including the associated infrastructure needs, which becomes a very competitive option. There may well be trade-offs in such activities as China seeks to establish a commercial technology presence while at the same time is keen to obtain overseas resources to support its national energy needs.

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