Non-fuel uses of coal

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Preface

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

IEA Clean Coal Centre is an organisation set up under the auspices of the International Energy Agency (IEA) which was itself founded in 1974 by member countries of the Organisation for Economic Co-operation and Development (OECD). The purpose of the IEA is to explore means by which countries interested in minimising their dependence on imported oil can co-operate. In the field of Research, Development and Demonstration over fifty individual projects have been established in partnership between member countries of the IEA.

IEA Clean Coal Centre began in 1975 and has contracting parties and sponsors from: Australia, Austria, Brazil, Canada, China, the European Commission, Germany, India, Italy, Japan, New Zealand, Russia, South Africa, Thailand, the UK and the USA. The Service provides information and assessments on all aspects of coal from supply and transport, through markets and end-use technologies, to environmental issues and waste utilisation.

Abstract

Industrial products and carbon-based materials such as basic chemicals, plastics and fibres are currently derived mostly from petroleum and natural gas. Materials and chemicals from coal are recognised as an important, practical and profitable source, especially in countries with large coal reserves. Therefore products from coal are an area for further coal utilisation, research and development mainly in these countries. The traditional source of coal chemicals, tars or liquids from by-product coke ovens, has steadily decreased in the last decades. However, there are opportunities for new applications and markets for coal chemicals through gasification. Liquefaction is in general used to produce other types of fuel, for example, for transportation and residential use. Technologies for converting coal-to-chemicals such as methanol-to-olefins (MTO), methanol-to-propylene (MTP), mono-ethylene-glycol (MEG), dimethyl ether (DME) and other chemicals are currently being demonstrated and proving efficient, reliable and profitable. Nonetheless, among the many issues facing the non-fuel uses of coal are capital investments, process technological issues, processing costs and environmental policy and impact. Furthermore, high water consumption and CO_2 emissions in coal-to-chemicals processes can play a major role in deciding whether to construct such facilities or not. Application of new technologies for coal-based chemicals is currently mainly in China.

Acronyms and abbreviations

AA	acrylic acid
AC	activated carbons
ACN	acrylonitrile
API	active pharmaceutical ingredients
bbl	barrel
BDO	butanediol
BSNABC	Beijing Shennong Kexin Agribusiness Consulting Co. Ltd. (China)
Bt	billion tonnes
BTX	benzene, toluene and xylene(s)
CaC_2	calcium carbide
CAER	Center for Applied Energy Research (UK)
CAGR	compound annual growth rate
CCRI	China Coal Research Institute (China)
CCS	carbon capture and storage
CCTEG	China Coal Technology & Engineering Group (China)
CIAB	Coal Industry Advisory Board (France)
CMS	carbon molecular sieves
CO	carbon monoxide
CO_2	carbon dioxide
CPCPC	Consortium for Premium Carbon Products from Coal (USA)
CS_2	carbon disulphide
COS	carbon oxysulphide
CRI	China Research and Intelligence Co. Ltd (China)
CTL	coal-to-liquids
CTO	coal-to-olefins
DEG	diethylene glycol
DME	dimethyl ether
DMTO	Dalian methanol-to-olefin technology (China)
EIA	Energy Information Administration (USA)
FT	Fischer-Tropsch
Gt	gigatonnes
H_2S	hydrogen sulphide
IAGS	Institute for the Analysis of Global Security (USA)
IDA	International DME Association (USA)
IFA	International Fertilizer Industry (France)
IEA	International Energy Agency (France)
LPG	liquefied petroleum gas
MEG	mono-ethylene-glycol
MTBE	methyl tertiary-butyl ether
MTO	methanol-to-olefins
MTP	methanol-to-propylene
MTX	toluene methanol methylation to xylene
NETL	National Energy Technology Laboratory (USA)
NDRC	National Development and Reform Commission (China)
PH	polyoromatic hydrocarbons
PE	polyethylene

PET	polyethylene terephathalate
PP	polypropylene
PVC	poly vinyl chloride
RMB	Reminbi
SG	synthetic gas (syngas)
SHMTO	Shenhua Group methanol-to-olefin technology (SHMTO) (China)
SNG	synthetic natural gas
SO_2	sulphur dioxide
TEG	triethylene glycol
UCG	underground coal gasification
US DOE	United States Department of Energy
VAM	vinyl acetate monomer
VCM	vinyl chloride monomer
WCA	World Coal Association

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1 Introduction

Coal has been historically an important feedstock for the production of chemicals requiring carbon-based raw materials. In the mid-20th century, oil and natural gas gradually displaced coal as the primary source of feedstock for the chemical industry. However, in recent years, the volatility in oil and natural gas prices and security of supply issues have renewed interest in coal as a source for feedstock. Coal comprises 60% of global energy resources (*see* Figure 1). It is a fuel used in many sectors throughout the world. Converting it into viable products can be categorised into three main areas, power production, fuels and chemicals. The most significant uses of coal are in electricity generation, steel production, cement manufacturing and as a liquid fuel. Approximately, 6.6 Bt (or 6.6 Gt) of hard coal and 1 Bt (or 1 Gt) of brown coal were used worldwide in 2012. Since 2000, global coal consumption has grown faster than any other fuel. The five largest coal users are China, USA, India, Russia and Japan, accounting for 76% of total global coal use (WCA, 2013). For coal utilisation in power generation and fuels visit www.iea-coal.org

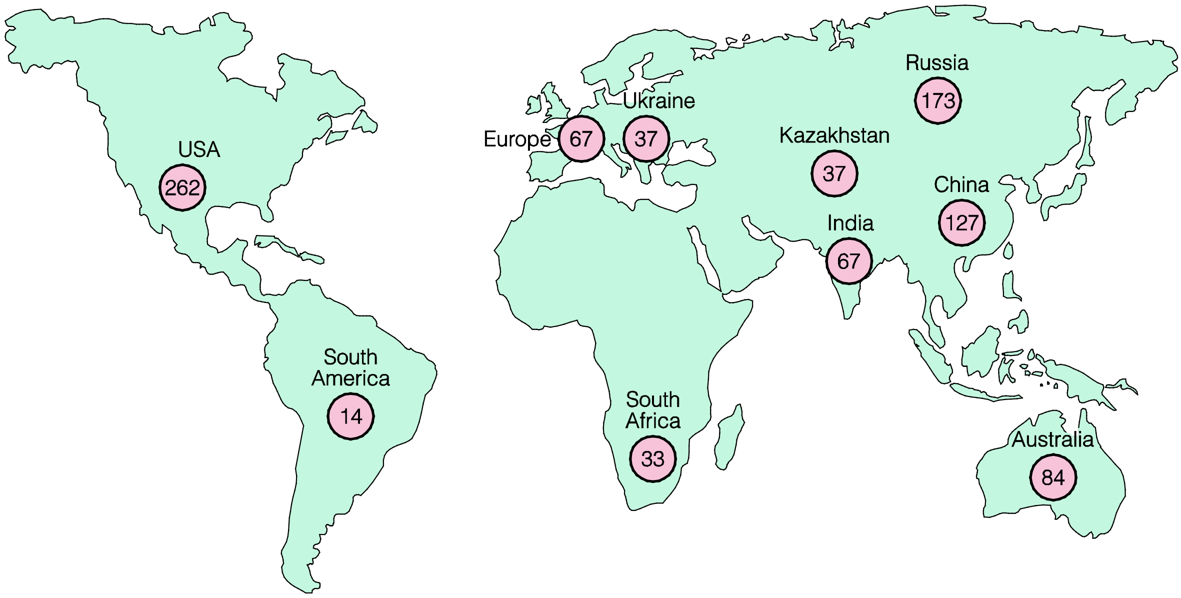

Figure 1 – Share of coal in the global energy resources (Palmer, 2013)

Other users of coal include alumina refineries, paper manufacturers, and the chemical and pharmaceutical industries. Non-fuel uses of coal include chemical products such as refined coal tar which is used in the manufacture of chemicals, for example creosote oil, naphthalene, phenol and benzene. Ammonia gas recovered from coke ovens is used to manufacture ammonia salts, nitric acid and agricultural fertilisers. Thousands of different products have coal or coal by-products as a component. These include soaps, aspirins, solvents, dyes, plastics and fibres, such as rayon and nylon. Coal is also an essential ingredient in the production of specialist products including (WCA, 2013):

- Activated carbon – used in filters for water and air purification and in kidney dialysis machines.

- Carbon fibre – an extremely strong, but light weight reinforcement material used in construction, fishing rods, golf clubs, mountain bikes, tennis rackets and some motorbikes.
- Silicon metal – used to produce silicones and silanes which in turn are used to make lubricants, water repellents, resins, cosmetics, hair shampoos and toothpaste.

An important reason for increasing interest in coal as a source of chemicals is feedstock security especially in regions with high recoverable reserves of coal and greater dependence on imported oil and/or gas. The list of potential chemicals that can be derived from coal is almost boundless, given that coal provides both the hydrogen and carbon needed for petrochemical production (Nexant, 2010).

Polygeneration or the co-production of power, fuels and chemicals from the same facility is under active consideration. This involves gasifying the coal or other fuels to produce syngas. A portion of the syngas is converted to high-value products such as liquid fuels, gaseous fuels and chemical products. The remainder is combusted to generate electric power. The relative amounts of syngas used for power generation or used for conversion to fuels and chemicals is dependent on market demands. This enables the facility to make more efficient use of the feedstock and maximise revenue streams (US DOE, 2001). Polygeneration will not be discussed in this review. Carpenter (2008) has recently reviewed issues relating to polygeneration from coal.

The chemical processing of coal and coal-derived substances for making carbon materials and organic chemicals was the subject of an IEACCC review by Song and others (2005). The report focuses on both the unique, premium carbon products as materials and the phenolic and aromatic compounds that can be converted to value-added organic chemicals. It targets an audience that makes use of structural features of coal, rather than alternative chemicals that are already produced from petroleum and natural gas as commodity chemicals in large quantities in industry worldwide. This review discusses the general non-fuel uses of coal including replacing crude oil and gas in the production of chemicals from coal. The ways in which coal may be converted to chemicals include carbonisation, gasification followed by conversions of the synthesis gas (syngas) and liquefaction/hydrogenation. These are discussed in Chapter 2. In Chapter 3, the non-fuel uses of coal are presented. Commercial application and economics of coal conversion to chemicals are discussed in Chapters 4 and 5.

Materials and chemicals from coal are recognised as important, practical and profitable products especially in countries with little or no oil and/or gas resources and therefore are an area of increasing interest and for future coal utilisation research and development.

2 Coal conversion process

The three main processes of coal conversion to products in the chemical industry are carbonisation, gasification and liquefaction. Figure 2 is a simplified flowsheet of the coal transformation routes (Minchener 2011, Deutsche Bank, 2007).

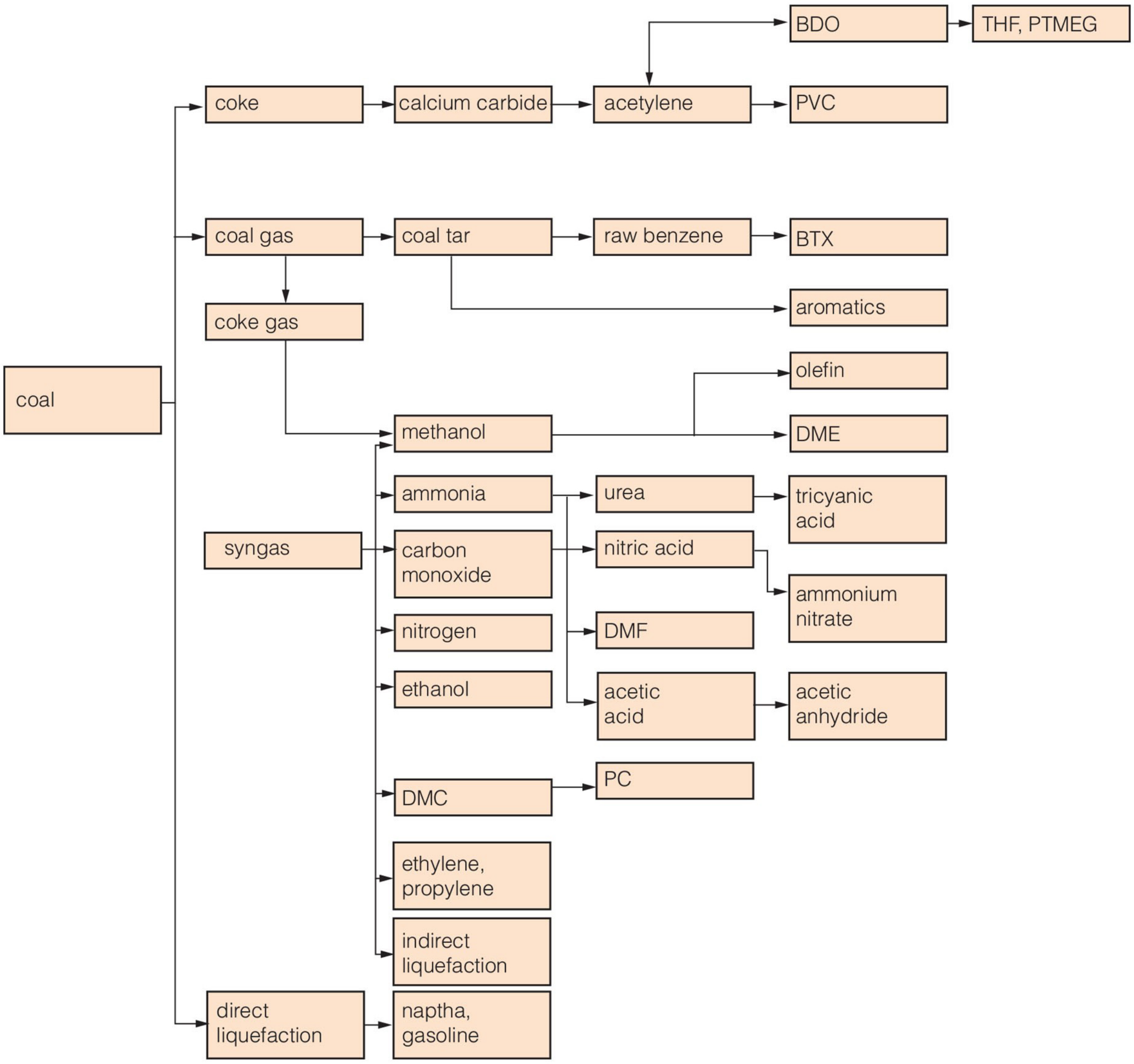

Figure 2 – Simplified flowsheet of the various coal transformation routes (Minchener, 2011; Deutsche Bank, 2007)

2.1 Coal carbonisation

Coal tar is a principal liquid product resulting from the carbonisation of coal, that is, the heating of coal in the absence of air in a coking oven, at temperatures ranging from about 900°C to 1200°C (1650°F to 2200°F) (Speight, 2013; Worsham, 2010). Coal tar, coal tar pitch and coal tar creosote are similar mixtures obtained from the distillation of coal tars. Coal tars are by-products of the carbonisation of coal to produce coke and/or gas. They are complex combinations of polyaromatic hydrocarbons (PAHs), phenols, heterocyclic oxygen, sulphur and nitrogen compounds. Coal tar creosotes are distillation products of coal tar. They consist of aromatic hydrocarbons, anthracite, naphthalene and phenanthrene derivatives. Approximately 75% of the coal tar creosote mixture is PAHs and their methyl and polymethyl derivatives, and heteronuclear compounds. Speight (2013) defines the term 'tar' as usually applying to the volatile and non-volatile soluble products that are produced during the carbonisation or destructive distillation (thermal decomposition with the simultaneous removal of distillate) of various organic materials including coal. Furthermore, distillation of the tar yields an oil (volatile organic product often referred to as benzol or benzole, which is an impure form of benzene, toluene and xylene (BTX) and other hydrocarbons, and a non-volatile pitch. Benzene is used in the manufacture of numerous products including nylon, gammexane, polystyrene, phenol, nitrobenzene and aniline. Toluene is a starting material in the preparation of saccharin, trinitrotoluene and polyurethane foams. Xylenes mixtures can be marketed as specialty solvents (Speight, 2013). Coal tar chemicals production from low-rank coals using mild-temperature pyrolysis was the topic of a study by Skov and others (2007).

At the first stage, coal is heated to 350°C to 450°C when the grains of coal soften and form a continuous and viscous plastic layer. Volatile components of the coal in the form of low-temperature or primary tar are released from the heating coal. As they ascend through the hot coke, chemical reactions governed by temperature and contact time occur, creating high-temperature coke-oven tar, other by-products, and coke-oven gas. These carbonisation products collect above the charge in the coke oven and exit the oven through a standpipe to the collector main en route to the by-products plant. Carbonisation is complete when heat transfer causes the two plastic layers to meet at the oven centre-line, the resultant mass being the hardened open structure of coke. This hot mass, between 1000°C to 1100°C, is pushed from the oven and quenched (Reeve, 2000). Yield would be typically about 60 kg coal tar per tonne of coal. A typical coal tar composition would be as follows (Reeve, 2000):

- light oil, up to 200 °C, 5% (benzene, toluene, xylene, heavy solvent naphtha);
- middle oil, 200–250 °C, 17% (tar acids: phenol, cresols, xylenol, higher tar acids; tar bases: pyridine, heavy bases, naphthalene);
- heavy oil, 250–300 °C, 7% (methyl-naphthalene, dimethyl-naphthalene, acenaphthene);
- anthracene oil, 300–350 °C, 9% (fluorene, phenanthrene, anthracene, carbazole); and
- pitch, 62%.

Higher boiling fractions of the distillate from the tar contain pyridine bases, naphtha, coumarone resins, quinoline, isoquinoline and quinaldine. Pyridine is used in the production of rubber chemicals, textile water repellent agents and in the synthesis of drugs. For greater detail *see* Speight (2013).

Gas separated from the tar has to be treated to remove substances such as ammonia, hydrogen sulphide (H_2S), light oil, and naphthalene. Coke oven gas also contains a variety of organic sulphur compounds including carbon disulphide (CS_2), carbon oxysulphide (COS), and mercaptans. The composition of a typical treated coke oven gas is given in Table 1, most important components include hydrogen, methane, and carbon monoxide.

Table 1 – Composition of a typical coke oven gas (Reeve, 2000)

Composition	Volume, %
Hydrogen	57
Methane	29
Carbon monoxide	5.8
Ethylene	2.5
Carbon dioxide	1.5
Ethane	1.35
Hydrogen sulphide	0.7
Light oil	0.5

As shown in Figure 3, typical yields from high temperature carbonisation of bituminous coking coals are 70% solid products and 30% gaseous and liquid products. The yield of coal tar (liquid product) from a tonne of coal is 33.50 litres, which is about 3–4 wt% based on coal (Song and others, 2005). Tars (3–4% of coal wt), according to Samuel and others (2008), are considered the most generally known source of chemicals from coals. Coal tar components have been used as raw materials for the production of dyes, plastics, synthetic fibres and pharmaceuticals and solvents. The tars and their distillates fractions are complex mixtures of hundreds of individual compounds, *see* Figure 4. Separation and purification of these from coal tar fractions are therefore also complex. Coke production and the impact of environmental legislation was the subject of a review by Reeve (2000). One tonne of coal will yield approximately the following yields of coke and coal chemicals (Reeve, 2000):

- blast furnace coke, 750.80 kg;
- coke breeze (large coke particulates) 45.90 kg;
- coke oven gas, 285.345 m^3;
- tar, 27.34 litres;
- ammonium com pounds, 7.9 kg;
- ammonia liquor, 55.135 litres; and
- light oil, 8.12 litres.

Charcoal is the solid carbon residue following the carbonisation of coal which can be used as raw material in the fabrication of briquettes. According to Speight (2013), charcoal manufacture is also used in forest management for disposal of refuse.

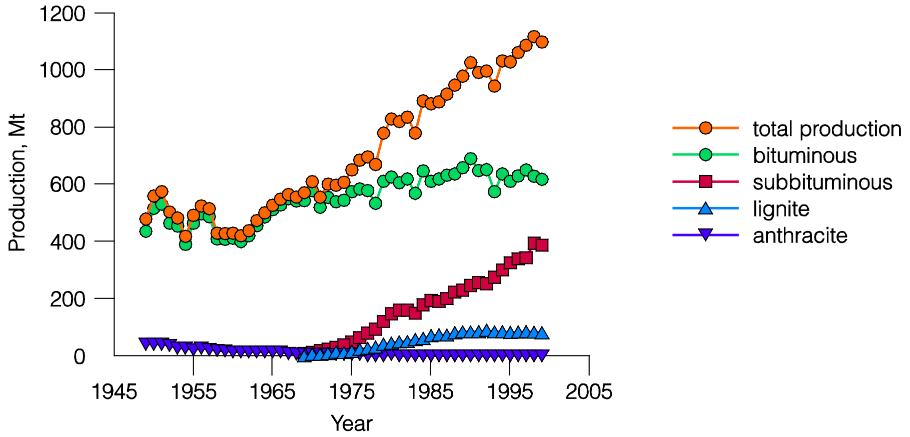

Figure 3 – Yields of products from coal carbonisation in coke ovens for making metallurgical coke (Song and others, 2005; Baron and others, 1998)

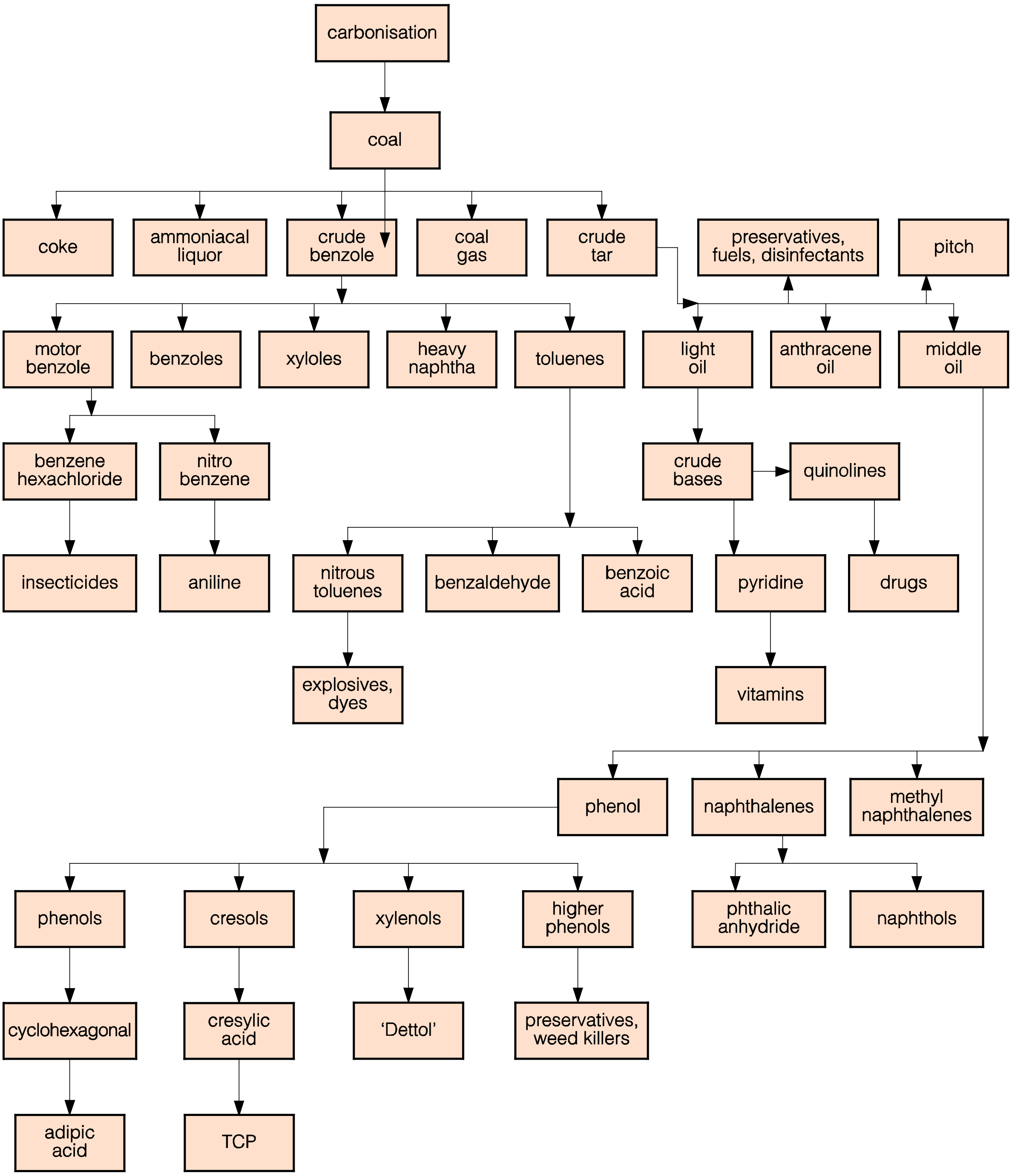

Figure 4 – General pathways for production of some chemicals through pyrolysis of coal (Samuel and others, 2009)

In 2008, coal tar pitch and bituminous coal used for coke making were major feedstocks for coal-based carbon materials. Samuel and others (2008) forecast that heavy liquids from coal liquefaction and low temperature pyrolysis tars and coals of all ranks can become further feedstocks. Adsorbent carbons for water/air purification, medical applications and developing carbon molecular sieves would be the main uses from such feedstock. In 2008, Samuel and others estimated that coal used worldwide for the production of activated carbons and carbon molecular sieves was about 200,000 t/y and 3000 t/y respectively. Graphite and other advanced carbon materials offer a new market opportunity for anthracite. However, this would require the development of schemes to replace petroleum products thus adding significant value to and creating demand for anthracite. Replacing 25% of petroleum coke would create a market of 1.5 Mt for anthracite (Samuel and others, 2008). Guo and others (2013) discuss the development and experimental work on products derived from coal tar pitch for use as anode material in lithium ion batteries.

2.2 Coal gasification

Coal gasification offers a versatile and clean method of converting coal into not only electricity but also hydrogen and other valuable products. Gasification, which is a thermo-chemical process, breaks down the coal into its basic chemical constituents. In modern gasifiers, coal is typically exposed to steam and carefully controlled amounts of air or oxygen under high temperatures and pressures. Under these conditions, molecules in coal break apart, initiating chemical reactions that typically produce synthesis gas (syngas), hydrogen (H_2), carbon monoxide (CO) and other gaseous compounds. Advantages of gasification include (Liu, 2012):

- product flexibility: a variety of commodities can be produced from the syngas including methanol and ammonia which are key building blocks for further chemical synthesis,
- low emissions: gasification produces lower emissions due to the high temperatures and pressures used to produce the syngas,
- feedstock flexibility: gasification plant designs have been developed to accommodate various grades of coal including lignite, and
- high efficiency: steam produced by a gasification process can be effectively integrated to meet the needs in a chemical plant.

The process options for coal gasification can generally be divided into four categories based on reactor (bed) configuration, fixed bed, fluidised bed, entrained bed and molten salt. Speight (2013) discusses these processes in detail. Chemicals can be produced from the three principal products of coal gasification (syngas, hydrogen and carbon monoxide). These can be used as chemical 'building blocks' for a wide range of commercial products. Figure 5 illustrates utilisation options for coal-derived syngas that can be further converted into marketable products including chemicals (Nexant, 2010). Fundamentals of coal gasification are not discussed in this review. For further and detailed information on coal gasification *see* coal online and other publications at www.iea-coal.org. For details on coal-to-chemicals gasification processes, advantages, challenges and experience visit www.netl.doe.gov (NETL, 2013).

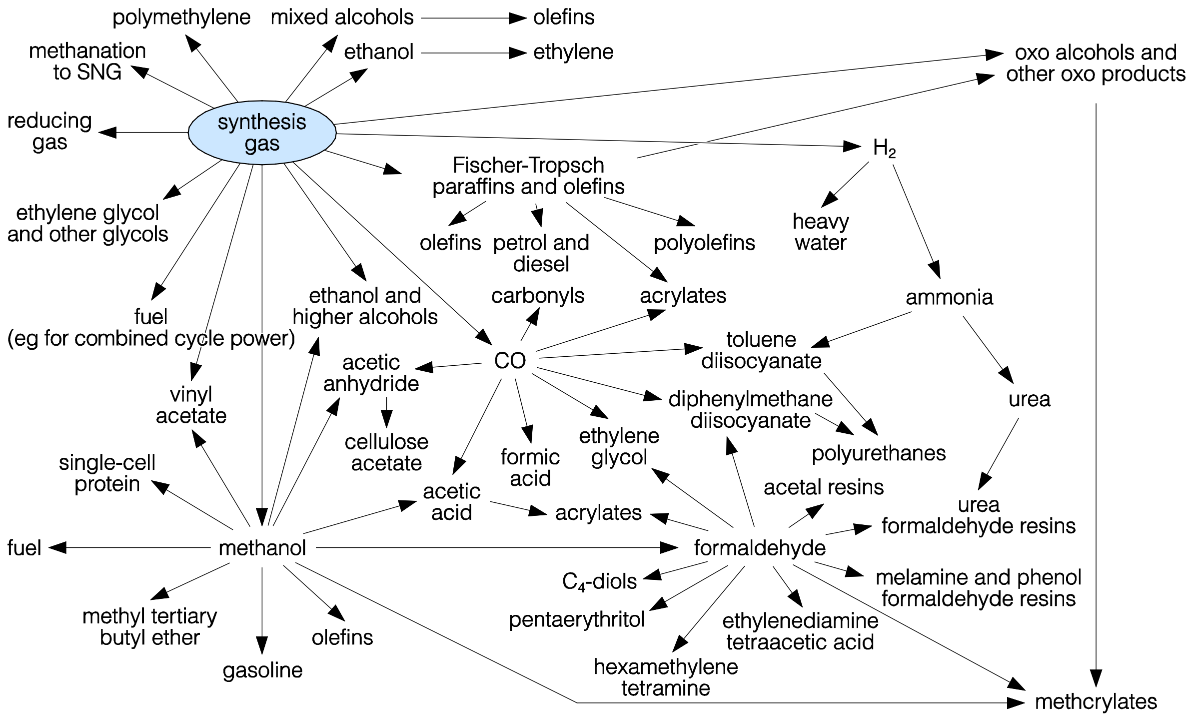

Figure 5 – Routes to chemicals from methane via synthesis gas (syngas) (Speight, 2013)

Gasification has been used in the chemical industry since the 1930s. In 2007, 420 gasifiers were in operation in 142 plants worldwide, of which 55% used coal as feedstock and 32% used petroleum residue. About 44% of the total syngas from these gasifiers was used to produce chemicals, 30% to produce liquid fuels and 18% for power generation. There were 45 operating plants gasifying coal in 212 gasifiers with a gasification capacity of 30,825 MWth of syngas. The majority of coal gasification plants constructed in the recent past have been in China for the chemicals industry and this trend continues today. By 2010, there were seven new coal plants with ten gasifiers producing 4690 MWth of syngas. These data only include gasifiers utilising internationally recognised technologies and do not include, for example, the thousands of small communal gasifiers in China (Fernando, 2008; Hotchkiss, 2003a,b; Childress, 2008, 2010; US DOE, 2010, 2007a,b).

Typical syngas composition produced from coal gasification is shown in Table 2. The products from the gasification of coal may be of low-, medium- or high-heat (Btu) content as dictated by the process as well as the ultimate use of the gas (*see* Figure 6). Pollutants such as particulate matter and sulphur compounds must be removed prior to using the gas (Speight, 2013). The exact composition is less important when the syngas is utilised as fuel. It is much more important if the syngas is used to produce chemicals. Gasification results in the major proportion of the feed fuel heating value being associated with the CO and H_2 components of the syngas and their relative amounts depend on the gasifier technology. Most processes utilising syngas require a certain H_2/CO ratio. The required ratio for different applications is shown in Table 3. In non-fuel applications, the raw syngas is passed to a shift convertor in which the water gas shift reaction is employed to change the H_2/CO ratio (Schmid, 2008; Fernando, 2008).

Table 2 – Typical syngas composition (Ratafia-Brown and others (2002); Fernando (2008)

Gas	**Composition, volume %**
H_2	25–30
CO	30–60
CO_2	5–30
H_2O	2–30
CH_4	0–5
H_2S	0.2–1
COS	0–0.1
NH_3 + HCN	0–0.3

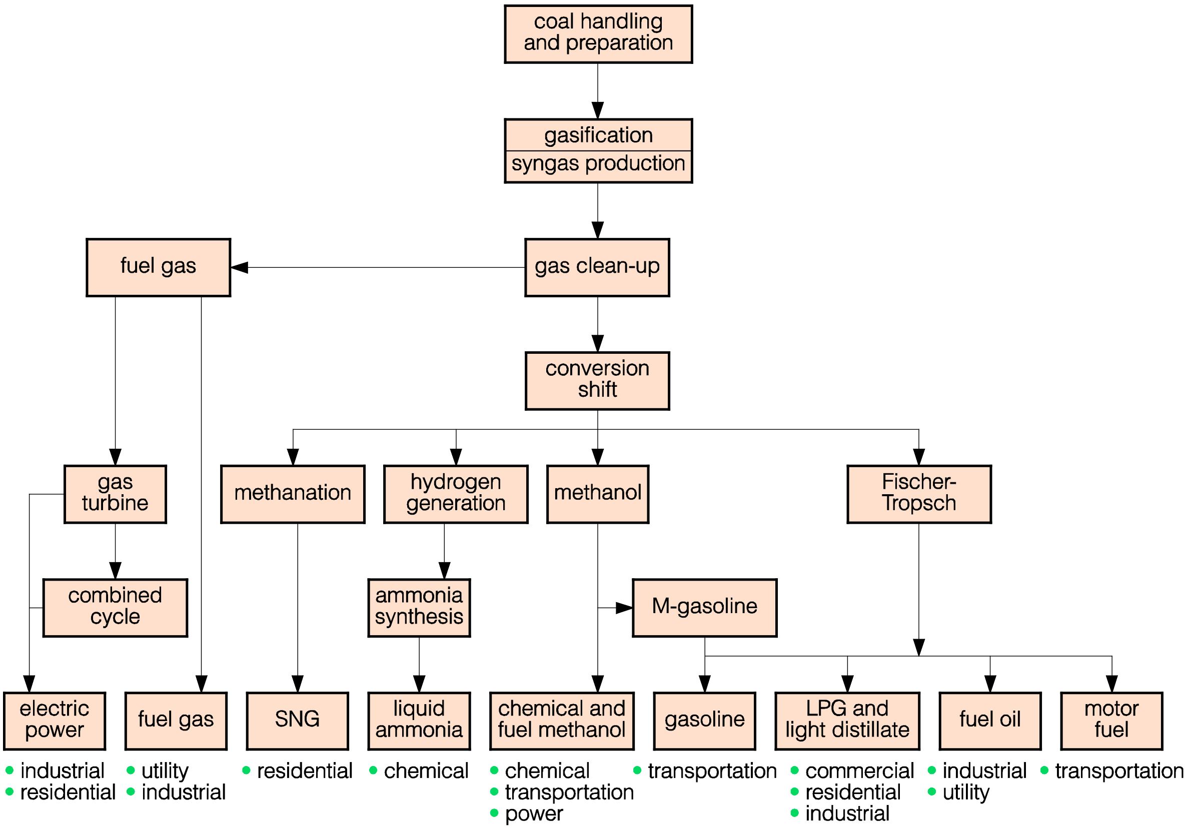

Figure 6 – Uses of various gaseous products from coal (Speight, 2013)

Table 3 – Syngas composition required for different applications (Schmid, 2008; Fernando, 2008)

	H_2/CO ratio
Syngas composition produced	
Coal	0.3–0.8
Oil	0.8–1.0
Product requirement	
Integrated gasification combined cycled (IGCC)	undefined
IGCC with CO_2 removal	maximum
Synthetic natural gas (SNG)	approximately 3
Methanol synthesis	2.4–3.0
Fischer-Tropsch synthesis	approximately 2
Hydrogen production	maximum

The majority of syngas used worldwide in 2012 from all fuels was for the production of chemicals, liquid fuels and power generation. The majority of planned gasifiers (~40%) are for chemical production and liquid/motor fuels (~29%), power generation (~22%) and gaseous fuels (~9%). Three technologies dominate 93% of the market. Sasol-Lurgi have 12 plants accounting for 34% of gasification capacity. GE gasifiers are used in 72 plants and account for 31% of capacity and Shell gasifiers are used in 41 plants and account for 28% of capacity. Gasification feedstock distribution is Coal: 63%, petroleum: 15%, gas: 13%, petcoke: 9% and biomass/waste: <1%. In the case of coal, of the total syngas produced, 49% is used for FT (Fischer-Tropsch) liquids, 32% for chemicals, 11% for power generation and 8% for gaseous fuels. In the case of oil, 63% is used for chemicals, 27% for power production and 10% for gaseous fuels. Petcoke and biomass are gasified mainly for power production (Gasification Technologies council, 2013). Table 4 contains a list of major coal gasification plants worldwide for the production of chemicals. These data only include plants using internationally recognised technologies and may not be an exhaustive list. It can be seen that the majority of coal gasification plants producing chemicals are in China. Although they mostly incorporate either GE or Shell technologies, Chinese technology is becoming more widely used. Few problems have been reported regarding the operation of coal gasifiers in chemical plant (Gasification Technologies Council, 2013).

Syngas generated from gasification can be used to produce pure hydrogen which can be used as an intermediate in the production of chemicals such as ammonia. A mixture of H_2/CO generated from syngas can be used to produce chemicals such as methanol and pure CO can be used to produce chemicals such as acetic acid. For the production of ammonia, the tar and any impurities in the raw gas must be removed.

Table 4 – Coal-to-chemicals gasification plant (in operation/under construction and planned) worldwide by year (Gasification Technologies Council, 2013)

Plant Name	Year	Country	Technology Name	Feedstock	Cap.	Units	Product	Cap.	Units	Syngas output
Gorazde Ammonia Plant	1952	Bosnia and Herzegovina	Low Pressure Winkler Process	Lignite	52.5	Mt/d	Ammonia			16.4
PLA Fertlizer Plant	1958	China	Lurgi Fixed-bed Dry Bottom	Lignite	1480	Mt/d	Ammonia	300000	t/y	280
Kingsport Integrated Coal Gasification	1983	USA	GE Gasification Technology	Bituminous coal	1225	t/d	Acetic acid	680	Mt/d	218.7
Ube City Ammonia Plant	1984	Japan	GE Gasification Technology	Coal & petcoke	1650	Mt/d	Ammonia	1250	Mt/d	293.9
Shaanxi Ammonia Plant	1987	China	Lurgi Fixed-bed Dry Bottom	Anthracite	1200	Mt/d	Ammonia			312
Lanzhou Gas Plant	1991	China	Lurgi Fixed-bed Dry Bottom	Coal	800	Mt/d	Methanol	200000	t/y	187
Lu Nan Ammonia Plant	1993	China	GE Gasification Technology	Bituminous coal	350	Mt/d	Ammonia	200	Mt/d	71.8
Shanghai Coking & Chemical	1995	China	GE Gasification Technology	Anthracite	1500	Mt d	Methanol			209.2
Shaanxi Ammonia Plant	1996	China	GE Gasification Technology	Coal	1640	Mt/d	Ammonia	900	Mt/d	278.9
Gas Plant No. 2	1997	China	GE Gasification Technology	Coal			Methanol			104.6
Zhong Yuan Dahua Group Ltd.	2000	China	Lurgi Fixed-bed Dry Bottom	Coal				312		
Puyang Ammonia Plant	2000	China	Lurgi Fixed-bed Dry Bottom	Anthracite	1200	Mt/d	Ammonia			312
Hefei City Ammonia Plant	2000	China	GE Gasification Technology	Coal	898.1	Mt/d	Ammonia	667	Mt/d	191.4
Haolianghe Ammonia Plant	2004	China	GE Gasification Technology	Coal			Methanol			279.6
Haolianghe Ammonia Plant	2004	China	GE Gasification Technology	Coal			Ammonia			201.6
Hualu Hangsheng	2004	China	OMB (Opposed Multi-Burner)	Coal	750	t/d	Ammonia	200000	t/y	176.56
Sinopec, Zhijiang	2005	China	Shell Gasification Process	Coal	2000	t/d				273.4
Liuzhou Chemical	2005	China	Shell Gasification Process	Coal	1200	Mt/d	Ammonia			232
Shaanxi Shenmu Chemical Plant	2005	China	GE Gasification Technology	Coal						263
Jinling	2005	China	GE Gasification Technology	Coal		t/d	Methanol			174.3
Jinling	2005	China	GE Gasification Technology	Coal			Ammonia			287.1

Yankuang Cathay	2005	China	OMB (Opposed Multi-Burner)	Coal	2300	t/d	Methanol	300000	t/y	422.61
Hualu Hengsheng Ammonia Plant	2005	China	Multi Component Slurry Gasification	Coal	1200	t/d	Ammonia	300000	t/y	280
Shanxi Fertlizer Plant	2005	China	SEDIN	Coal	840	t/d	Ammonia	200000		186
Yueyang Ammonia Plant	2006	China	Shell Gasification Process	Coal	2000	Mt/d	Ammonia			466.2
Hubei Shuanghuan Chemical	2006	China	Shell Gasification Process	Coal	900	t/d	Ammonia			177.7
Sinopec Anqing	2006	China	Shell Gasification Process	Coal	2000	Mt/d	Ammonia			465
Weihe Chemical	2006	China	GE Gasification Technology	Coal		t/d				395
Kuitun Amminia Plant	2006	China	GE Gasification Technology	Coal	1200	t/d	Ammonia	300000	t/y	280
Hualu Hengsheng Methanol Plant	2006	China	Multi Component Slurry Gasification	Coal	1200	t/d	Methanol	300000	t/y	280
Shanxi Fengxi Methanol Plant	2006	China	Tsinghua Oxygen Staged Gasification	Coal	500	Mt/d	Methanol	125000	t/d	116
Dalian Dahua	2007	China	Shell Gasification Process	Coal	1100	Mt/d	Methanol			232
Anning Yuntianhua	2007	China	Shell Gasification Process	Coal	2700	Mt/d	Ammonia			465
Huashan Yunzhanhua	2007	China	Shell Gasification Process	Coal	2700	Mt/d	Ammonia			465
Yongcheng Phase 1	2007	China	Shell Gasification Process	Coal	2250	Mt/d	Methanol			424
Nanjing Wison	2007	China	GE Gasification Technology	Coal	1500	t/d	Methanol			350
Huisheng Jiangsu	2007	China	GE Gasification Technology	Coal	800	t/d	Methanol			230
Fengdeng Zhejiang Ammonia Plant	2007	China	Multi Component Slurry Gasification	Coal	1200	t/d	Ammonia	300000	t/y	280
Juhua Zhejiang Methanol Plant	2007	China	Multi Component Slurry Gasification	Coal	2400	t/d	Methanol	600000	t/y	560
Kaixiang Chemical Plant	2008	China	Shell Gasification Process	Coal	1100	t/d	Methanol			257
Puyang Plant	2008	China	Shell Gasification Process	Coal	2000	t/d	Methanol			463
Zhonghua Yiye Methanol Plant	2008	China	GE Gasification Technology	Coal	2400	t/d	Methanol	600000	t/y	560
Yanzhou Yulin Methanol Plant	2008	China	GE Gasification Technology	Coal	3000	t/d	Methanol	750000	t/y	700
Yanchang Yulin Methanol Plant	2008	China	GE Gasification Technology	Coal	1000	t/d	Methanol	250000	t/y	230

Yankuang Lunan	2008	China	OMB (Opposed Multi-Burner)	Coal	1150	t/d	Ammonia	240000	t/y	220.5
Zao Zhuang New Gas Co	2008	China	U-GAS Gasification Technology	Coal	600	t/d	Syngas	22000	Nm³/h	55
Anhui Linquan Chemical	2008	China	Hangtian-Lu (HT-L)	Coal	800	t/d	Methanol	150	kt/y	187
Henen Puyang Long Yu Chemical	2008	China	Hangtian-Lu (HT-L)	Coal	600	t/d	Methanol	150	kt/y	140
Sanwei Methanol Plant	2008	China	Multi Component Slurry Gasification	Coal	800	t/d	Methanol	200000	t/y	187
Lu'an CTL Demo	2009	China	Unspecified Gasification Technology	Coal	2900	Mt/d				676
Shaanxi Shenmu Chemical Plant (II)	2009	China	GE Gasification Technology	Coal	2000	t/d	Methanol	500000	t/y	467
Tengzhou Fenghuang Fertilizer Plant	2009	China	OMB (Opposed Multi-Burner)	Coal	3000	t/d	Methanol	600000	t/y	551.23
Jiangsu Linggu	2009	China	OMB (Opposed Multi-Burner)	Coal	2000		Ammonia	450000	t/y	373.23
Jiangsu SOPO	2009	China	OMB (Opposed Multi-Burner)	Coal	3000	t/d	Methanol	600000	t/y	551.23
Shenhua Ningmei	2009	China	OMB (Opposed Multi-Burner)	Coal	3000	t/d	Methanol	750000	t/y	689
Jutai Methanol Plant	2009	China	Multi Component Slurry Gasification	Coal	3600	t/d	Methanol	900000	t/d	840
Huaihua Anhui Ammonia Plant	2009	China	Multi Component Slurry Gasification	Coal	1200	t/d	Ammonia	300000	t/y	280
Tianjin Chemical Plant	2010	China	Shell Gasification Process	Coal	4000					1124
Guizhou Chemical Plant	2010	China	Shell Gasification Process	Coal						562
Ningbo Wanhua	2010	China	OMB (Opposed Multi-Burner)	Coal	2400	t/d	Methanol			551.23
Xianyang Methanol Plant	2010	China	Multi Component Slurry Gasification	Coal	2400	t/d	Methanol	600000	t/y	560
Huating Zhongxu Methanol Plant	2010	China	Multi Component Slurry Gasification	Coal	2400	t/d	Methanol	600000	t/y	560
Yunnan Methanol & DME Plant	2011	China	BGL Gasification Technology Zemag	Coal	5000	t/d	Methanol	1200000	t/y	1120
Hulunbeier Ammonia Plant	2011	China	BGL Gasification Technology Zemag	Lignite	3100	t/d	Ammonia	500000	t/y	397
Inner Mongolia Chemical Plant	2011	China	Shell Gasification Process	Lignite	20000	Mt/d	Methanol	1667000	Mt/y	3373
Xinao Methanol Plant	2011	China	GE Gasification Technology	Coal	3000	t/d	Methanol	750000	t/y	700
Shenhua Baotou Coal-to-Olefins Plant	2011	China	GE Gasification Technology	Coal	6000	t/d	Methanol	1875000	Mt/y	1750

Sanwei Neimenggu Methanol Plant	2011	China	GE Gasification Technology	Coal	5000		Methanol	1200000	t/y	1167
Shenhua Ningxia C/Polypropylene I	2011	China	Siemens SFG Gasification Process	Coal	8000	t/d	Methanol	1667000	Mt/y	1912
Shilin Methanol Plant	2011	China	TPRI	Coal	1000	t/d	Methanol	300000	t/y	280
Wansheng Methanol Plant	2011	China	Multi Component Slurry Gasification	Coal	1200	t/d	Methanol	300000	t/y	280
Xinsheng Methanol Plant	2011	China	Multi Component Slurry Gasification	Coal	1200	t/d	Methanol	300000	t/y	280
Vinachem	2012	Vietnam	Shell Gasification Process	Coal	2000	t/d	Ammonia	1000	t/d	109
Tongzi Chemicals Plant	2012	China	GE Gasification Technology	Anthracite	2400	t/d	Methanol	300000	t/y	560
Anhui Huayi	2012	China	OMB (Opposed Multi-Burner)	Coal	3000	t/d	Methanol	750000	t/y	689.03
Yankuang Xinjiang Coal Chemicals	2012	China	OMB (Opposed Multi-Burner)	Coal	3000	Mt/d	Ammonia	750000	Mt/y	689
Manzhuoli Methanol Plant	2012	China	TPRI	Lignite	3000	t/d	Methanol	600000	t/y	560
Yima JV Plant	2012	China	U-GAS Gasification Technology SES	Coal	2400	t/p	Methanol	300000	Mt/y	550
Henan Coals Zhongxin Chemical	2012	China	Hangtian-Lu (HT-L)	Coal	1200	t/d	Methanol	300	kt/y	280
Shandong Luxi Chemical	2012	China	Hangtian-Lu (HT-L)	Coal	1200	t/d	Ammonia	300	kt/y	280
Shandong Ruixing Chemical	2012	China	Hangtian-Lu (HT-L)	Coal	1200	t/d	Ammonia	300	kt/y	280
Henan Jinkai	2012	China	Hangtian-Lu (HT-L)	Coal	4800	t/d	Ammonia	1200		1120
Linquan Chemical Phase 2	2012	China	Hangtian-Lu (HT-L)	Coal	720	t/d	Ammonia	180	kt/y	168
Datang Hulunbuir Ammonial Plant	2012	China	Tsinghua Oxygen Staged Gasification	Coal	500	t/d	Ammonia	125000	t/y	290
Wison MTO	2013	China	Unspecified Gasification Technology	Coal	3540	Mt/d	Methanol	885000	Mt/y	826
Hebi	2013	China	Shell Gasification Process	Coal	2000	t/d	Chemicals			546
Datong	2013	China	Shell Gasification Process	Coal			Chemicals			546
YYTH Shuifu	2013	China	Shell Gasification Process	Coal	2000	t/d	Chemicals			232
Kaixiang Chemical Plant II	2013	China	Shell Gasification Process	Coal	1100	t/d	Methanol	275000	Mt/y	256
Shanghai Coking & Chemical Corp.	2013	China	OMB (Opposed Multi-Burner)	Coal	2000	Mt/d	Methanol			448

Guizhou Kaiyang	2013	China	OMB (Opposed Multi-Burner)	Coal	1100	t/d	Ammonia	250000	t/y	252.65
Yantai Wanhua	2013	China	OMB (Opposed Multi-Burner)	Coal	3000	t/d	Ammonia			700
Rongxin Inner Mongolia Methanol	2013	China	OMB (Opposed Multi-Burner)	Coal	6000	Mt/d	Methanol	1500	kt/y	1400
Sinopec Yangzi PetroChemical Co.	2013	China	OMB (Opposed Multi-Burner)	Coal	1000	Mt/d	Hydrogen			233
Eerduosi Jingchentai Methanol Plant	2013	China	Tsinghua Oxygen Staged Gasification	Coal	1400	t/d	Methanol	300000	t/y	325
Xinjiang Guanghui Hami SNG Plant	2013	China	SEDIN	Subbituminous coal	9912	Mt/d	Methanol	1200000	Mt/y	1750
Gunaghui Xinjiang Methanol Plant	2013	China	SEDIN	Coal	4800	Mt/d	Methanol	1200000	t/y	1120
Guodian Neimenggu Methanol Plant	2013	China	SEDIN	Coal	1200	Mt/d	Ammonia	300000	t/y	280
Qinghai Yanhu	2014	China	OMB (Opposed Multi-Burner)	Coal	4400	t/d	Methanol	1100	kt/y	1027
Yankuang Neimeng	2014	China	OMB (Opposed Multi-Burner)	Coal	5000	t/d	Methanol	1250	kt/y	1167
Jinmei Zhongneng Chemical	2014	China	Hangtian-Lu (HT-L)	Coal	1600	t/d	Ammonia	400	kt/y	373
Luneng Baoqing	2014	China	Hangtian-Lu (HT-L)	Coal	1200	t/d	Ammonia	300	kt/y	280
Lianyungang CTO Plant	2015	China	Unspecified Gasification Technology	Coal	10000	Mt/d	Methanol	2500000	Mt/y	2330
Shenhua Ningxia C/Polypropylene II	2015	China	SEDIN	Coal	10600	Mt/d	Methanol	2650000	Mt/y	2500
Neimenggu Methanol Plant	2015	China	SEDIN	Coal	5344	Mt/d	Methanol	1670000	t/y	1558
Sinopec Guizhou MTO Plant	2016	China	Unspecified Gasification Technology	Coal	7200	Mt/d	Methanol	1800000	Mt/y	1680
Hebi CTO Plant	2016	China	Unspecified Gasification Technology	Coal	7200	Mt/d	Methanol	1800000	Mt/y	1680
Total CPI MTO Plant	2016	China	Unspecified Gasification Technology	Coal	12000	Mt/d	Methanol	3000000	Mt/y	2800
Yanchang Yulin CTO Plant	2016	China	Unspecified Gasification Technology	Coal	7200	Mt/d	Methanol	1800000	Mt/y	1680
China Coal Yulin CTO	2016	China	Unspecified Gasification Technology	Coal	7200	Mt/d	Methanol	1800000	Mt/y	1680
Pucheng CTO Plant	2016	China	Unspecified Gasification Technology	Coal	8160	Mt/d	Methanol	2040000	Mt/y	1900
Dow-Shenhua Yulin CTO Plant	2016	China	Unspecified Gasification Technology	Coal	12000	Mt/d	Methanol	3000000	Mt/y	2800

Fujian Shenyuan Ammonia Plant	2016	China	Unspecified Gasification Technology	Coal	2450	t/d	Ammonia	250000	Mt/y	500
Huizhou Refinery H2 Plant	2016	China	E-Gas	Coal	5000	Mt/d	Hydrogen			1385
Shenhua Xianjing CTO	2016	China	GE Gasification Technology	Coal	7500	Mt/d	Methanol			1750
Paradip Ammonia Plant	2016	India	BGL Gasification Technology	Coal	3200	t/d	Ammonia			500
MidAmerica C2L	2016	USA	Siemens SFG Gasification Process	Coal	3273	Mt/d	Methanol			763
Jincheng Project	2016	China	Siemens SFG Gasification Process	Anthracite	4000		Ammonia	300000	Mt/y	890
Jiangsu Three-Star Ammonia Plant	2016	China	OMB (Opposed Multi-Burner)	Coal	1800	Mt/d	Ammonia	450000	Mt/y	420
Inner Mongolia Jingneng Hydrogen	2017	China	OMB (Opposed Multi-Burner)	Coal	4000	Mt/d	Hydrogen	250000	t/d	930

Then the syngas is desulphurised and the CO shift reaction is employed to convert CO to CO_2, which is then removed. It is possible to transpose the order in which these processes take place. Methanol is an important intermediate in the manufacture of formaldehyde and about 9% of world methanol production is based on the gasification of coal or heavy residues. Methanol production takes place in the pressure range 5–10 MPa over a copper catalyst by the reaction of hydrogen with carbon oxides. Worldwide production of hydrogen is greater than 1 billion m^3/d and approximately a fifth is manufactured from coal. Hydrogen has a wide range of uses in the chemical, metals, electronics and food industries. In recent years there has been a move towards the 'hydrogen economy' and towards the use of hydrogen for the production of electricity and for transportation. These moves are mainly due to concerns about global warming and the security of energy supplies (Fernando, 2008).

Based on Chinese experience, the factors when selecting the gasification technology for coal-based, ammonia-producing plants include coal type, economics and environmental performance (Li, 2004). In **coal type**, each gasification technology is usually suitable or is designed for coals with set specifications; some may allow a variety of coals while others may not. The chosen gasification technology should be applicable to local coals. **Economics** may be the most important factor in selecting a gasification technology. This is affected by factors such as coal price, capital cost, process performance and so on. Generally speaking in China, experience shows that an imported technology with high performance has high capital cost, while a domestic technology with lower performance has lower capital cost. When the gasification needs pure oxygen and an air separation unit, the capital cost could increase to an unacceptable level. Therefore, a compromise must be reached between the capital cost and performance. For example, in Shanxi province, the atmospheric gasification process is most suitable because of the low capital cost (without air separation unit) and low anthracite prices there. The atmospheric gasification technology, also called UGI gasification in China, is an old technology (~50 years) in which the gasifier uses air, instead of oxygen and steam as agent; only lump anthracite coal or coke (diameter 13-50 mm) can be used.

In 2004, there were more than 500 coal-based plants (about 3000 gasifiers) in operation in China using the atmospheric gasification process. The gasifier represented about 60% of the Chinese total capacity. Over the years, the technology has been improved in many aspects such as automatic control, grate structure and gas distribution, water treatment and using briquettes of powdered coal. The **Environmental** aspect is sometimes the key factor when selecting a process. With increasingly strict environmental regulations, ammonia producers have to choose clean coal technology or adopt other technologies to meet the regulations. This of course results in increased cost. Li (2004) concluded that although the coal-based ammonia production in China depends on many factors, the final decision should be based on comparing the technologies and their economics.

The process of producing olefins from coal, coal-to-olefins (CTO), begins with gasification. According to Tullo and Tremblay (2008), the future for coal chemicals is to produce olefins. Coal is partially oxidised with oxygen and steam into synthesis gas, or 'syngas,' a mixture of hydrogen, carbon monoxide, carbon dioxide, and trace impurities like hydrogen sulphide. In another reactor, water and carbon monoxide are passed over a metal-based catalyst to yield equal parts hydrogen and carbon dioxide in what is known as the water-gas shift reaction. To make methanol the water-gas shift runs until there are 2 moles of hydrogen for every mole of carbon monoxide. When hydrogen or ammonia is the desired product, the reaction proceeds all the way to carbon dioxide and hydrogen.

Methanol is raw material for the next stage of the coal-to-chemicals route: the conversion into olefins via the intermediate dimethyl ether. The major vendors of this technology are UOP (USA) and Lurgi (Germany), the respective chemical engineering arms of Honeywell and Air Liquide. Although similar, the catalysts used in the UOP and Lurgi processes lead to different product slates. The UOP/HYDRO technology, also called methanol-to-olefins, uses SAPO-34, a silicon-aluminium-phosphorus-based molecular sieve. The Lurgi technology, dubbed methanol-to-propylene, is based on a ZSM-5 type catalyst, which contains zeolite. The pores in the UOP catalyst are smaller than those in ZSM-5. After the methanol enters the pores and reacts, the smaller molecules can exit the pores while the larger by-products remain. As a result, the UOP process produces ethylene and propylene as well as some heavier olefins, which has led the UOP to pair its technology with a cracking technology, developed with Total Petrochemicals, to convert butylene and hexane into ethylene and propylene. The Lurgi process yields propylene but no ethylene. Other products include gasoline and propane. Neither Lurgi nor UOP had commercial-scale plants in operation in 2008. Lurgi has licensed its technology to Datang International Power Generation and Shenhua's Shenhua Ningxia Coal, both of which are building plants in China with about 500,000 t/y of capacity (Tullo and Tremblay, 2008).

According to Yuzhuo (2013), Shenhua Group (China) has developed a next-generation methanol-to-olefins (SHMTO) technology, and the Dalian Institute of Chemical Physics of the Chinese Academy of Sciences has completed research and development leading to the second generation of methanol-to-olefins (DMTO-II) technology. Both technologies will be applied at commercial plants that are currently under construction. There are also plans for further optimisation and improvement of the entire process, including gasification, purification, and methanol synthesis, so as to form a complete process that improves the stability and economics of large plants.

Higman (2013) discusses the state of the gasification industry including coal-to-chemicals installations throughout the world. The information is presented in a world gasification industry database available to the public at http://www.gasification.org/database1/search.aspx. In 2013, the database contained 747 active and under construction projects utilising 1742 gasifiers. Of those, 234 projects with 618 gasifiers are in operation, 61 projects with 202 gasifiers under construction and a further 98 projects with 550 gasifiers in the planning phase. The total number of coal-to-chemicals gasification plants currently in operation, under construction and planned throughout the world is shown in Table 4. Higman (2013) considers that it is not surprising that coal has come to and will continue to dominate the gasification feedstock market in general due to the high price of crude oil. This is shown in Figures 7 and 8. Higman (2013) concludes that gasification capacity continues to grow on a worldwide basis, the majority of which is in the Chinese coal-to-chemicals industry.

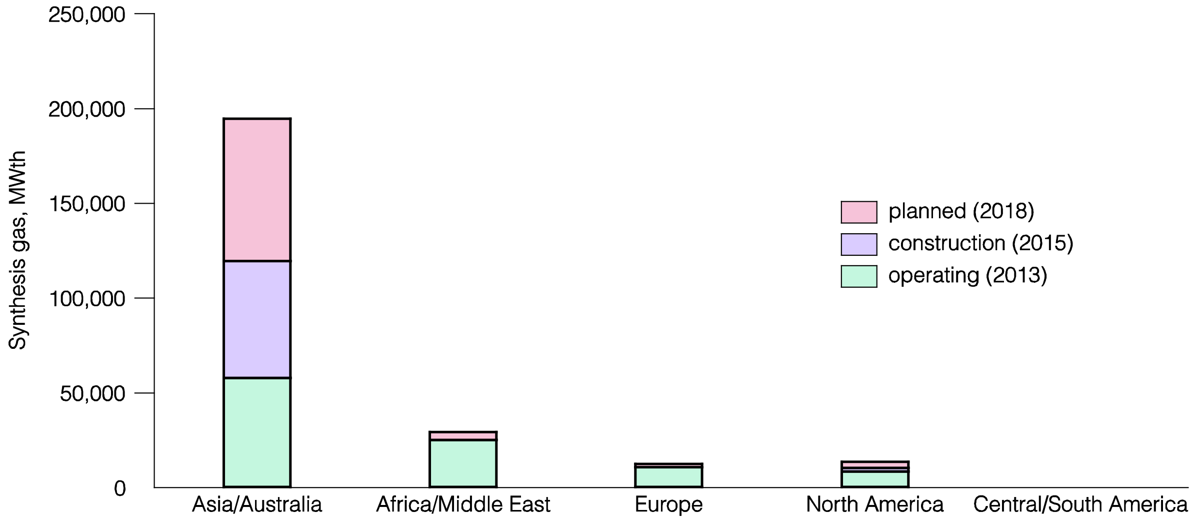

Figure 7 – Gasification capacity (syngas, MWth) by primary feedstock (operating, under construction and planned) (Higman, 2013)

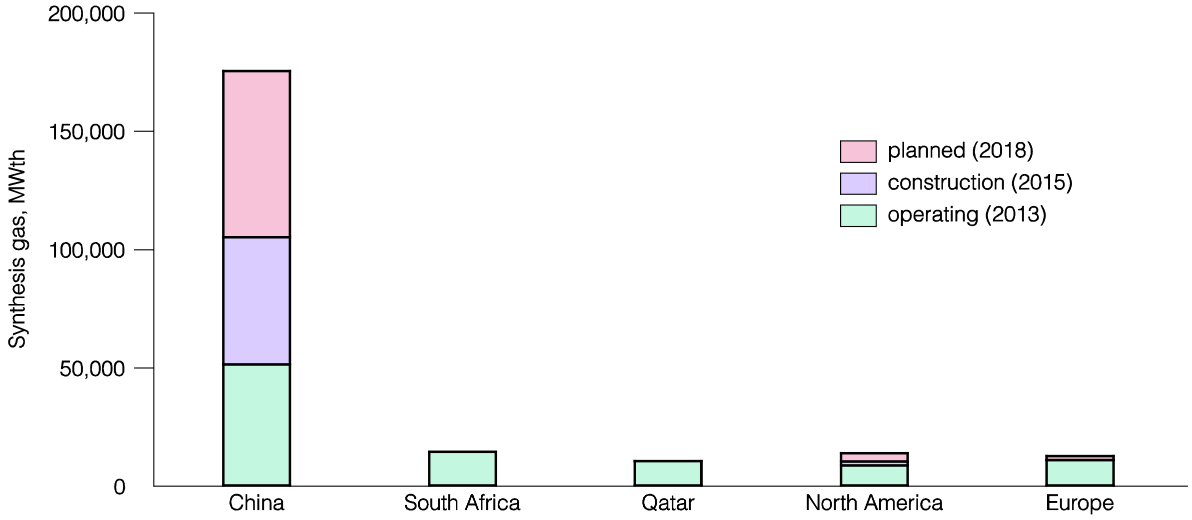

Figure 8 – Numbers of gasifiers by primary feedstock (operating, under construction and planned) (Higman, 2013)

2.3 Coal-to-liquids (CTL)

Concerns over supply security and the price of oil have led to a renewed interest in coal as an alternative, not only for the production of transport fuels, but also for chemicals. Historically, the process has been used to convert coal into a substitute for liquid fuels in countries with little or without a secure supply of petroleum, for example South Africa. This report discusses the ***non-fuel uses of coal*** and therefore will briefly present but not detail the use of liquefied coal as fuel. The following is presented to clarify potential uses of coal besides power generation and industrial combustion.

The process options for coal liquefaction can generally be divided into four categories, pyrolysis, solvent extraction, catalytic liquefaction and indirect liquefaction (*see* Figure 9). Speight (2013) discusses coal liquefaction technologies and processes in detail.

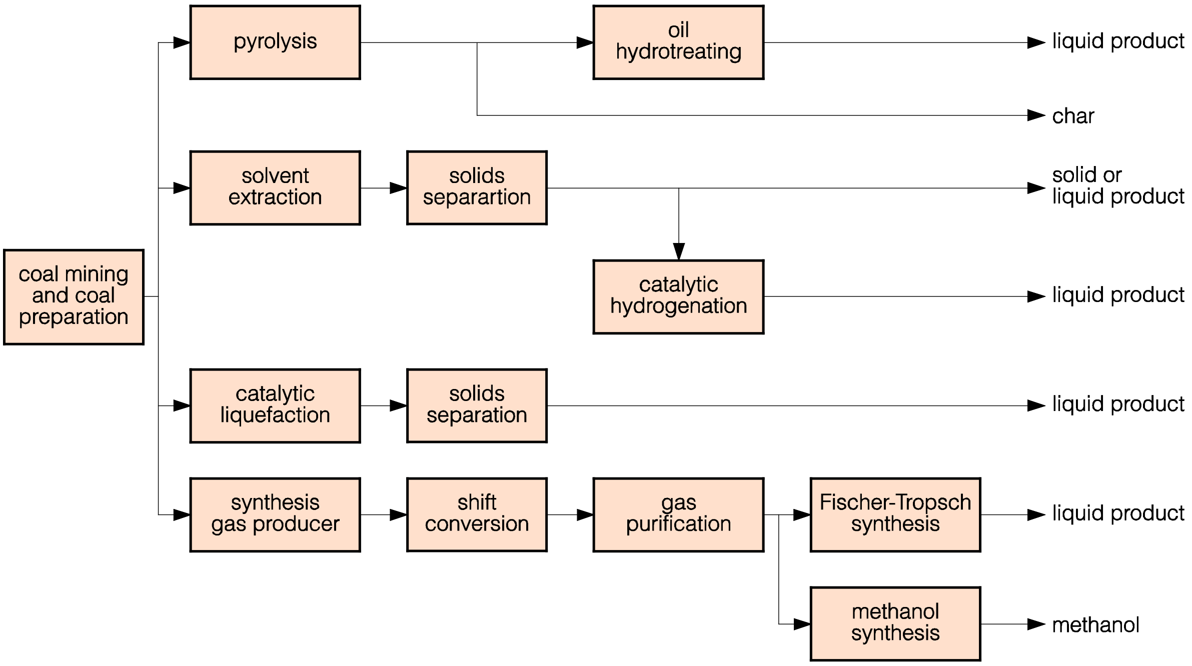

Figure 9 – Coal liquefaction process types (Speight, 2013)

Coal-to-liquids (CTL) describes both direct coal liquefaction technologies and coal gasification, combined with Fischer-Tropsch (also known as F-T) synthesis to produce liquid fuels. Direct liquefaction works by dissolving the coal in a solvent at high temperature and pressure. The process is highly efficient, but the liquid products require further refining to achieve high grade fuel characteristics. The F-T synthesis was first developed in Germany during the early decades of the 20th century and has been further developed and improved in South Africa by Sasol. The F-T reaction involves passing hydrogen and carbon monoxide in a specific ratio over iron catalysts at elevated temperatures and pressures. The fixed-bed system employs a precipitated iron catalyst. Predominantly heavy hydrocarbons of an aliphatic nature are produced with carbon chains up to 100. These straight-chain hydrocarbons yield waxes and high quality diesel oil, which is also used as raw material for the production of high quality biodegradable detergents. The fluid-bed system, based on catalytic cracker technology, has the advantage of high production capacity and scale-up potential. The quantity of ethylene obtained is augmented by ethane cracking. The light olefins can be used as petrochemical feedstock or refined, for example by polymerisation, and the product added to the motor fuel pool. The product cut in the gasoline range yields gasoline by using conventional refinery techniques. The oxygenated chemicals, when sold as such, fetch higher prices than when sold as motor fuels (Hoogendoorn and others, 1981). Traa (2012) presents an overview of existing technologies for the production of fuels as well as chemicals from coal.

Coal gasification, as discussed above, is already applied widely in the production of chemicals and fertilisers, notably in China where, according to IEA-CIAB (2006), 8000 coal gasifiers were in operation. Following the oil crisis of the 1970s, significant coal liquefaction research and development were undertaken in Australia, Europe, Japan and the USA, although much of this development work was subsequently put on hold as oil prices stabilised from the mid-1980s and through the 1990s. Due to the increasing oil prices, China and Japan have constructed several CTL plants and have plans for further projects aiming to produce millions of barrels per day by 2020. In the USA, new incentives were introduced in early- to mid-2000 for coal-based transport fuels (CIAB, 2006).

A number of products can be developed using these processes – ultra-clean petroleum and diesel, as well as synthetic waxes, lubricants, chemical feedstocks and alternative liquid fuels such as methanol and dimethyl ether (DME). Coal liquefaction has been discussed in detail by Speight (2013) and in previous IEA Clean Coal Centre (IEACCC) publications by Couch (2008) and Minchener (2011).

South Africa has been producing coal-derived fuels since 1955 and has established a commercial CTL industry in operation today (WCA, 2013). Not only are these fuels used in cars and other vehicles, South African energy company Sasol's coal liquid fuels also have approval to be utilised in commercial jets. Currently around 30% of the country's gasoline and diesel needs are produced from indigenous coal. The total capacity of the South African coal liquid operations now stands in excess of 160,000 bbl/d (barrels per day). Coal liquid fuel is particularly suited to countries that rely heavily on oil imports and that have large domestic reserves of coal. There are a number of CTL projects around the world at various stages of development. Liquid fuels from coal can be delivered from an existing pump at a filling station via existing distribution infrastructure and used, without modification, in the current vehicle fleet. Fuels produced from coal also have potential outside the transportation sector. In many developing countries, health impacts and local air quality concerns have driven calls for the use of clean cooking fuels. Replacing traditional biomass or solid fuels with liquefied petroleum gas has been the focus of international aid programmes. Liquefied petroleum gas however, is an oil derivative and is thus affected by the price volatility of crude oil. Coal-derived DME is receiving particular attention today as it is a product that may be used as a domestic fuel. DME is non-carcinogenic and non-toxic to handle and generates less carbon monoxide and hydrocarbon air pollution than liquefied petroleum gas. DME can also be used as an alternative to diesel for transport, as well as for on and off-grid power applications. The benefits of converting coal-to-liquids are that:

- coal is affordable and available worldwide enabling countries to access domestic coal reserves. It also has a well-established international market resulting in a decreased reliance on oil imports and thus improving energy security,
- coal liquids can be used for transport, cooking, stationary power generation, and in the chemicals industry,

- coal-derived fuels are sulphur-free, low in particulates, and low in nitrogen oxides, and
- liquid fuels from coal provide ultra-clean cooking fuels, alleviating health risks from indoor air pollution

The conversion of any feedstock to liquid fuels is an energy intensive one. Emissions across the entire process have to be considered. While the CTL process can be more CO_2 intensive than conventional oil refining, there are options for preventing or mitigating emissions. For CTL plants, carbon capture and storage (CCS) can be a relatively low cost method of addressing CO_2 concerns. Where co-processing of coal and biomass is undertaken, and combined with CCS, greenhouse gas emissions over the full fuel cycle may be as low as one-fifth of those from fuels provided by conventional oil (WCA, 2013). Prospects and challenges for carbon capture and storage in China was the subject of an in depth review by Best and Levina (2011).

3 Products derived from coal

The majority of industrial and carbon-based materials such as basic chemicals, plastics and fibres are currently derived from petroleum and natural gas. According to Nexant (2006), essentially all of the important, first-stage, organic petrochemicals were made from coal during the period of 1900-30. The coke oven industry provided the by-products ammonia, ammonium sulphate, benzene, toluene and phenols. In the fuels and fuels-chemicals sector, straight chain hydrocarbons, alcohols and other organic chemicals from synthesis gas were produced. However, the use of coal for the production of organic chemicals diminished over time as a consequence of both cost (compared to oil and gas) and environmental concerns. However, the list of potential chemicals that can be derived from coal is almost boundless, given that coal provides both the hydrogen and carbon needed for petrochemical production (Nexant, 2006). Processes for the production of specific chemicals from coal are typically proprietary systems using specialised catalytic technologies, requiring particular process design/operation.

Song and others (2005) discussed, in an in-depth review, the following non-fuel uses of coal:

- high temperature carbonisation of bituminous and subbituminous coals to make metallurgical coke;
- manufacturing carbon materials such as activated carbons (AC), carbon molecular sieves (CMS), and carbon for production of chemicals such as phosphorus (phosphoric acid);
- making specialty carbon materials such as graphite, fullerenes, nano-tube and diamond;
- pyrolysis of coals to make aromatic chemical feedstocks along with other products;
- gasification of coal to make synthesis gases and other chemicals;
- the use of coal tars from carbonisation, gasification and pyrolysis for making aromatic and phenolic chemicals;
- the use of coal tar pitch for making binder pitch, mesocarbon microbeads, carbon fibres, and activated carbon fibres;
- making humic materials such as humic acids and calcium humates which can be used as soil modifiers and fertilisers;
- making composite materials such as coal/polymer composites and coal/conducting polymer composites; and
- other non-fuel uses of coal and coal-derived by-products (such as carbon-in-ash and materials from coal ash).

According to Song and others (2005), coal has several positive attributes when considered as a feedstock for aromatic chemicals (*see* Davidson, 1980), and carbon-based materials. However, several challenges face the use of coal. The main issues are structural complexity, processing difficulties, presence of many components in organic matrix at each stage of conversion, inorganic impurities, capital investments, processing costs and environmental impact. Furthermore, water consumption in coal conversion processes is high and therefore plays a major role in deciding whether or not to build a plant. According to Schneider (2011), converting coal to 1 t of chemicals requires 15–20 m^3 (3950–5300 gallons) of water. As a result the focus has been on petroleum feedstocks for most carbon products, with the exception of metallurgical coke, activated carbon and binder pitches. However, there are indications that crude oil derived products may lose their price advantage over coal especially in coal producing countries such as China and the USA.

As discussed in Chapter 2, producing chemicals from coal through gasification has been used since the 1950s and, as such, already has a share, albeit small, of the chemicals market. An example is the production of methanol, of which, 9% worldwide is produced by gasification. Many chemicals are high-value products and gasification provides the option of using relatively inexpensive coal to produce them. Methanol and ammonia are especially important as key building blocks for further chemical synthesis.

The non-fuel uses of coal are growing in countries with domestic coal supplies and demand for chemical products such as ammonia-based fertilisers and methanol. The latter not only for direct use but also as a building block in other chemical syntheses (US DOE, 2010).

The US remains the world's largest producer of bulk chemicals and refined petroleum products. However, China has become the world's largest producer of steel, aluminium and cement. The growing Chinese economy gave rise to a number of coal-to-chemicals facilities also, some already in operation and several are planned for the future. In the USA, the non-combustion use of coal is minimal compared to natural gas and petroleum products (*see* Figure 10) (EIA, 2012). Coal's share in the mix amounted to approximately 0.6 million tons (0.55 Mt) only compared to 398 million ft^3 (~68637 barrels of oil equivalant) of natural gas and 996 million barrels of petroleum products (EIA, 2012). Global competition for export markets, foreign investments, and raw materials is intense. The International Energy Agency (IEA) projects global industrial energy demand to more than double by 2030 (Brown and others, 2010).

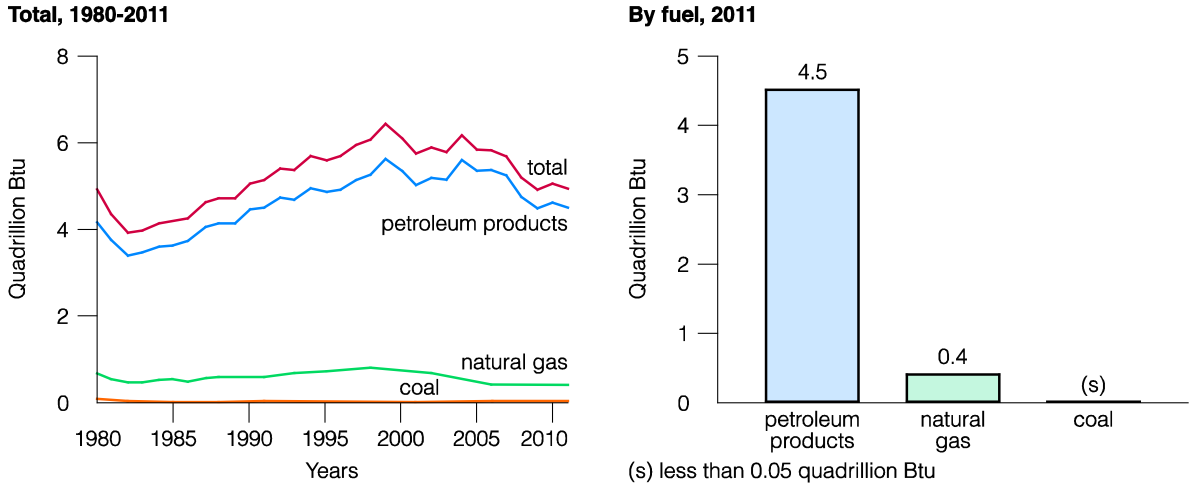

Figure 10 – Non-combustion use of fossil fuels by fuel (USA) (EIA, 2012)

Research, development, demonstration, and commercial application with respect to technologies for the non-fuel use of coal are an area of increasing interest. Non-fuel products from coal include:

- coke and other carbon products derived from coal;

- coal-derived, carbon-based chemical intermediates that are precursors of value-added chemicals and polymers; and
- chemicals from coal-derived synthesis gas.

Carbon and oxygen are both key elements in organic chemistry. Therefore, there are a wide range of chemicals that may utilise CO_2 as a feedstock for production, including organic acids, alcohols, esters, and sugars. Potential uses of CO_2, based on current markets, could come from acetic acid, which has a current global market of ~6 Mt/y. Acetic acid can be produced by direct catalysis of CO_2 and methane (Parsons Brinckerhoff and Global CCS Institute, 2011). Examples of chemicals produced from methane are shown in Table 5. Many chemicals from coal are being produced, used and developed including formaldehyde, methanol, ammonia/urea, methanol-to-olefins (MTO), mono-ethylene-glycol (MEG) and DME, acetic acid, acetylenes such as vinyl chloride monomer (VCM), poly vinyl chloride (PVC), butanediol (BDO), vinyl acetate monomer (VAM), acrylic acid (AA), acrylonitrile (ACN) and naphthalene derivates. Chemicals from coal are boundless, traditional and otherwise, and therefore are **not** all discussed in this review.

Table 5 – Examples of chemicals produced from methane (Speight, 2013)

Basic derivative/source	Uses
Ammonia	Agricultural chemicals (as ammonia, salts, urea), fibres, plastics, industrial explosives
Carbon black	Rubber compounding, printing ink, paint
Methanol	Formaldehyde (mainly for resins), methyl esters (polyester fibres), amines and other chemicals, solvents
Chloromethanes	Chlorofluorocarbons for refrigerants, aerosols, solvents, cleaners, grain fumigants
Hydrogen cyanide	Acrylonitrile, adiponitrile, methyl methacrylate

3.1 Traditional products

In general, traditional non-fuel uses of coal or coal-to-chemicals production focus on the coking/coal tar/benzene production, calcium carbide/acetylene/PVC manufacture, ammonia/urea fertiliser industry and methanol production (*see* Figure 11).

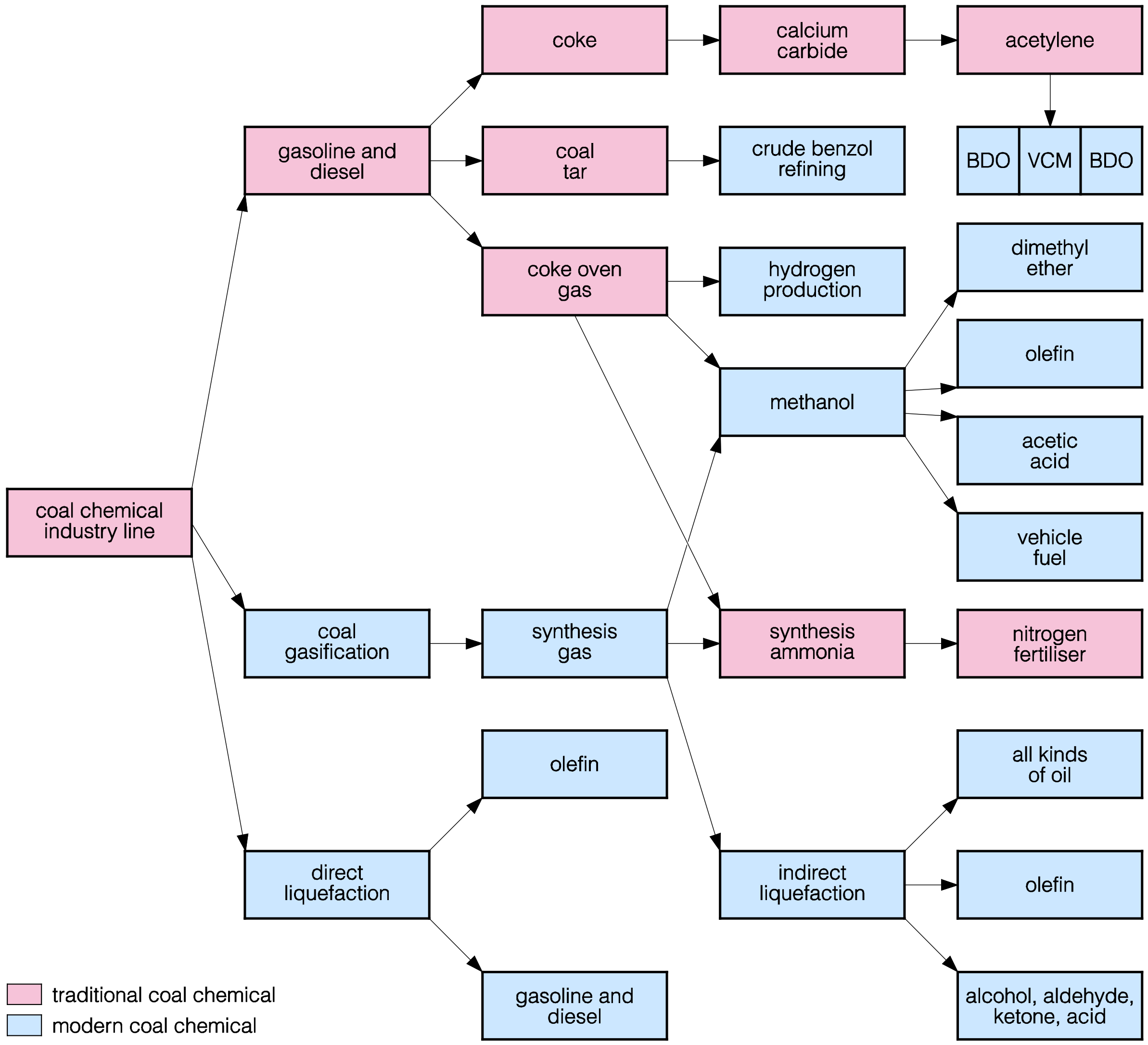

Figure 11 – Traditional and modern coal-to-chemicals conversion technologies (Xiangkun, 2013)

3.1.1 Coal tar

Many commercially important compounds are derived from coal tar. High-temperature coal carbonisation in coke ovens for making metallurgical coke is discussed in detail by Speight (2013), Song and others (2005) and Reeve (2000). Low-temperature tars result when coal, peat or lignite are carbonised at temperatures not exceeding 700°C (1300°F). Table 6 compares the general ranges of products from high-temperature and low-temperature tars. Tar acids, phenolic compounds that react with caustic soda to form water-soluble salts, are extracted from coal tar after it has been distilled. Tar bases are the alkaline constituents of distillate oils, remaining after tar acids have been removed. One of the bases that are recovered is pyridine, a colourless nitrogenous liquid that has a pungent odour and produces derivatives that are of pharmaceutical value. Pitch is the material remaining after the removal of pyridine and other distillates; it is useful in the aluminium industry for the manufacture of electrodes.

Table 6 – General ranges of products from high temperature and low temperature coal carbonisation (Speight, 2013; Song and others, 2005; Owen, 1979)

Products	Low temperature tars, wt% dry coal	High temperature tars, wt% dry coal
Gas	5–8	17–20
Liquor	13–15	2–3
Light oils	1–2	0.5–0.8
Tar	8–10	3–5
Coke	70	75

Coal tar, a product of coke ovens, is also a source of chemicals such as anthracene to carbon black naphthalene to phthalic anhydride among others. In modern usage the word naphtha is usually accompanied by a distinctive prefix. Coal-tar-naphtha is the volatile commercial product obtained by the distillation of coal tar. Shale naphtha is obtained by the distillation of oil produced from bituminous shale by destructive distillation. Petroleum naphtha is a name used primarily in the USA for petroleum distillate.

The traditional source of coal chemicals, tars or liquids from by-product coke ovens, has steadily decreased in the last decades. So, although the opportunities are increasing for new applications and markets for coal chemicals, the traditional source of those chemicals continues to decline. Speight (2013), Minchener (2011) and Song and others (2005) discuss traditional products derived from coal in detail.

3.1.2 Calcium carbide/acetylene production

Calcium carbide (CaC_2) is manufactured by heating a lime and carbon mixture to 2000 to 2100°C in an electric arc furnace. The lime is reduced by carbon to calcium carbide and carbon monoxide (CO), according to the following reaction: $CaO + 3C \rightarrow CaC_2 + CO$. Sources of carbon for the reaction include petroleum coke, metallurgical coke, and anthracite. The lime and carbon source are conveyed to an electric arc furnace, the primary piece of equipment used to produce calcium carbide. The calcium carbide product is used primarily in generating acetylene and in iron desulphurisation. Acetylene from coal can be used to produce a variety of chemicals including VCM and PVC (Nexant, 2006). Coal can serve as a direct feedstock for the production of acetylene by calcium carbide hydration, that is the combining of calcium carbide with water produces acetylene. Acetylene is a colourless and flammable gas. It is composed of a mixture of two hydrogen and two carbon atoms and is a member of a group of hydrocarbons known as alkynes or acetylenes. This discovery of acetylene led to the widespread use of the gas as a lighting fuel due to the bright and clear light that it produces when combusting. Many street lights, interior lights, automobile headlights, lanterns, mining lamps and other general lighting during the late 1800s and early 1900s were fuelled by acetylene. It is still used as a fuel for lighting in areas where electric or natural gas light is not possible or practical. Acetylene-based chemicals such as vinyl acetate, acetic acid and acrylic acid are common components of many chemicals and plastics.

Vinyl chloride monomer (VCM) is used primarily for the production of poly vinyl chloride (PVC) homopolymer and copolymer resins. VCM is among the top twenty largest petrochemicals in world production. In 2011, the major consumers of VCM, in descending order, were China, North America, Western Europe, Japan, Taiwan, Republic of Korea and India, constituting over 75% of total world consumption (IHS Chemical, 2012). According to ICIS (2009), in terms of VCM technology, China differs from the rest of the world in that its dominant VCM process is based on the calcium carbide route via acetylene and hydrogen chloride. The calcium carbide is obtained from coal. This is an obsolete technology in other parts of the world. The attraction for China is that the technology uses coal and not ethylene as a feedstock for making the intermediate ethylene dichloride, which is used elsewhere. However, disadvantages of the acetylene-based process are that it is highly polluting and has a high energy requirement. PVC applied products cover a wide range, including pipes and fittings, profiles and tubes, wire and cable, windows, doors, floorings, film and sheet, and bottles. While the most important ultimate end-use markets are commercial, residential, and non-residential construction, a wide variety of PVC converted products is also used in agricultural, electrical (wire and cable), and health care markets. China is forecast to continue to expand its VCM/PVC capacity. It is also expected that producers that can use cheap coal sources will remain competitive compared to ethylene based production. IHS Chemical (2012) state that coal-acetylene-based VCM/PVC production increased at nearly 20%/y during 2005-10. However this is forecast to slow to about 7–8%/y over the next six years. In Europe, PVC growth has been slow and usage more concentrated in certain industrial segments such as window profiles, pipes and fittings. In areas of packaging, bottles and short lived consumer groups, PVC is being gradually replaced with polyethylene terephathalate (PET) and poly olefins. In the USA, the situation for PVC is similar to that in Europe especially following the economic downturn and the collapse of the vinyl construction materials market (ICIS, 2009).

3.1.3 Ammonia/urea

Ammonia is the basic chemical used to produce nitrogenous fertiliser. More than 80% of the energy required for producing fertiliser products goes into the manufacture of ammonia. Ammonia is produced from water, air and energy. The energy source is usually hydrocarbon that provides hydrogen for fixing the nitrogen. Energy is also required in the form of steam and power. Ammonia may be produced with coal, natural gas and/or oil. Global ammonia capacity by feedstock in 2007 is shown in Figure 12 (IFA, 2013a). Industrial nitrogen applications are illustrated in Figure 13 (Yara, 2012). Ammonia, urea or nitric acid can be used as traded raw materials, for example, urea in the glue industry and ammonia in acrylonitrile production (textile fibres). Other applications include abatement of NOx emissions from power plants, industry as well as vehicles. Derived products from nitric acid include technical grade ammonium nitrates for explosives and calcium nitrate for a range of applications including odour control, wastewater treatment, treatment of drilling fluids and catalyst applications for the production of rubber gloves. Other uses of nitrates include nitrous oxide (N_2O or laughing gas) for the medical sector and liquid CO_2 for use in the food and beverage sectors (Yara, 2012).

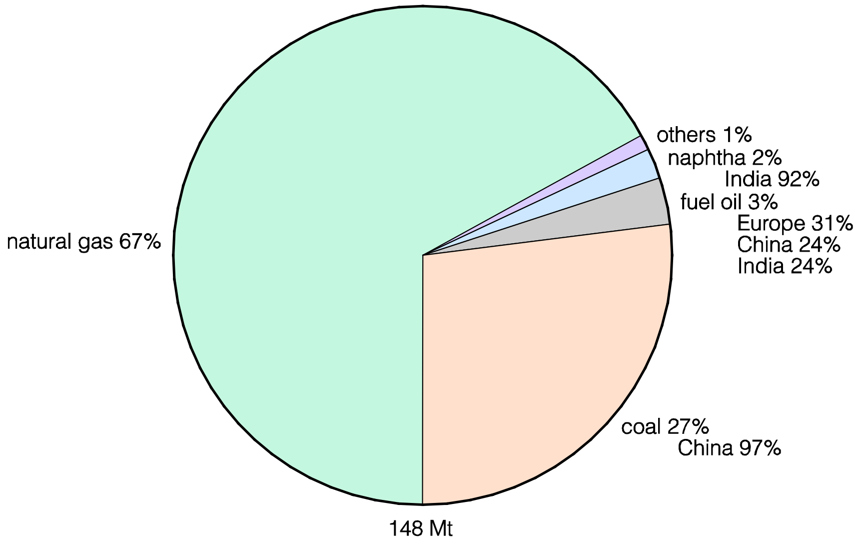

Figure 12 – Global ammonia capacity by feedstock, 2007 (IFA, 2013a)

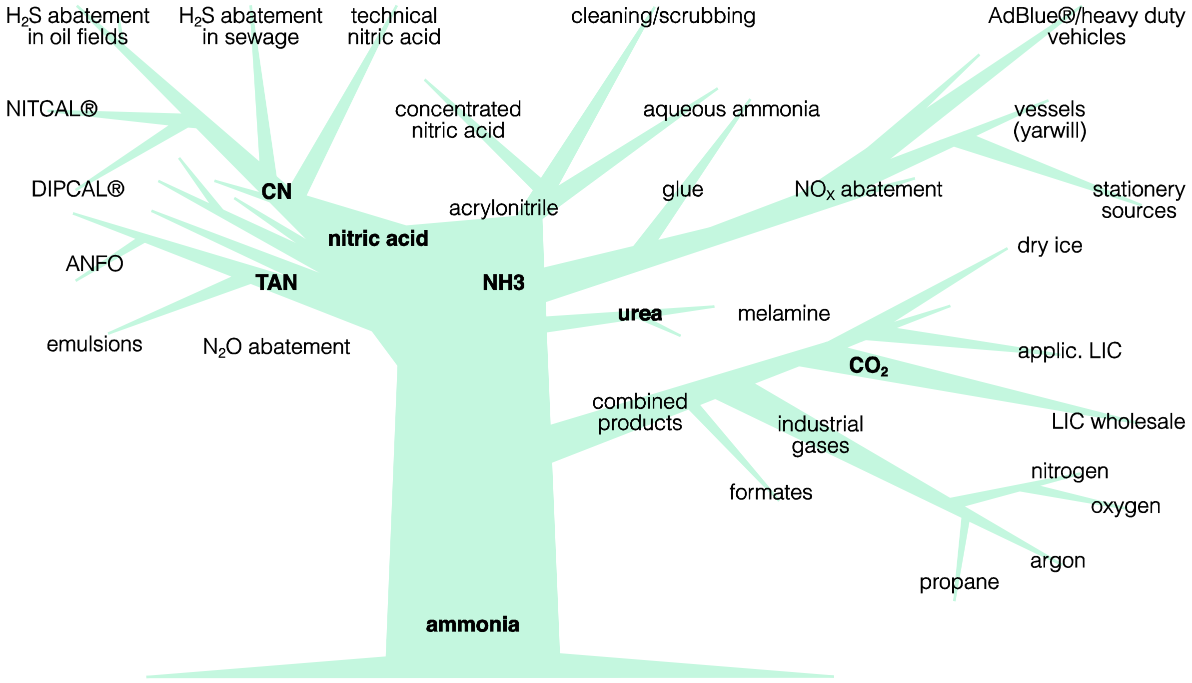

Figure 13 – Industrial nitrogen applications (Yara, 2012)

An approximate comparison of the energy consumption, cost of production and the capital cost of the plants for three feedstocks are given in Table 7 (GSE Systems, 2013). The steam reformation process of light hydrocarbon, particularly natural gas, is considered the most efficient route for the production of ammonia. Other routes are the partial oxidation of coal and/or oil, which are used for the gasification of heavier hydrocarbon feedstock, to produce ammonia. An air separation unit is required for the production of O_2 for the partial oxidation step. Nitrogen is added in the liquid nitrogen wash to remove impurities from the synthesis gas and to obtain the required hydrogen/nitrogen ratio. The partial oxidation is a non-catalytic process, which takes place at high pressure (>50 kg/cm^2) and temperatures around 1400°C. Some steam is added for temperature moderation. A detailed description of the partial oxidation process for the production of ammonia and urea is given by GSE Systems (2013). A coal-based ammonia plant is composed of several sections (*see* Figure 14) (Li, 2004).

Table 7 – An approximate comparison of the energy consumption, cost of production and the capital cost of fertiliser manufacturing plants for three feedstocks (GSE Systems, 2013)

	Natural gas	Heavy oil	Coal
Energy consumption	1.0	1.3	1.7
Investment cost	1.0	1.5	2.4
Production cost	1.0	1.2	1.7

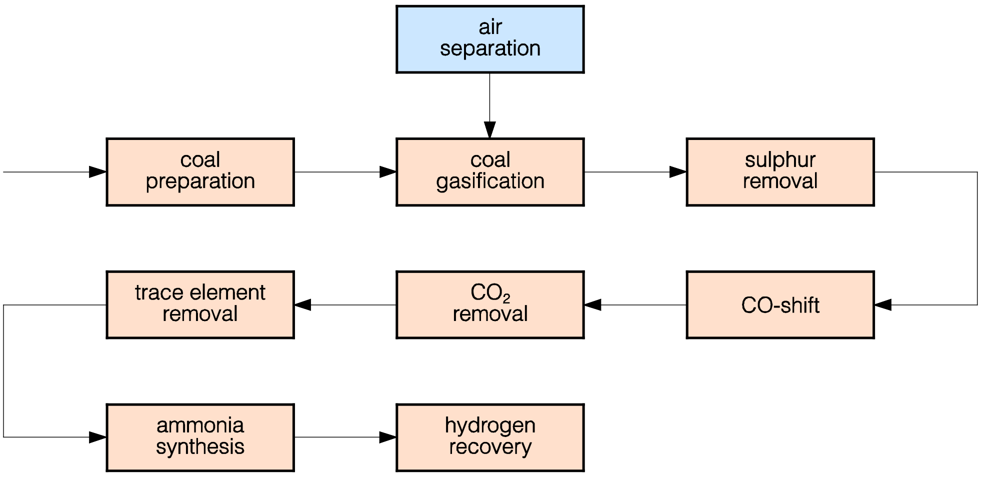

Figure 14 – The production of synthetic ammonia in a coal-based plant (Li, 2004)

According to Dawn (2005), about 77% of world ammonia production capacity in 2005 was based on natural gas while 5–10% was based on oil or coal, where mostly partial oxidation was used. In India, almost 82% of the nitrogen is in the form of urea and therefore most of the input energy is in the production of ammonia and urea. Also in India, about 49% of the total existing urea capacity in 2005 was based on natural gas while naphtha, fuel oil and other sources, mainly coal, accounted for 30%, 10% and 11% respectively. Dawn (2005) discusses the potential for coal as fuel for the fertiliser industry in Pakistan.

In 2003, China was the world's largest ammonia producer (Li, 2004). According to national statistics, in 2002, ammonia production reached 36.54 Mt and in 2003 increased further to 37.5 Mt. It was expected at the time that the ammonia production in China would continue to increase at a rate of 2~3% per annum in the coming decade. The forecast was accurate and the trend seems to continue until 2010. Wenshan (2000) discussed the situation of China's synthetic ammonia and urea production based on natural gas and oil. Global nitrogen fertiliser supply, demand and trends are discussed by Prud'homme (2012). World nitrogen fertiliser producers in 2010-11 are given in Figure 15 (IFA, 2013b).

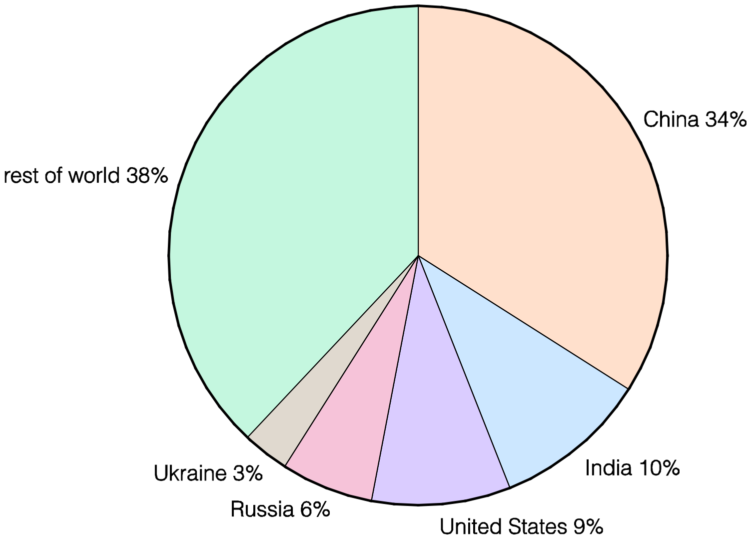

Figure 15 – Top world nitrogen fertiliser producers (2010-11) (IFA, 2013b)

Yara (2012) discussed urea production in China, which is based mainly on anthracite coal, highlighting that the growth in Chinese urea production slowed down in 2010 compared to 2009. However, the sustained increase in the price of anthracite coal in China lifted the break-even costs of production (*see* Figure 16). The slowing down of the growth is due to the authorities in China signalling a policy in the direction of increased focus on efficient production and improvement in nutrient use efficiency rather than further growth in production (*see* Figure 17).

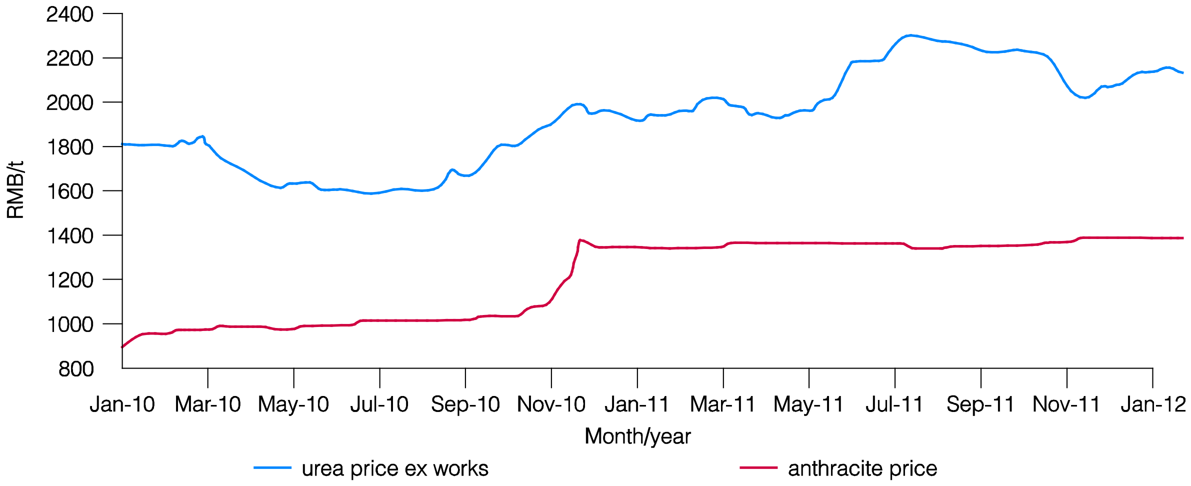

Figure 16 – Chinese urea cost and domestic anthracite price from January 2010 -12 (Yara, 2012)

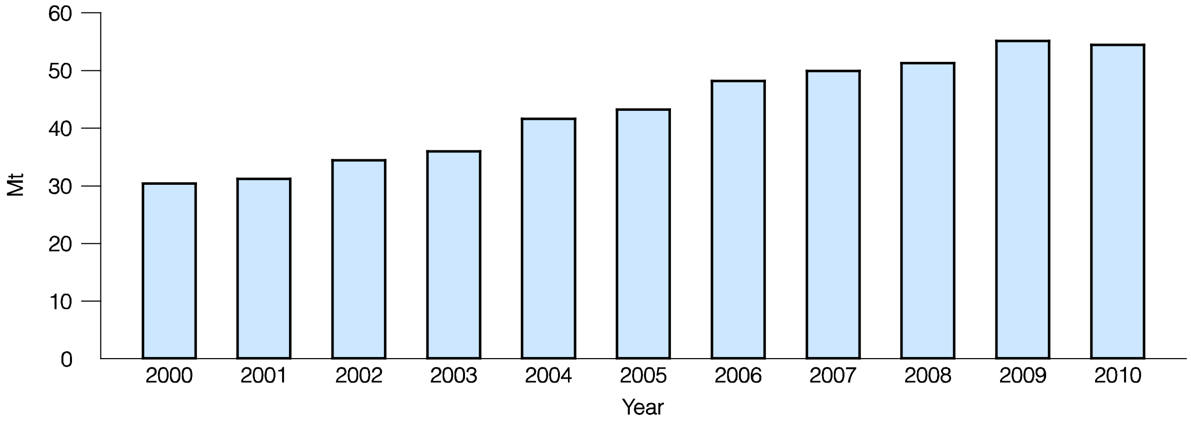

Figure 17 – Chinese urea production growth from 2000-10 (Yara, 2010)

In China, demand for coal in the chemical industry –according to OECD/IEA (2009) – comes mainly from the production of chemical products such as synthetic ammonia, urea, methanol and DME. Demand for coal continues to grow with increasing demand for chemical fertilisers as coal is the primary feedstock for ammonia synthesis in China. Output of chemical fertilisers rose 14% in 2006 to 53 Mt and synthetic ammonia production increase 7% to 49 Mt.

The findings of a market research report by the Fertiliser Department of China National Chemical Information Centre published in May 2011, included the following:

- China's fertiliser industry has enjoyed preferential policies in raw materials, transportation, taxes, water, electricity, gas and other aspects;
- the industry output ranked first in the world in 2011, accounting for approximately one third of the world's total output. The industry produces many varieties of nitrogen fertiliser. The output of urea, ammonium bicarbonate, ammonium chloride, ammonium sulphate and ammonium nitrate accounts for 60.3%, 9.2%, 4.5%, 1.2% and 2.4% of China's total output, respectively. 76.4% of China's nitrogen fertiliser is produced from coal as the raw material;
- China's nitrogen fertiliser production gradually increased in recent years. In 2009, output reached 48.637 Mt. However, due to the market downturn, output dropped to 45.21 Mt in 2010. In 2010, urea output also decreased to 54.70 Mt. Currently, there are 114 urea producers in China, of which 20 have a production capacity of over 1 Mt/y;
- China's nitrogen fertiliser consumption accounts for one third of the global total. It is forecast that, China's nitrogen fertiliser consumption will continue to grow but at a slower pace;
- due to the market downturn in the first half of 2010, China's nitrogen fertiliser producers operated at a loss. However, from late September, driven by the rise in export prices and the drop in supply, nitrogen fertiliser prices rose rapidly. The report considered that in 2011, the nitrogen fertiliser market would have many uncertainties, but overall, the situation would be better than in 2010;
- finally, as China's nitrogen fertiliser industry was facing oversupply and its competitiveness was considered relatively weak, it was forecast that during the '12th Five-Year Plan' period (2011-15), developmental and structural adjustments, improvements in existing plant and restrictions on the growth of new capacity, would be carried out.

Production capacity and volume by the end of 2012 are shown in Table 8. The raw material/feedstock share in the production of synthetic ammonia is illustrated in Figure 18 (Shulan, 2013). In September 2013, Marketinfoguide reported that according to a review by the CRI (2013), data at the end of 2012 shows that anthracite accounted for 50.5% of the total 71.3 Mt urea production capacity from 393 enterprises in China while non-anthracite urea production accounted for 18.5%. The trend is towards continuing increase of non-anthracite based production. The industry is moving into regions with rich coal resources. Advanced, large-scale facilities are being put into production in Mongolia, Xinjiang, Ningxia and Shanxi among other provinces. CRI (2013) statistics indicate that urea production capacity is currently 3.44 Mt in Mongolia with a further capacity under construction or planned for 9.36 Mt. This is expected to reach 12.8 Mt by the end of 2015. In Xinjiang, urea production capacity stands at 5.06 Mt with a further capacity (under construction and planned) to reach 4.18 Mt. By the end of 2015, this is expected to reach 9.24 Mt. The review discusses the many aspects of the nitrogenous fertiliser industry in China including the scale, costs, performance and restructuring of the industry (CRI, 2013). Analysis and forecasting the Chinese fertiliser industry was the subject of an in-depth review by the Beijing Shennong Kexin Agribusiness Consulting Company (BSNABC) published in February 2013.

Table 8 – Chinese nitrogen fertiliser industry production capacity and volume by the end of 2012 (physical quantity, 10,000 t) (Shulan, 2013)

	Synthetic ammonia		**Urea**	
	Production capacity	**Production volume**	**Production capacity**	**Production volume**
China	6850	6008.2	7148	6192.6
World	20300	16600	19150	16760
Percentage	33.7	36.2	37.3	36.9

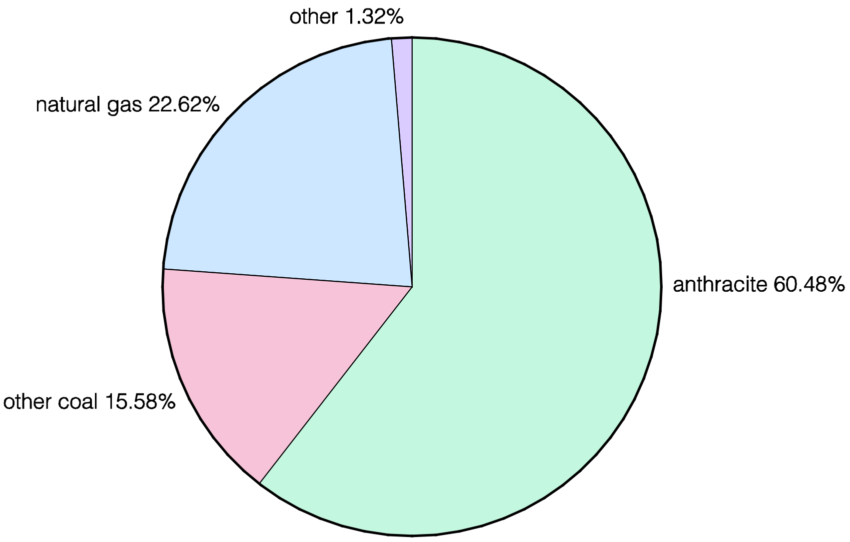

Figure 18 – Chinese synthetic ammonia by feedstock at the end of 2012 (Shulan, 2013)

3.1.4 Methanol

Methanol is produced following reactions between coal and steam producing syngas (synthesis gas) the components of which are carbon monoxide and hydrogen. These are then converted to methanol through an additional chemical reaction. Traditional uses of methanol include derivatives such as formaldehyde, methyl tertiary-butyl ether (MTBE) (a fuel octane enhancer), acetic acid and methyl methacrylate (a plastic additive). Fuel applications are one of the primary demand drivers (IHS, 2013a). Sutton and Roberts (2007) discuss methanol production through gasification being a key step in the return of chemicals from coal.

In 2012, China produced 43% (26.5 Mt) of the total world methanol representing 54% of the global capacity. However, IHS (2013a) consider that the global methanol industry is reaching the end of a significant wave of capacity expansions as capacity was added at the rate of 14.3%/y since 2007 whilst demand was growing at ~8.6%/y. In 2004, methanol was produced in the USA for mostly non-fuel usage. At that time, there were eighteen US methanol production plants, with a total annual capacity of over 2.6 billion gallons (~9.8 million m^3). However, most of the methanol was produced from natural gas. According to the Institute for the Analysis of Global Security (IAGS) (USA), coal was considered a potential and clean source of methanol. However, the recent discovery, exploration and use of shale gas in the USA makes it a strong competitor with coal in the US market. A commercial-scale power plant in Tampa, Florida, was built under the auspices of the US Department of Energy (US DOE) to prove the feasibility of converting coal to syngas on a large scale. For details on the technology *see* US DOE (2003). However, the syngas in the plant is utilised as fuel for gas turbine electric generators. Nevertheless, IAGS (2004) considered that the same proprietary process could be taken a step further, by reacting the carbon monoxide and hydrogen in the syngas over a catalyst, to produce methanol on a large scale.

IHS Chemicals carry out long-term market studies including plant capacities and supply/demand analysis on chemicals markets (www.ihs.com). In a recent global market study on projections for the period 2012-22, IHS found that global methanol demand, driven by China and boosted by olefin production, increased 23% during the two-year period of 2010-12 (IHS Chemical Week, 2013). Furthermore, annual demand for the product is expected to increase by >8% from 61 Mt in 2012 to 137 Mt in 2022. The numbers are significant especially when compared to the slowing of the annual increase in global methanol demand by 4% in 2008 and 2% in 2009. The demand growth, according to IHS (2013a) is being led by China across all derivatives, as well as fuel applications in China and the rest of the world. The industry is expected to advance to a more balanced position in 2015-16. In China, coal-based olefin plants are tipped to account for almost 15% of the total feedstock base for ethylene in 2015 from a current share of 2% (Pandey, 2013). In the USA, the driving factor behind methanol capacity additions is the abundant supply of shale gas while the availability of low-cost coal is the driving force in China. China also has large shale gas reserves. However, the country has little or no infrastructure to mine the shale gas, many formations of which are quite deep and require large quantities of unavailable water in the western provinces. In addition, there are no pipelines connecting western reserves to eastern population centres, thus creating another barrier to shale gas production. However, interest remains high in China's shale gas reserves both from the domestic government and international bodies. Methanol-to-olefins (MTO) and methanol-to-propylene (MTP) are discussed in greater detail in section 3.2.

3.1.5 Formaldehyde

Formaldehyde can be produced from coal indirectly through dehydrogenation and partial oxidation of MeOH using a silver catalyst, based on the following reactions:

$CH_3OH \rightarrow HCHO + H_2 \quad \Delta H = +$ 36,700 Btu/lb (~85,364 kJ/kg) mole

$CH_3OH + \frac{1}{2}\, O_2 \rightarrow HCHO + H_2O \quad \Delta H = -$ 67,300 Btu/lb (~156,540 kJ/kg) mole

Equilibrium conversion and potential side reactions are highly temperature dependent. The overall reaction temperature is controlled by the quantity of air (O_2) used, and the addition of inerts, such as water and/or nitrogen. In a typical MeOH oxidative dehydrogenation process to produce commercial grade formaldehyde, a mixture of methanol and water is mixed with air and recycled gas. The total feed mixture is then vaporised by heat exchange against hot reactor effluent. The vaporised feed mixture is fed into the catalytic reactor to form formaldehyde. Excess reaction heat is removed by generating steam. The reactor effluent, after cooling by heat exchanging with incoming feed, is scrubbed with water in the absorber to remove the formaldehyde product as a 55% solution. Water can be added to produce commercial grade formaldehyde at 37% concentration. A portion of the product gas leaving the top of the absorber is recycled, and the remainder is incinerated. Typical overall formaldehyde yield is in the range of 92% to 95%. (NETL, 2013).

3.1.6 Phenols

The potential utilisation of coal-derived phenolic compounds is discussed by Song and Schobert (2001). Phenol is one of the major industrial organic chemicals. Phenolic compounds are abundant in coal-derived liquids and include phenol, cresol, catechol, methylcatechol, naphthol, and their derivatives. Liquids from coal liquefaction, pyrolysis, gasification, and carbonisation are potential sources of phenolic chemicals, although certain processing and separation are needed. There are opportunities for coal-based phenolic chemicals, because industrial applications and potential new applications exist. Phenol remains the largest-volume chemical derived from benzene, and its production consumes about 20% of the total benzene production. In addition to synthesis, phenol is also produced in smaller quantities from tar and coke-oven water from coal coking and low temperature carbonisation of low-rank coals. Phenols, cresols and xylenols can be recovered by washing coal-derived liquid with alkaline solutions and treating the acid solution with CO_2.

Although the market for phenol is relatively small and one large, commercial, coal liquefaction plant could saturate a market, proactive measures can open up new opportunities and new applications. If phenol can be produced in larger quantities, other applications of phenol may become attractive in addition to its current uses, which may also become competitive to some other industrial manufacturing processes that currently do not use phenol (Song and Schobert, 2001).

3.2 Recent and new developments/products

Specialty chemicals are of relatively high value with diverse end product markets. They are generally characterised by their innovative aspects. Products are sold for what they can do rather than for what chemicals they contain and include electronic chemicals, industrial gases, adhesives and sealants as well as coatings, industrial and institutional cleaning chemicals, and catalysts. The definition of fine chemical varies by approach, the term is used generally to refer to products in the chemical industry that are manufactured in small quantities but in a large variety for greater added-value than those that are mass produced. Examples of fine chemicals include pharmaceuticals, agricultural chemicals, products for electronic applications, paints and coatings, dyes and other colourants, adhesives, synthetic detergents and cosmetics. According to Meyring and Jin (2012), the main dynamic in the increasingly competitive pharmaceuticals sector is the shift of manufacturing to countries such as China and India. The global pharmaceutical outsourcing market is growing, particularly in the fields of highly potent active pharmaceutical ingredients (API) and bio-pharmaceuticals. China and India have the fastest growing domestic pharmaceutical markets, which are expected to grow at a compound annual growth rate (CAGR) of 14% from 2010 to 2015 (IHS, 2012). China's pharmaceuticals industry output is expected to reach US$1.57 billion by 2020 (Meyring and Jin, 2012).

Tsinghua University, Dalian Institute of Chemical Physics of the Chinese Academy of Sciences, and others are developing a coal-to-aromatics technology. Huadian Coal Industry Group has constructed and commissioned the world's first 10,000 t/y coal-to-aromatics pilot plant. According to Yuzhuo (2013), efforts will be made to eventually develop the first industrial-scale, coal-to-aromatics demonstration project, which will focus on key technologies such as design and enlargement of the methanol-to-aromatics reactor, reaction heat control, engineering optimisation, as well as industrial application of paraxylene catalysts. Aromatics are discussed in detail by Song and others, 2005.

3.2.1 Carbon-based materials

Song and others (2005) discuss in detail the strategies and status for producing carbon materials from coal. The authors consider that since carbon dominates the composition of coals, coals can be considered as already carbon-based materials. Coal can be used for making not only the industrially important materials such as coke, pitch, and activated carbon and carbon molecular sieves, but also for making new carbon materials such as fullerenes and carbon nanotubes. It can also be used for making materials that have potential agricultural and industrial applications such as humic acids and coal/polymer composites. The authors consider that the incentive comes from the combination of the highly aromatic nature of coals with the expanding opportunities for aromatic specialty and/or fine chemicals and monomers, especially those with polycyclic ring systems, and continuing demand for carbon based materials. Minchener (2011) discussed in detail, coal-to-oil, gas and chemicals in China, and opportunities for research in coal derived chemicals were the subject of a study by Samuel and others (2008).

The Consortium for Premium Carbon Products from Coal (CPCPC) was managed by The Pennsylvania State University (USA). It focused on the development, commercialisation, and promotion of technologies to produce high value-added carbon products from coal and coal-derived feedstocks. The consortium ran from 1 October 1998, through 31 December 2010. CPCPC was an industry-driven consortium whose members proposed research initiatives in areas they identified as being strategically important to the coal and carbon/graphite industries. The CPCPC had approximately 130 members over a 12-year period. Members included: anthracite and bituminous coal producers, manufacturers of specialty carbon and graphite products, activated carbon producers, municipally-owned water treatment facilities, anthracite filter media producers, carbon fibre and composite producers, aluminium producers, carbon black and coal tar pitch producers, battery manufacturers, coal-fired electric utilities, humic acid producers, firms specialising in coal cleaning and plant construction and academia (CPCPC, 2010).

Numerous projects were undertaken within the CPCPC programme. These include 'technical and economic assessment of mild coal extraction, activated carbons for CO_2 capture from coal-derived pitch/polymer blends, mechano-thermal method to produce carbon nanotubes from anthracite coal, carbon foam production through plasticisation of coal tar binder pitch, preparation and characterisation of coal-derived carbon materials as novel adsorbents for sulphur removal from liquid fuels, novel electrochemical capacitors using coal-derived carbons, removal of SO_2 and NOx over coal/petroleum-based activated carbons, investigation of carbon foams produced from pitch via blowing agents and premium carbon products from coal: continuation of a sulphur-based approach'. These and many other projects and findings are presented in detail by Miller (2007). For the final reports on all projects visit http://www2011.energy.psu.edu/cpcpc/about.html.

Premium carbon products and organic chemicals from coal was the subject of a review by Song and others (2005). The objective was to review carbon materials and organic chemicals from coal and to identify approaches and strategies as well as new directions for research. The review focuses on the unique, premium carbon products as materials, and the phenolic and aromatic compounds that can be converted to organic chemicals.

3.2.2 Olefins and polymers

Olefins, also called alkenes, are any unsaturated hydrocarbon containing one or more pairs of carbon atoms linked by a double bond. Olefins, such as ethylene and propylene, can be produced from coal gasification indirectly by catalytic cracking of MeOH, commonly called the methanol-to-olefins (MTO) process (NETL, 2013). Olefins are used as building block chemicals for making other petrochemicals and polymers. Commercially, the most important olefins are ethylene, propylene and butadiene. Other olefins used in the production of petrochemicals and polymers include butene, isobutene (or isobutylene), hexane and octane. According to Ramesh (2013), olefin production has and continues to boost demand for coal-based methanol in China.

Polymers are substances that contain a number of structural units joined by the same type of linkage. In the natural world, they have been around since the beginning of time. For example, starch, cellulose, and rubber all possess polymeric properties. Man-made polymers have been studied since 1832. According to Parsons Brinckerhoff and Global CCS Institute (2011), a new approach to polymer processing is to combine traditional feedstocks with CO_2 to synthesise polymers and high value chemicals. The technology transforms carbon dioxide into polycarbonates such as polypropylene carbonate and polyethylene carbonate, using a zinc-based catalyst in a reaction with epoxide molecules.

Today, the polymer industry is larger than the aluminium, copper and steel industries combined. Polymers have applications that far exceed those of any other class of material available to man. Current applications extend from adhesives, coatings, foams, and packaging materials to textile and industrial fibres, composites, electronic devices, biomedical devices, optical devices, and precursors for many newly developed high-tech ceramics. In agriculture and agribusiness, polymeric materials are used in and on soil to improve aeration, provide mulch, and promote plant growth and health. In medicine, many biomaterials, especially heart valve replacements and blood vessels, are made of polymers such as Dacron, Teflon and polyurethane. In developing consumer products, plastic containers, for example, of all shapes and sizes are light weight and less expensive than the more traditional containers. Clothing, floor coverings, garbage disposal bags, and packaging are also other polymer applications. In industry automobile parts, wind shields for fighter planes, pipes, tanks, packing materials, insulation material, wood substitutes, adhesives, matrix for composites, and elastomers are all polymer applications used in the industrial market. Even in sports, playground equipment, various balls, golf clubs, swimming pools, and protective helmets are often produced from polymers. Hence the value of developing coal derived-polymers, in theory to use existing and domestic sources instead of importing the necessary products to develop such polymers.

According to Samuel and others (2008), worldwide consumption of synthetic polymers is: plastics 56%; fibres 18%, synthetic rubber 11%; and coatings and adhesives 15%. In general, polymers are divided into thermoplastic and thermosetting materials The essential difference between thermoplastic and thermosetting materials is that thermoplastics remain permanently fusible so that they soften and eventually melt when heat is applied allowing the material to be reclaimed and recycled, whereas cured thermoset polymers do not soften, and only char and break down at high temperatures. Compared with thermoplastics, thermosetting materials are generally harder, more rigid and more brittle, and their mechanical properties are not heat sensitive. They are also less soluble in organic solvents. They have many applications, for example, as epoxy resins they are used in bonding, encapsulation, laminating and surface coating. As melamine formaldehyde they are used in work-tops, tableware, buttons, electrical insulation. As urea formaldehyde they are used in electrical fittings, paper and textile coating and wood adhesives. As polyester they are used in car manufacture and carbon fibre used in bicycles and sail boats. Thermoplastic polymer resins are commonly used today. Examples of products manufactured with them include: water bottles (PET), packaging containers (polypropylene), safety glass lenses (polycarbonate), toys (PBT), window frames (vinyl), carrier bags (polyethylene), piping (PVC), aeroplane armrests (PEI) and footwear (nylon).

Based on the above, in the end use, plastics can be divided into commodity plastics and engineering plastics. The latter are superior in mechanical properties, possess high durability and compete with metals, ceramics and glass in a variety of applications. They are primarily used in transportation (cars, trucks and aeroplanes), construction (housing, plumbing and hardware), electrical and electronic parts (business mechanics and computers), communications (consoles, TVs, telephones) and consumer goods such as cookware. Heat resistant polymers have significant commercial value. These are discussed in detail by Samuel and others (2008).

The **Olefin polymer** is a macromolecular compound that forms during polymerisation or co-polymerisation of unsaturated olefin hydrocarbons (R, R' = H, CH_3, C_2H_5, etc). The best known olefin polymers are polyethylene R = R' = H) and polypropylene R = H, R' = CH_3) (The Free Dictionary, 2013). According to Tullo and Tremblay (2008), the future vision for coal is to make olefins, which can be transformed into chemical industry mainstays such as ethylene oxide, polyethylene, and polypropylene. Newly developed technologies that can convert MTO are making this goal a reality.

Olefin polymers are characterised by high crystallinity, which imparts satisfactory mechanical strength, high dielectric constants, and resistance to the action of corrosive substances (with the exception of strong oxidising agents, for example, HNO_3). However, they have low adhesion to metal and other surfaces. To improve adhesion, polar groups, such as >CO and –COOH, are introduced into the macromolecules by co-polymerisation or treatment of the polymers. This makes it possible to extend the use of olefin polymers. Olefin polymers are unequalled among thermoplastic materials in the scale of their industrial production and their wide range of uses as films and fibres, electrical insulation coatings, and moulded objects. Important, industrially-produced olefin polymers include not only polyethylene and polypropylene but also their copolymers, ethylene-propylene rubbers. The importance of these rubbers comes both from their valuable technical properties and from the availability of cheap petrochemical raw materials (ethylene and propylene).

In 1973, world production of polyethylene was about 10 Mt, and production of polypropylene was about 2.4 Mt. Polyisobutylene R = R' = CH_3), as well as copolymers of isobutylene (for example, butyl rubber), are of industrial significance. Poly-l-butene is produced on a small scale in the USA and the Federal Republic of Germany; it is characterised by the absence of creep and is used for the production of pipes. Highly heat-stable olefin polymers are also produced—for example, poly-4-methyl-l-pentene, which is produced in the UK and the USA and has a Vicat softening point of 180°C. A method has been developed in the USSR for the production of polyvinylcyclohexane, with a Vicat softening point of 225°C. Polymers of this type are promising materials for a number of uses in medicine and radio electronics. The Vicat softening temperature can be defined as the temperature at which a flattened needle with a 1 mm^2 tip penetrates 1 mm into the surface of a specific sample.

Cohen and others (2012) discussed the current status and potential future of China's CTO industry. The authors consider that by the end of the 12th Five-Year Plan (2011-15), China's olefin production (including CTO and MTO) may exceed 56 Mt resulting in some overcapacity. After 2015, overcapacity could accelerate further, reaching 71 Mt (*see* Figure 19).

Modern production of chemicals from coal involves mainly gasification to produce syngas and subsequently products such as methanol which is converted to olefins (methanol-to-olefins, MTO) including ethylene and propylene (methanol-to-propylene, MTP), producing ethanol from acetic acid (AA) and manufacturing ethyl glycols such as mono-ethylene-glycol (MEG) via oxalate esters. In addition, non-fuel uses of coal include, coal treatment processes using methodologies such as solvent-extraction techniques that produce low ash, low sulphur, coal-based chemical feedstocks; and waste utilisation, including recovery, processing, and marketing of products derived from sulphur, carbon dioxide, nitrogen, and ash from coal.

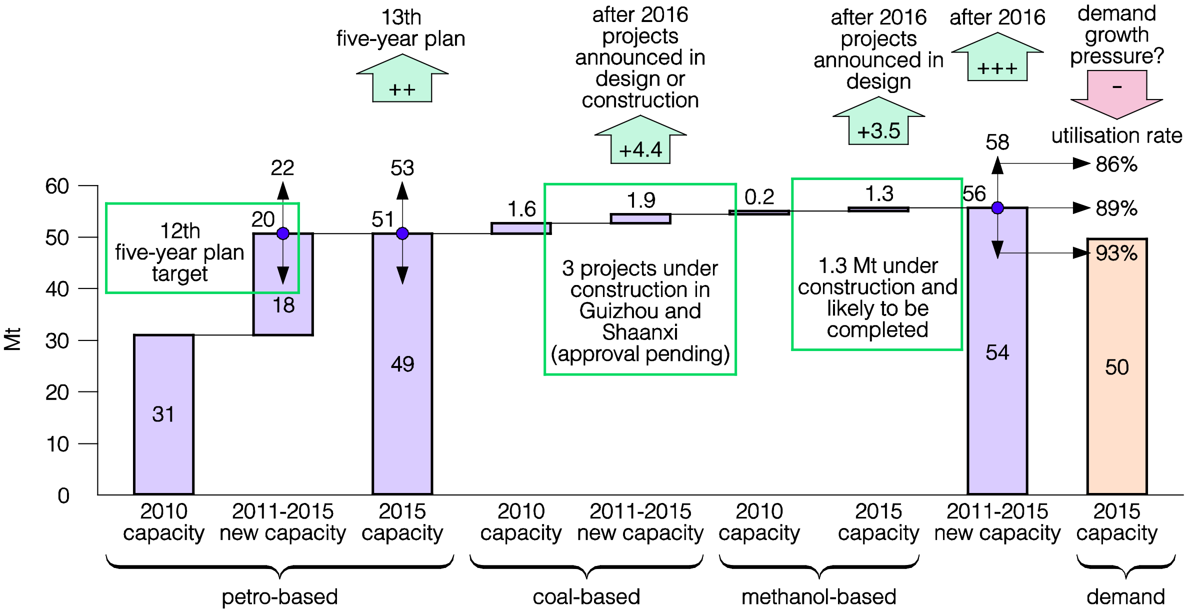

Figure 19 –China olefin capacity 2010 versus 2015 (Cohen and others, 2012)

3.2.3 Ethylene glycols

Ethylene glycol is a clear, odourless, viscous liquid that can produce dramatic toxicity. In an industrial setting, it is used as a solvent or as the raw material for a variety of processes. It is found most commonly as antifreeze for automotive cooling systems and hydraulic brake fluid. The humectant (a hygroscopic substance used to keep things moist) properties of ethylene glycol products also make them ideal for treating textile fibres, tobacco, paper adhesives, printing ink, leather and cellophane. It's used in the manufacture of polyester films and fibres, polyethylene terephathalate (PET) solid state resins, plasticisers and elastomers. It's commercially available in three grades: fibre grade, industrial grade and antifreeze grade. Ethylene glycol is widely used as an industrial organic intermediate.

MEG is considered an important, commercially available ethylene glycol, accounting for about 90% of global production. Diethylene glycol (DEG) and triethylene glycol (TEG) are produced as by-products in the manufacture of MEG. MEG is used predominantly in the manufacture of polyethylene terephathalate (PET) fibre, more commonly known as polyester. Polyester fibre is a popular, versatile and in increasingly greater demand synthetic fibre. Polyester has wide-ranging use as filament yarns in clothing, furnishings, and technical textiles; and as staple fibres in bed sheets, bedspreads, curtains and draperies. Other uses for MEG include PET for bottles (for example, water), PET film, and use in antifreeze and other industrial uses (Nexant 2011). According to Nexant (2011), a migration from conventional ethylene-based MEG production to coal-based production could potentially lead to a shift in the global MEG market. Global MEG consumption in 2009 is shown in Figure 20 (Nexant, 2011). Global MEG trade, historic, existing and future forecast, is shown in Figure 21 (Chemsystems, 2010). According to Yuzhuo (2013), coal-to-MEG technology is available in Japan and the USA. The first coal-to-MEG commercial-scale demonstration project in the world (Tongliao GEM Chemical 200 kt per year) was built in China and began operation in December 2009. The facility includes several technologies including some developed in China and aims to demonstrate, at industrial scale, the economic feasibility and actual operation of MEG production through carbonylation and hydrogenation of synthesis gas. In addition, the focus of the R&D includes the scale-up of major equipment, such as dimethyl oxalate synthesis reactors and dimethyl oxalate hydrogenation reactors, optimisation of technologies for wastewater treatment and reuse, MEG distillation efficacy and product quality improvements, and identification of other economic and practical coal-to-MEG routes (Yuzhuo, 2013).

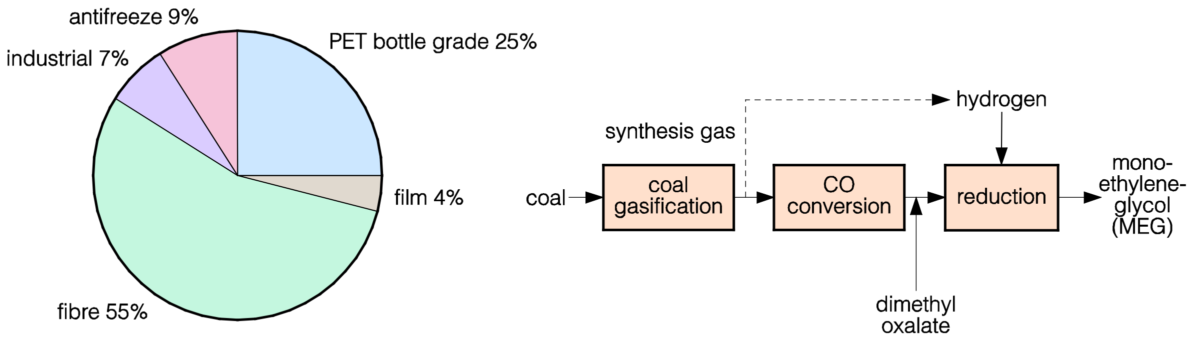

Figure 20 – Global MEG consumption (2009, ~18 Mt) and coal-to-MEG conversion process (Nexant, 2011)

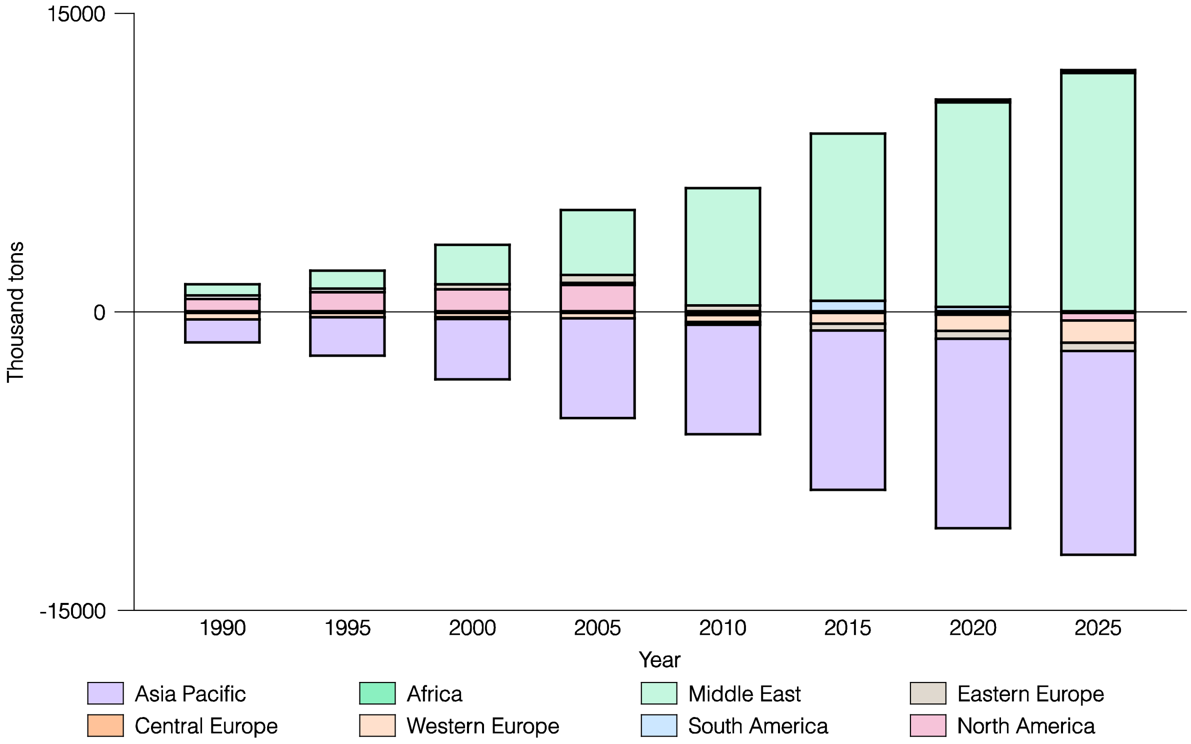

Figure 21 – Global MEG trade by region from 1990 to 2025 (Nexant, 2010)

3.2.4 Dimethyl ether (DME)

According to Lee and Gogate (1992), **DME** can be produced effectively from syngas in a single-stage, liquid phase process. The origin of the syngas includes a wide spectrum of feedstocks including coal. DME is used as a propellant in aerosol formulations to replace chlorofluorocarbons. It is non-toxic and degrades easily in the troposphere. Several aerosol-based household products include colognes, hair sprays and dyes, personal care mousses, antiperspirants, and air fresheners. DME can also be used as an intermediate for the preparation of many chemicals including methyl sulphate, which is an important commercial commodity as a solvent, and also as an electrolyte in high-energy density batteries. Although DME has been used for decades in the personal care industry, it is now being increasingly exploited for use as a clean-burning alternative to LPG (liquefied petroleum gas), diesel and gasoline (IDA, 2013).

3.3 Developments in China

A recent IEA CCC report by Minchener (2011), provides a review of the overall coal-to-chemicals products sector in China, which includes various coal-to-oil and coal-to-gas developments together with the key coal-to-chemicals initiatives, policy and strategy issues in the country. Therefore, only the most recent developments in China are discussed here.

Methanol production in China rose to nearly 11 Mt in 2006. In 2009, in a bid to mitigate rising reliance on imported oil, coal-to-liquids projects to produce chemicals have received greater attention. For example, DME was listed in the national medium- and long-term development plans for science and technology. By 2010, DME production increased by 4 Mt. The share of coal in the Chinese chemical industry in 2005 was 4.6% (96 Mt), in 2010 4.7% (180 Mt) and is projected to increase to 7.9% (250 Mt) by 2020. However, despite initially encouraging such projects, the authorities are now taking a more cautious approach towards new ones as these not only raise demand for coal in a tight market but also impact the environment and the scarce water resources in the coal bearing regions. Jianjun Tu (2012) discusses water use with coal in China, including the coal-to-chemicals industry, which stood at 2% of the total in 2008. OECD/IEA (2009) discuss the coal-to-chemicals and coal-to-liquids policies in China.

IHS (2013a) forecast that China's methanol consumption will triple from 31 Mt in 2012 to 97 Mt in 2022. IHS (2013a) consider that over 40 Mt of new Chinese methanol capacity, forecast for the period 2012-22, is to supply the market with the downstream derivatives MTO, MTP and/or DME. According to IHS (2013a) in 2012, Northeast Asia, Europe and North America were the world's largest methanol importing regions (>80%). Europe is forecast to increase its imports moderately whereas Northeast Asia is expected to triple its methanol imports in the period 2012-22. The large new capacity to be built in North America using shale gas is expected to balance the situation there by 2022. The Middle East and South America continue to be the two largest exporting regions (70%) (IHS, 2013a). The top 10 companies in coal-based methanol in China are listed in Table 9 (Ramesh, 2013).

Table 9 – The top ten companies in coal-based methanol production in China in 2012 (Ramesh, 2013; IHS 2012)

Company	Capacity, Mt/y
HNCC Group	1900
Yankuang Gruop	1700
China BlueChem	1600
Shanghai Huayi	1400
Berun Unichem	1350
JiuTai Energy	1000
Kingboard Chem	970
ENN Group	720
East Hope Group	700
Huadian Yutianhua	610

According to CCR (2013), in addition to four coal-to-methanol plants currently in operation, 54 MTO projects and 27 coal-to-MEG projects are either under construction or in the planning stage. Current coal-to-MEG capacity in China is approximately 1 Mt/y with forecasts of ~2 Mt/y capacity increase by 2015 and a potential of over 12 Mt/y by 2025 (Nexant, 2011). According to IHS (2013a), by 2020, it is forecast that the coal-based olefin capacity in China could reach 15 Mt/y and coal-to-MEG capacity could reach 2 Mt/y.

As part of its effort to diversify energy sources, China developed coal-to-chemicals plants in Ningxia region at a cost of around Yuan 100 billion (~US$13 billion, 2007). Shenhua Ningxia Coal Industry Group invested a further Yuan 16.4 billion (~US$2.2 (2007)) in 2008. The first group of plants to produce methanol and other chemicals from coal were constructed in the Ningdong Chemical Resource Base which is located near coal deposits containing 80% of Ningxia's known coal reserves. The facilities reportedly convert more than 5 Mt of coal annually into dimethyl ether, olefin and methanol. Several CTL plants are under construction and expected to go into production in 2020 when the base will have a liquefaction capacity of 10 Mt and be able to produce 830,000 t of methanol and 1.22 Mt of olefin (CoalTrans, 2007). In China, in May 2013, two MTO plants, two MTP plants and four MEG plants were in commercial operation and one MEG plant was operating at pilot scale (Pang, 2013) (*see* Figure 22).

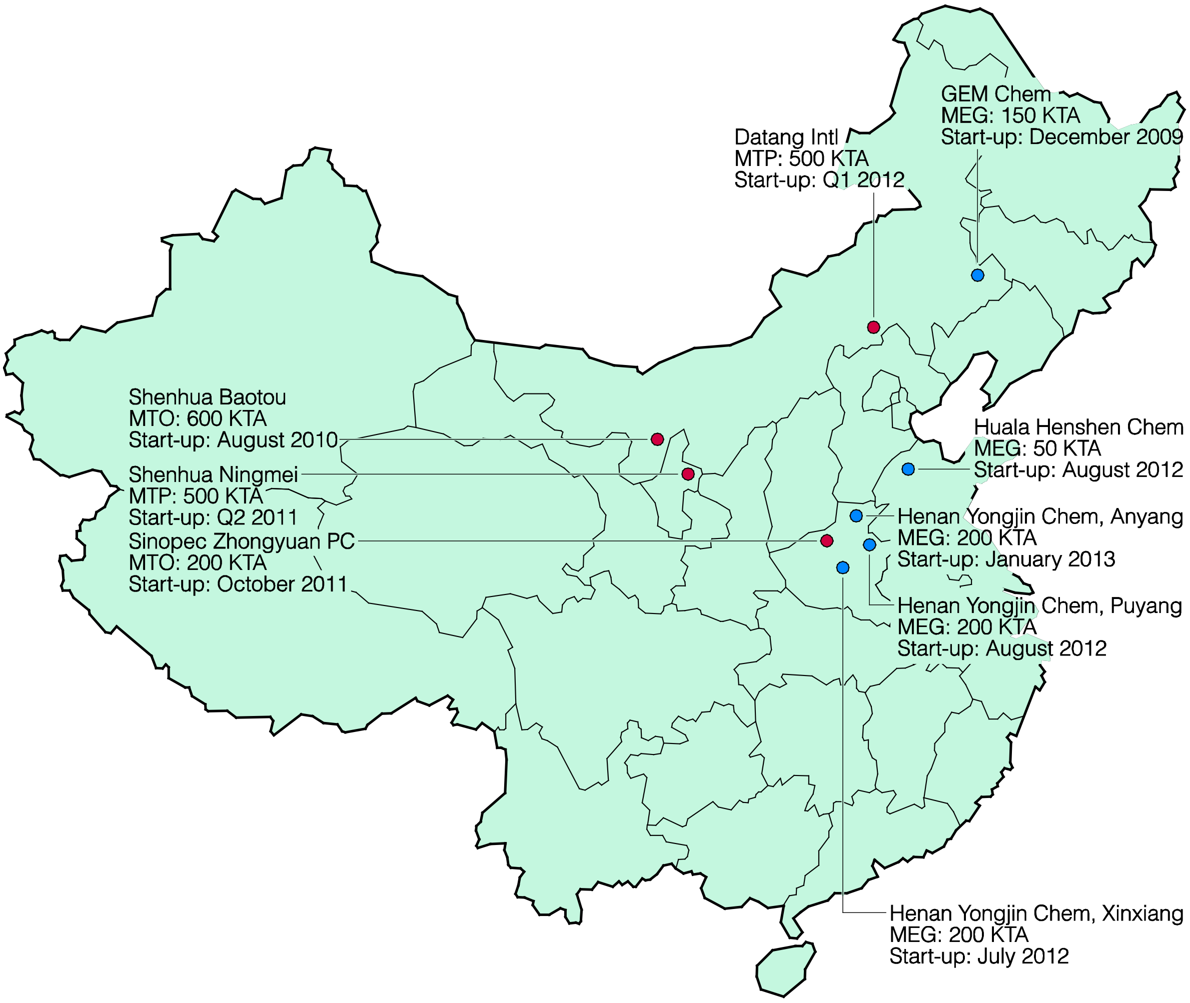

Figure 22 – MTO, MTP and MEG plants currently in operation in China (Pang, 2013)

Meyring and Jin (2012) discuss China's chemical industry entering a new era with sustainability. The authors state that although most of the Chinese coal is used for power production, the coal-to-chemicals sector is growing fast. As of 2012, the coal-to-chemicals sector was connected to five different chemical supply chains: methanol, olefins, PVC, aromatics and ammonia/urea. Six CTO projects are expected to come on stream by 2016, most supporting the manufacture of polyethylene and polypropylene resins. Another 13 coal-to-chemicals projects are at various stages of development. Most coal chemical projects have targeted the fuel market with products such as synthetic oil, methanol and DME, but slowly, units are aiming for higher value-added markets for plastics and fibres. According to AsiaChem (2013), the Ministry of Energy listed 15 coal processing projects (RMB 400 billion) in the provinces of Xinjiang, Inner Mongolia and Ningxia. The projects focus on coal-to-oil, olefins and natural gas. The Shenhua Group, China's largest coal producer, in a joint venture with General Electric, have recently formed the GE Shenhua Gasification Technology Company. The Zhong Tian He Chuang Energy Company, a joint venture between Sinopec and China Coal Group, plans to build a 350,000 t/y polypropylene plant in Ordos (Inner Mongolia) to produce a full line of polypropylene (PP) resins, including homopolymers, random copolymers and impact copolymers, to serve the Chinese chemical market.

In 2011, the Chinese authorities implemented stricter controls on the proliferating coal-to-chemicals projects due to environmental and technological concerns. This occurred as new capacity became greater than demand. As a result, the National Development and Reform Commission (NDRC) centralised approval of these projects, stripping local governments of these powers (Kempf, 2011). New rules demand that a coal-based olefin plant must have, at least, a 500,000 t/y capacity, while a 1 Mt/y limit is set for coal-to-methanol, coal-to-methyl tertiary butyl ether (MTBE) and coal-to-liquids facilities. For coal-to-natural gas projects, the capacity must be at least 2 billion m^3/y, while a coal-to-mono-ethylene-glycol (MEG) plant must at least have a 200,000 t/y capacity. The authorities continue to encourage the manufacture of key products such as nitrogen fertilisers, agricultural chemicals, chloro-alkaline, sodium carbonate, calcium and carbide, which are produced by six companies generating annual sales revenue of RMB 100 billion. The authorities plan to increase the number of companies operating in this segment. The 12th Five-Year Plan (2011-15) places special attention on developing organic materials, resins, synthetic fibres and monomers as, in China, there is a general oversupply of low-end petrochemical products and a shortage of more sophisticated and higher-valued items. Hence, the industry is undergoing an upgrade driven by demand for more sophisticated, specialty chemicals. The 12th Five-Year Plan aims to increase the output of such chemicals and materials. Data from the National Bureau of Statistics of China indicates that in 2011 growth in specialty chemicals was 21% and 7% for other basic chemicals. The Chinese specialty chemicals market saw a total revenue of US$ 74.6 billion in 2011, representing a compound annual growth rate of 10.9% between 2007 and 2011 (source: Specialty Chemicals in China, 7th May 2012, Market Research Report). A characteristic of the sector, however, is its fragmentation. There are almost 10,000 domestic specialty chemicals companies in China, far more than for any other chemical segment, but they are unable to meet China's demand due to technological lag. A total of 44 local companies are yet to develop their product portfolios adequately to provide complete solutions to customers. It is expected that growth in basic chemicals will slow down, while specialty chemicals will experience increasing growth, especially as end-use industries progress and develop further (Meyring and Jin, 2012). Park and Kim (2012) considered that despite the high uncertainties surrounding the specialty coal-to-chemicals industry, such as technological issues, environmental regulations and water consumption, growth of the sector could have a considerable impact on supply and demand dynamics. Xu and Wang (2013) examined China's coal-to-chemicals strategy and governance challenges.

According to Parsons Brinckerhoff and Global CCS Institute (2011) Princeton University's Carbon Mitigation Initiative (USA) reported on carbon capture and storage opportunities in China, noting the following: 'China is unique in the large number (nearly 400) of existing and planned projects for making ammonia, methanol, and other fuels and chemicals from coal, natural by-products of which are nearly pure CO_2 streams. Some of the 20 carbon capture and storage demonstration projects called for by the G8 might be expeditiously located in China – taking advantage of the relatively low cost of capturing these CO_2 streams (compared with capturing CO_2 from power plant flue gases). The researchers' analysis identified 18 coal-chemicals/fuels facilities, each emitting 1 Mt/y or more of CO_2 that are within 10 km of prospective deep saline aquifer CO_2 storage sites and an additional eight facilities within 100 km.' Carbon capture and storage is discussed in several IEA Clean Centre reviews the latest of which is by Mills (2012). For other, detailed reviews on the subject visit www.iea-coal.org.

Lu (2013) considers that China is in the midst of a surge in coal-to-chemicals investment, with the competitiveness of these projects, which are based on a new generation of coal-to-chemicals technologies, hinging on the specific economics of the Chinese coal market.

4 Commercial application

In 2010, 41 large-scale, coal-to-chemicals plants were in operation worldwide, 35 of which were in China. According to Nexant (2006, 2012) China has shown continued activity in adopting non-fuel uses of coal, largely in converting coal to ammonia/urea, to calcium carbide-PVC and more recently to methanol and other chemicals. According to Xiangkun (2013), traditional and modern coal-to-chemicals plants in China, in 2013 include 900 ammonia plants (49.95 Mt/y), 221 methanol generating facilities (26.22 Mt/y) and 57 DME producing plants (6.2 Mt/y).

Coal as feedstock for chemical production is driven by a number of factors including (Sutton and Roberts, 2007):

- rapid increases in energy demand;
- higher oil and gas prices which make the coal routes to chemicals competitive;
- the emergence of new lower cost technologies for the large scale conversion of coal-to-chemicals;
- the strategic drive of coal rich countries to reduce reliance on imported oil or gas; and
- the ability for companies to own coal assets to give a long-term feedstock supply at a predictable price.

High value added carbon products from coal and coal-derived feedstock were the focus of the Consortium for Premium Carbon Products from Coal (CPCPC) as discussed in Chapter 3. Among the projects sponsored by the CPCPC and now commercially available are the all coal anode and the asymmetric electrochemical capacitor derived from coal. In a collaborative project between West Virginia University, Koppers Inc and Alcoa, (USA) test anodes representative of those used for aluminium smelting were developed. The all coal anode project produced materials that met industry standards for both binder pitch as well as anode-grade coke. Further research and development efforts, mainly funded by the US DOE National Energy Technology Laboratory (NETL) led to developing processes with enhanced economics for carbons for metal smelting applications. An environmentally clean process for producing binder pitch using raw coal as the main feedstock was developed. The process uses hydrogenated solvents to dissolve coal, allowing removal of mineral matter via centrifugation. The resulting feedstock is then distilled to create binder pitch, and the coal solvent is recovered and reused. Technical advances achieved included using mild hydro-treatment of coal liquids to produce an effective and cheaper solvent than previously achievable. The amount of hydrogen used was a factor of ten less than previously considered necessary and about 90% of the dry-ash-free coal was liquefied successfully. Commercial trials for binder pitch began in late 2007. The binder pitch was incorporated in arc furnace electrodes manufactured by GrafTech International Holdings Inc (USA). Twenty-one such electrodes have been produced, measuring 20 inches (~0.51 m) in diameter by 96 inches (~2.44 m) in length, and weighing over 0.75 t each (CPCPC, 2010).

The UK Centre for Applied Energy Research (CAER) investigated bituminous and anthracite coal use in electrochemical capacitor development. Lipka (2008) reported that by exposing coal (in ground form) to steam at 900°C for 20 minutes or less, porous carbons suitable as active materials for electrochemical capacitors can be prepared.

The majority of recently built gasification facilities utilising coal as feedstock for producing chemicals and thus, for non-fuel uses, are in China (*see* Table 4). The drive to construct and operate these facilities is a strategic issue for the Chinese authorities in order to reduce their dependence on imported feedstock such as oil or gas and use the abundant reserves of coal in the country (Boswell, 2012). Nevertheless, China's coal imports increased from 126 Mt in 2009 to 289 Mt in 2012 (Jianjun Tu, 2013). As seen in Table 4, a number of coal-to-chemicals facilities are already in operation and some are in the pipeline. The materialisation of the planned projects depends on (Nexant, 2010):

- infrastructure availability: existing means are in place for distribution of coal by rail and barge as well as via minemouth utilisation;
- cost advantage/stability: coal costs less than other hydrocarbon fuels/feedstock and is historically less volatile in price;
- diversity: utilisation of coal insulates against the price and availability shock potential of oil/natural gas.

According to Tullo and Tremblay (2008) coal's potential as a chemical raw material is greatest in China, India and the USA as these countries have approximately half of the world's coal reserves combined and seek to reduce dependence on foreign resources for oil and gas. As a result, they are exploring, for example gasification of coal to make methanol. In 2008, 14 coal-to-chemicals project licenses were granted by GE Energy in China. Half of these projects would produce ammonia, and most of the remaining projects yield methanol. The main uses for the methanol will be manufacturing chemicals and dimethyl ether (DME). Eastman Chemicals (USA) is involved in new coal-to-chemicals gasification projects in the USA. In a partnership with Green Rock Energy, the company is constructing two US$1.6 billion projects to make hydrogen, ammonia, methanol, and downstream chemicals from the coal-like refinery by-product, petroleum coke, otherwise known as 'petcoke'. Other chemical companies are looking to increase their involvement in coal and petcoke as well.

Issues with regard to using coal to produce chemicals include environmental considerations as well as impurities in coal. For example, in the USA according to Tullo and Tremblay (2008), environmental considerations have been an obstacle to coal-based chemicals due to CO_2 production, unless a facility is located in an area where disposal of the CO_2 at reasonable cost is possible. The obstacle remains even if there was no immediate pressure but carbon taxes are expected to be enacted sometime in the future. Technologies to capture impurities also add costs, but they are not considered as problematic as CO_2. In coal-to-chemicals, some of the carbon is captured in the final products themselves. In methanol production, for example, a large percentage of the carbon goes into the methanol. The closer the process gets to producing hydrogen or products with high hydrogen-to-carbon ratio, more of the carbon is converted into CO_2. In addition some of the CO_2 from a chemical-oriented gasification complex can be used to make a urea fertiliser (Tullo and Tremblay, 2008). Energy efficiency and environmental evaluation of all coal conversion technologies including coal-to-chemicals is the subject of research at the China Coal Research Institute (CCRI), China Coal Technology & Engineering Group (CCTEG) (Liu, 2013).

Instead of releasing the excess CO_2 into the air, chemical companies are considering enhanced oil recovery, whereby CO_2 is injected into the ground to pressurise oil wells and make them more productive. Eastman is considering this technology for its Gulf Coast projects. Dakota Gasification, which makes methane and chemicals from coal in Beulah, ND (USA), the only lignite-to-synthetic natural gas plant in the USA for >25 years, sells its by-product CO_2 to oil fields in Saskatchewan (Canada). However, according to Tullo and Tremblay, 2008), observers note that the market for such CO_2 is limited. Nevertheless, chemical-oriented gasification complexes are considered to lend themselves to such CO_2 management schemes. As the plants use pure oxygen in the gasification process, a side benefit is a purer by-product CO_2 stream that is more valuable to markets such as oil recovery.

Eastman Chemicals Company (USA) has been producing chemicals from coal for nearly 30 years in Kingsport, TN, USA. In 2011, 25% of the coal consumed at the facility was used to produce acetyl chemicals, acetic acid and acetic anhydride which are commonly used in pharmaceutical and industrial applications and can be processed into products like paints, fibres, photographic film, tool handles, cigarette filters and more. According to Eastman Chemical Company (2011), the organisation is the only US manufacturer that produces acetyl chemicals from coal through gasification. In Kingston, the company gasifies coal to make methanol, which is converted to chemicals. It is because of this experience with coal that the company is encouraged to invest further. The firm's coal-based production stream represents only about 20% of its product volumes but has provided about half of its profits in recent years (Tullo and Tremblay, 2008). The Kingsport plant is one of the earliest and most notable coal gasification-based chemical plants in the USA.

The Eastman Integrated Coal Gasification facility, first opened in 1983, was designed to process syngas from the gasification of southwest Virginia and eastern Kentucky coal, using what is now known as GE gasification technology. The intermediate products of syngas conversion are methanol and CO; these are further converted into products consisting of 500 million lb/y (~226,796 t/y) of acetic anhydride and acetic acid, enough to supply half of Eastman's raw acetyl needs. Acetyl chemicals are important to many of Eastman's products, but especially those at the Kingsport site, where five of seven manufacturing divisions rely on acetyls as a raw material. The success of the operation led to a decision to expand the plant capacity to an excess of 1 million lb/y (~453,592 t/y) to meet all of Eastman's needs (NETL, 2013).

The Huayi Group coal-to-chemicals plant is located in Shanghai, China. The facility is one of the earliest and most successful coal-to-chemicals plants in China. Partnered with Praxair for air separation technology and currently using GE gasifiers, it produces 800 kt methanol and 500 kt glacial acetic acid (glacial meaning undiluted with water). The plant brought in US$4.68 billion in revenue in 2007 and has developed further downstream processes to balance acetic acid production and to manufacture products like olefins, dimethyl ether, and others. (Huayi – Praxair Partnership in Integrated Coal to Chemical Site, Presentation, Gasification Technologies Conference, Oct 7, 2008.)

Minchener (2011) discussed coal-to-oil, gas and chemicals in China. In his future prospects analysis, he considered that the next five years will be pivotal in determining the extent of China's coal-to-oil, gas and chemicals deployment. In that period, the various large-scale trials and demonstration projects should provide sufficient data from continuous operation to allow a realistic assessment of the technical and economic feasibility of establishing commercial-scale plants. The coal-to-olefins trials commenced in 2010 and will provide the next stage of the technology assessments. For DME, one project had received a construction permission. For coal-to-MEG, only one facility is currently at the large-scale demonstration stage. Minchener (2011) considers that should China decide to pursue the deployment of coal conversion processes, it has the means to undertake the heavy engineering necessary to establish these large coal transformation production units. While it has drawn on international technology suppliers for many of the key components, through licences and joint ventures, increasingly Chinese companies are establishing their own intellectual property, with the prospect of reducing overall costs that should make the technology more competitive.

However, Minchener (2011) highlights that it is also evident that the Chinese Government is grappling with the same conflicting issues that the USA, Europe and Japan had to address during the oil price rises of the 1970s and 1980s, namely how to reconcile energy security with volatile prices that can make massive investments in coal transformation projects very uncertain. For China, the sheer scale of its continued rapidly growing energy economy, especially the transport sector, will make this an even more difficult problem to resolve. While the key companies taking forward coal transformation development projects towards commercial deployment are all strongly supportive in public, all note the need for strong government policy support in order to underpin the robust introduction of this capital intensive industry. It is also notable that the government directives refer to a steady approach to building up the coal transformation sector (Minchener, 2011).

Meyring and Jin (2012) discussed several new projects in China. For example, Solvay (Belgium) is currently in the process of constructing a new plant for fluorinated polymers at an industrial site in Changshu, Jiangsu province, China. The project, which is scheduled to be operational in 2014, has an expected investment of €120 million. The purpose is to manufacture products for end-use markets such as photovoltaic and lithium batteries and to serve the fast growing markets in China for electrical and electronic material, wire and cable, automotive, consumer and industrial applications. In April 2012, the Sinopec SABIC Tianjin Petrochemical Company launched a polycarbonate production complex with a 260,000 t/y capacity, in the Tianjin Binhai New Area. Demand growth for polycarbonate is the fastest among the top five engineering plastics in China. Evonik, is investing €350 million to construct new production facilities in Shanghai and Jilin in north China. In addition, in March 2012, the company began constructing a new organic chemicals production facility in Shanghai to supply innovative ingredients and specialty surfactants based on renewable raw materials for personal care, household care and the industrial specialties. In late 2011, the Swiss specialty chemicals company Clariant began operating an ethoxylation plant in Daya Bay in Huizhou, Guangdong province (Meyring and Jin, 2012).

Table 10 lists China's MTO)/ MTP projects through 2013/14 (ICIS, 2012) and Pang (2013) gives a map of coal-to-chemicals projects in China (*see* Figure 23). According to ICIS (2012), China imported 1.52 Mt of propylene, 815,400 t of ethylene, 3.87 Mt of polypropylene and 7.36 Mt of polyethylene in 2010, reflecting a big supply/demand gap in olefins. Domestic ethylene and propylene demand is expected to increase by at least 10% during 2010-15. The projects in Table 10 are already in operation or are currently under construction. In addition, more than 30 proposed projects, with combined capacity of more than 20 Mt, are expected to be constructed but most of these have not been approved by the Chinese government. This is because CTO projects with capacities below 500,000 t are not allowed to be built under regulations set by the National Development and Reform Commission (NDRC). CTO projects require major investment, consume large amounts of raw materials, energy and water; and also, cause pollution. Nevertheless, CTO projects are part of China's national energy strategy.

According to Yuangyi (2013), after the start-up of coal-to-olefins projects in Shenhua Baotou, Datang Duolun, Shenhua Ningmei, and Sinopec Puyang, the Ningbo Heyuan Project started up in February 2013, making five commercial MTO and MTP plants in total, with an annual total olefin capacity of 2.3 Mt. Xiuzhang (2013) reported on the progress of the Shenhua Group coal-to-liquids and coal-to-chemicals projects. Zhang (2004) discussed the Shenhua coal conversion technology and industry developments.

Table 10 – China methanol-to-olefins (MTO)/methanol-to-propylene (MTP) projects through 2013 (ICIS, 2012)

Project	Province	Status	Unit	Ethylene, kt	Propylene, kt	Start-up
Shenhua Ningxia Coal Industry Group	Ningxia	In operation	MTP	0	500	2010
Shenhua Group (Baotou)	Inner Mongolia	In operation	MTO	300	300	2010
Sinopec Zhongyuan Petrochemical	Henan	In operation	MTO	100	100	2011
Datang International (Duolun)	Inner Mongolia	In operation	MTP	0	460	2011
Ningbo Heyuan	Zhejiang	In operation	MTO	200	400	2012
Wison (Nanjing) Clean Energy	Jiangsu	In operation	MTO	135	160	2013
Datang International (Yulin)	Shaanxi	In operation	MTP	0	600	2013
Huayun Coal and Power	Shanxi	Under construction	MTO	100	112	2013/14
Ningbo Heyuan	Zhejiang	Under construction	MTO	200	400	2013/14

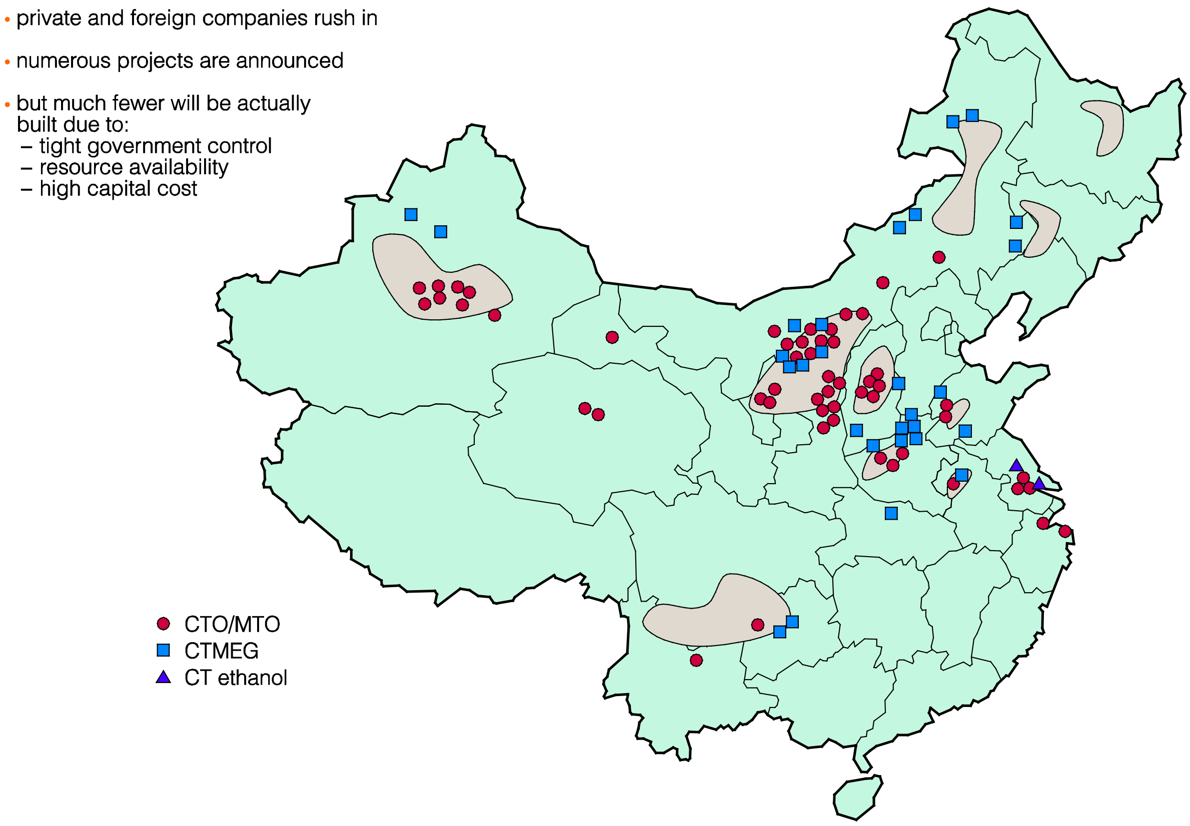

Figure 23 – Map of coal-to-chemicals planned projects in China (Pang, 2013)

In August 2010, the first CTO facility in the world, developed by the Shenhua Group Corp. (China) in cooperation with Dow Chemical (USA), began operation with an MTO production capacity of 600,000 t/y. The Shenhua Baotou CTO facility cost approximately US$10 billion and is located in Halinger, Jiuyuan District, Baotou of Inner Mongolia, to the west of Kundulun River and south of Baolan railway. It uses local coal as feedstock and utilises coal gasification technology to produce polyolefin products including polypropylene and polyethylene. The project uses the Dalian MTO technology (DMTO) and utilises five gasifiers and two spare units. Annual raw coal consumption of the facility is 3,450,000 t and annual fuel coal consumption is 1,280,000 t. Environmental concerns led to the Ministry of Environment forcing the shut-down of the facility for a while in May 2013. Liu (2013) discusses in detail the CTO industry and technology development in China.

Sinopec has developed and constructed a 200,000 t/y MTX (toluene methanol methylation to xylene) plant in Yangzi Petrochemical. The facility started operation in December 2012 and is considered a new route for the production of xylene by methanol.

According to Cohen and others (2012), three new CTO projects received/awaiting approval are due for completion by 2015 combining 1.88 Mt of olefin capacity. Sinopec Zhijin: 600 kt, Yanchang – China Coal Yulin: 600 kt and Pucheng Clean Energy: 680 kt. Another project between China Power Investment and Total is in the pipeline, which could provide additional capacity to the market after 2016 or 2017. For the four methanol-to-coal projects expected to be completed by 2015, most are located near the east coast and have a combined capacity of 1.49 Mt. Sinopec Puyang: 200 kt (in operation since 2011), Nanjing Wison (Huisheng): 300 kt, Ningbo Heyuan: 300 kt and Zhejiang Xingxing New Energy: 690 kt.

With the continuing improvement in gasification and other coal-to-chemicals technologies and increasing cost of conventional crude-/gas-based feedstock, the opportunity for coal-based chemicals will increase.

5 Economics

The non-fuel uses of coal are primarily dependant on factors including (Nexant, 2010):

- the price and availability of alternate feedstocks, that is oil and gas;
- advances in environmental protection technologies;
- advances in gasification technologies.

The economics of non-fuel uses of coal are reliant on the price spread of the competing fuels and availability of coal, that is countries with large recoverable reserves of coal and small reserves of oil and gas would have a greater incentive for the production of chemicals from coal. This creates a favourable cost position for chemicals from coals (*see* Figure 24).

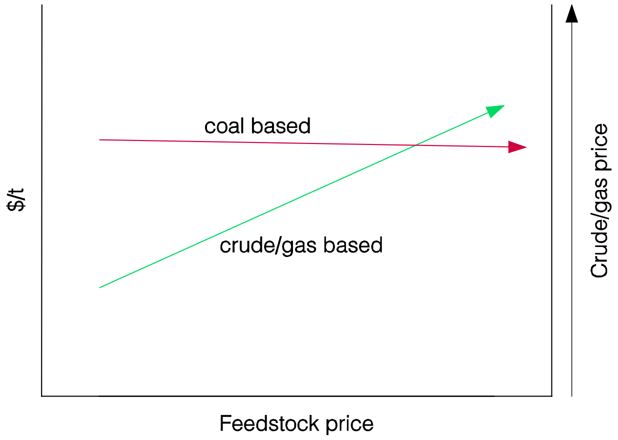

Figure 24 – Cost of production comparison between coal and crude/gas (Nexant, 2010)

On an energy-equivalent basis, coal is a fraction of the price of crude oil and/or gas. According to Tullo and Tremblay (2008), depending on the location, the capital costs of making chemicals from coal are much higher than those of traditional processes based on oil and natural gas. Thus, coal-based chemical plants require a relevant, sustained advantage in feedstock costs. When oil is selling at 50 US$/bbl, coal is a profitable option; below about 35 US$/bbl, the costly coal complexes become less profitable and hence less attractive.

Figure 25 shows the global, specialty chemicals industry market share in 2006. The revenue, which amounted to US$485 billion in 2006, according to Thompson and Zirah (2007) was dominated by sales in North America, Western Europe, Japan and China (US$39 billion). Forecasts in 2006 indicated that growth in the specialty chemicals market in Western Europe, Japan and North America would be around 3% between 2006 and 2011 while growth in China would be 9%, annually. This was actually exceeded as shown by research carried out by Marketline (2012).

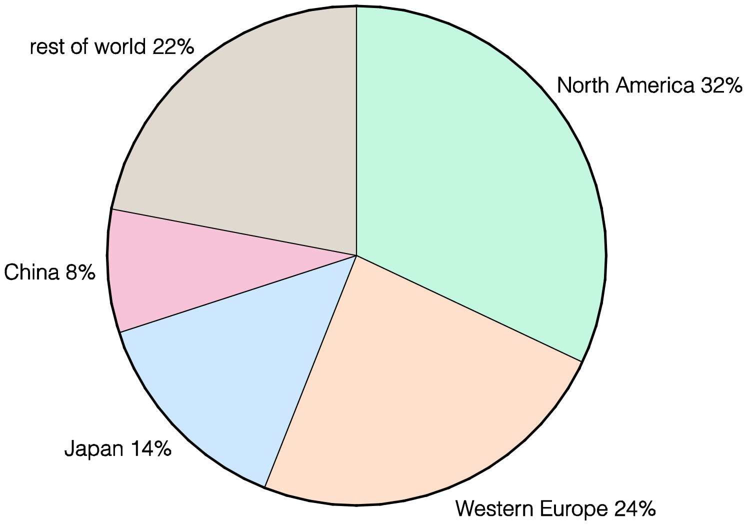

Figure 25 – Global speciality chemicals industry (market share, %) (Thompson and Zirah, 2007)

Horncastle and others (2011) discussed the disparity between ambitions and actual developments in China's coal-to-chemicals production highlighting critical questions regarding the long-term competitive threat from the technology compared to other feedstock. Key among these is the security of supply factors as there is debate regarding how much coal China is willing to devote to petrochemical feedstocks. According to Horncastle and others (2011), while China has large domestic petrochemical demand, it has larger and growing energy needs, which could require more coal and thus constrain its use as a petrochemical feedstock. In addition, the coal-to-chemicals processes entail several technical and economic issues. The plants required to convert MTO, for example, are capital intensive, in part because the mines are relatively remote but also because the technology generates low olefin yields (*see* Figure 26), requiring significant scale to become cost-competitive. Moreover, the quality of the coal is an important factor, both to reduce potential fouling during the gasification process and to ensure sufficient efficiencies and yields. For these reasons, the economics of coal as a feedstock are not yet clear, making it difficult to predict the eventual scope of the market disruption from such technology. For petrochemical producers that export to China, the country's rapidly growing demand for olefins, along with limited refinery capacity, ensures that current olefin imports are likely to continue for the foreseeable future. Coal's estimated share in ethylene production in China to 2025 is illustrated in Figure 27, keeping in mind that Horncastle and others (2011) consider this highly uncertain.

Marketline (2012) carried out a qualitative and quantitative investigation of specialty chemicals in China including market size (value 2007-11 and forecast to 2016). The study covered revenues generated from the sales of high value-added chemicals used in the manufacture of a wide variety of products. These included fine chemicals, additives, advanced polymers, adhesives, sealants and specialty paints, pigments and coatings. According to Marketline (2012), the total revenue of the Chinese specialty chemicals market was US$74.6 billion in 2011, representing a compound annual growth rate (CAGR) of 10.9% between 2007 and 2011. The most lucrative were the fine chemicals with total revenues of US$25.6 billion. However, Marketline (2012) forecasts that the market will decelerate with an anticipated CAGR of 8.8%

for the five-year period 2011-16, which is expected to drive the market to the value of US$113.9 billion by the end of 2016.

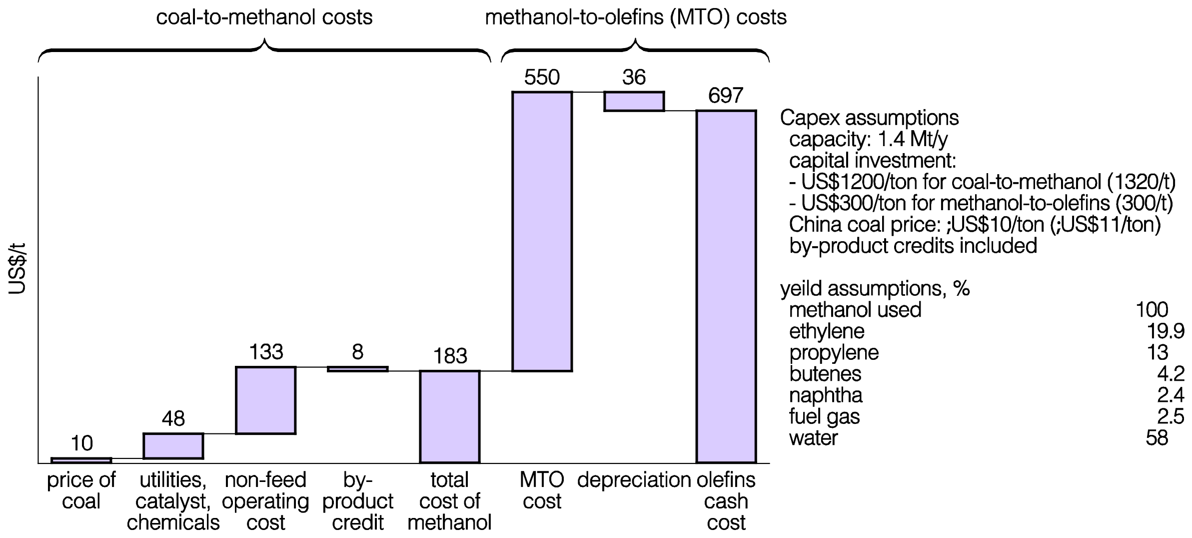

Figure 26 – Coal-to-olefins (CTO) cost structure and assumptions (2010) (Horncastle and others, 2011)

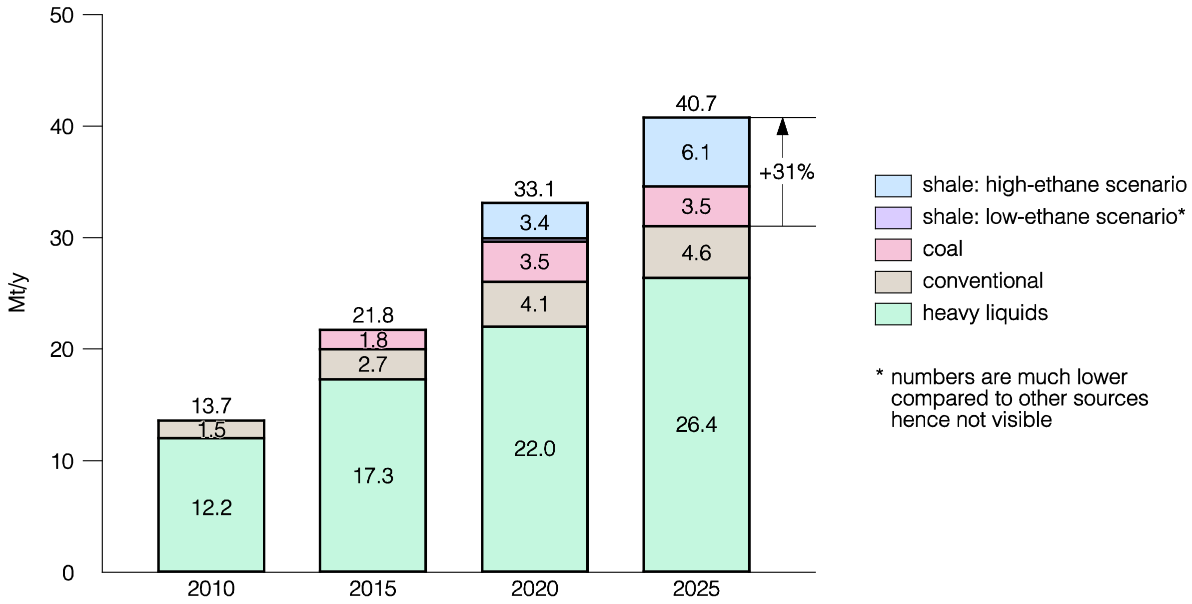

Figure 27 –Ethylene volumes based on feedstocks in China (2010-25 estimated; in Mt/y including coal and shale gas) (Horncastle and others, 2011)

An example/forecast of cost competitiveness of MEG from coal is given by Chemsystems (2010). The ethylene glycol global market is 18.9 Mt/y and growing at an average 3.7%/y. In 2010, China imported over 5 Mt of ethylene glycol, mainly from the Middle East. Other major exporters of MEG are Canada, South Korea and Taiwan. China plans to introduce approximately 2 Mt/y of new coal-to-MEG capacity by 2015, 0.8 Mt of which are already in production. Subject to the competitiveness of coal-based MEG, Chemsystems considers that there could be a paradigm shift in the structure of the global MEG industry especially as regards future trade flows beyond 2015 (*see* Figure 28).

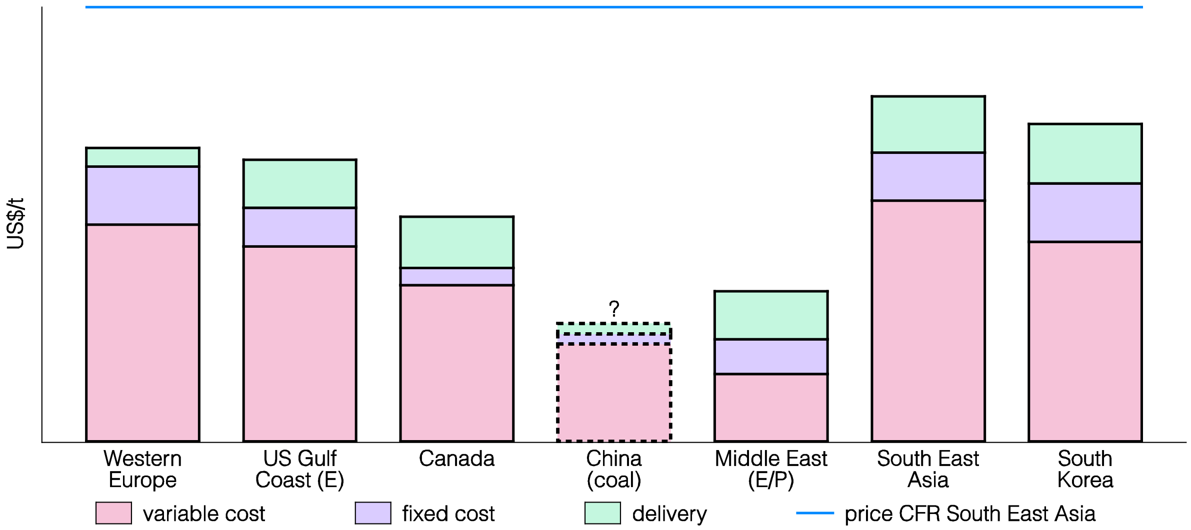

Figure 28 – Global MEG delivered cost competitiveness (Q, 2010) (Nexant, 2010)

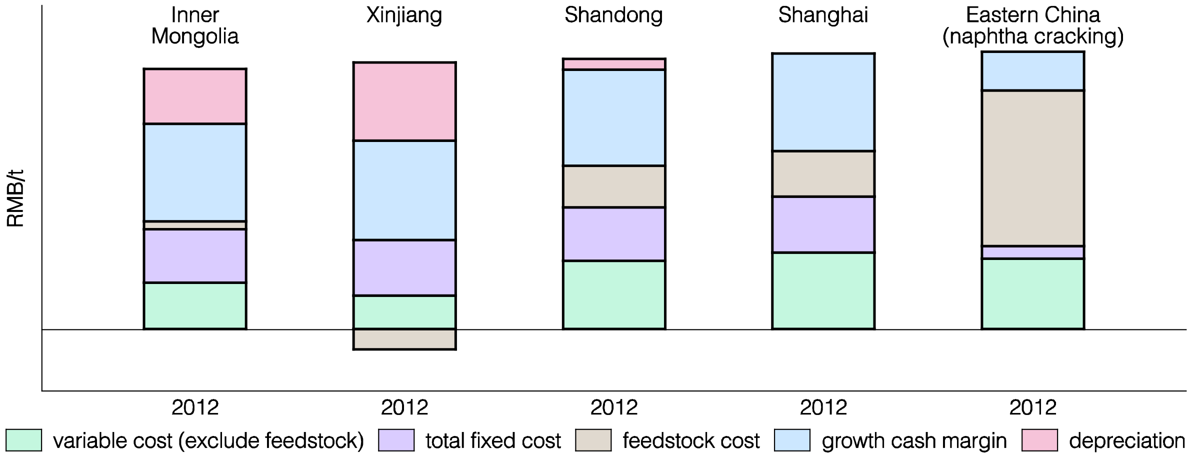

Figure 29 – 2012-16 average coal-to-polyolefin cost comparison (RMB/t) (Pang, 2013)

Pang (2013) compared the average cost of coal-to-polyolefin production in 2012 between four facilities currently in operation to naphtha cracking showing clearly the competitiveness of using local/feedstock coal to produce olefins (*see* Figure 29). Figure 30 illustrates the average coal-to-MEG cost comparison also using local/feedstock coal. However, Pang (2013) also highlighted the issues relating to coal-to-chemicals conversion in China. The majority of the facilities are located in the west or central China where the coal is found. These areas suffer from water shortage and water consumption for coal-based chemicals is necessarily high.

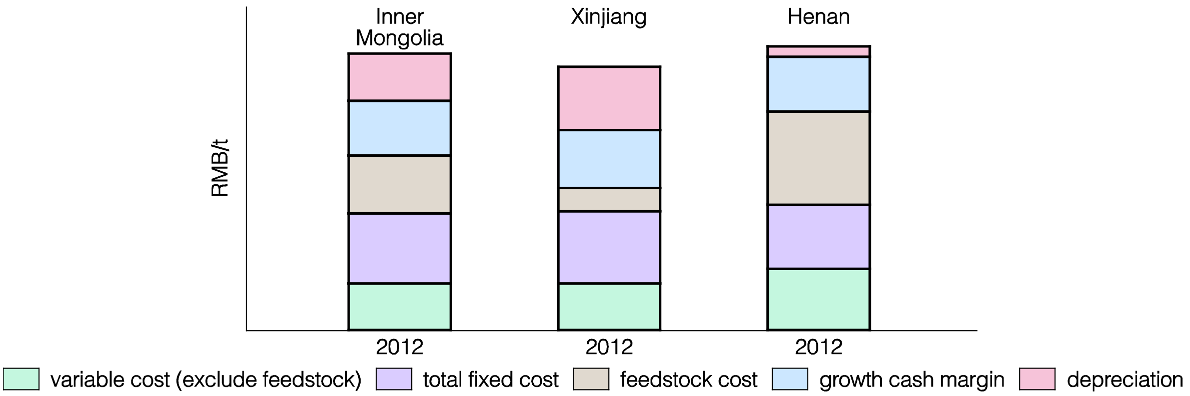

Figure 30 – 2012-16 average coal-to-MEG cost comparison (RMB/t) (Pang, 2013)

In addition, these facilities are capital cost intensive. Furthermore, although the MTO technologies have been proven successful to date, MEG remains relatively new and therefore must be monitored closely in order to reduce any unforeseen technological risks. Although China does not enforce a carbon tax levy currently. Pang (2013) considers that such a levy would be expected by 2020. Finally, waste disposal is another issue to be faced by the operators of these facilities. The carbon sludge from the processes could be used as construction material. However, west China has no requirement for such material hence the by product is disposed of in landfills. Despite these issues, Pang (2013) considers that, by 2017, coal chemicals will play a major role in olefins and MEG in China (*see* Figure 31).

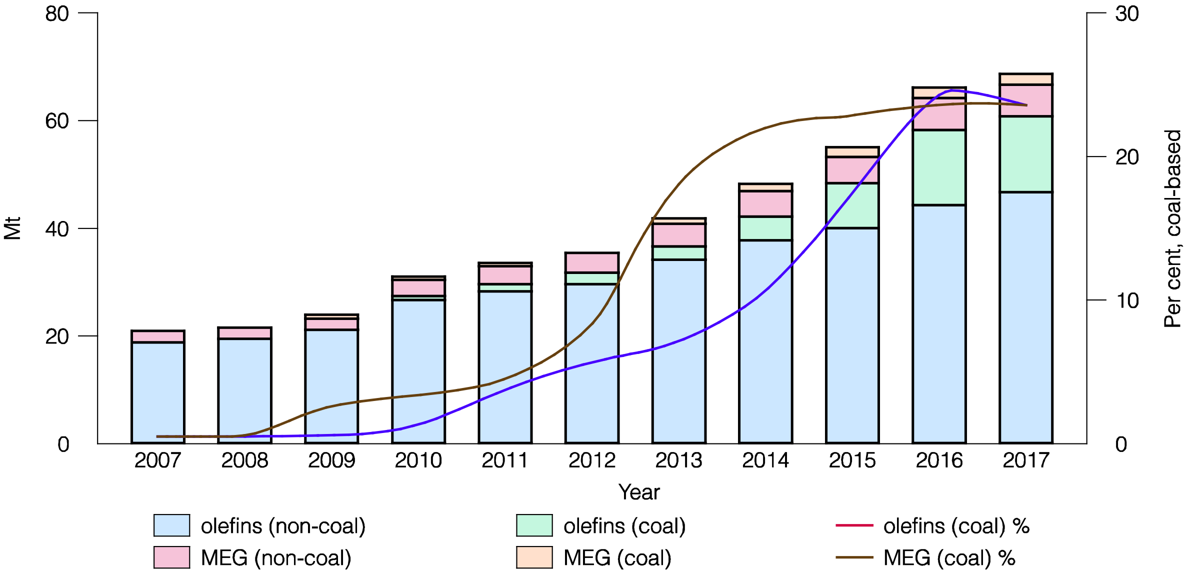

Figure 31 – Chinese coal-based and other feedstock capacity percentage share (actual and estimated) from 2007 to 2017 (Pang, 2013)

According to Cohen and others (2012), domestic demand for olefins and poly olefins increased steadily from 2005 to 2010 in China. The volume of consumption grew by 14% and 10% per annum, respectively, to reach 27.8 Mt (RMB 240 billion) of olefins and 30 Mt (RMB 335) of poly olefins. However, in 2010, imports represented ~9% of total Chinese consumption of olefins and 37% of poly olefins (*see* Figure 32). Hence the drive to build new CTO facilities to satisfy demand. However, the approval authorisation process is centralised at the National Development and Reform Commission (NDRC) level with set rules, such as, limiting annual CTO capacity to 4–5 Mt in 2015, to ensure asset efficiency and environmental protection. A financial modelling exercise carried out by Cohen and others (2012) showed that the coal route to produce olefin demonstrated a better cost position compared with the traditional oil (naphtha) route. However, the authors consider that optimism should be tempered with caution about CTO economics in the Chinese market. This is because the new technology presents challenges and risks such as the price and quality consistency of the coal, water supply access and cost, MTO technology stability and maturity, and sales and future integration capabilities. Furthermore, a major uncertainty of the economic viability of CTO projects concerns CO_2 tax, in that taxation, if and when introduced, would impact cost advantages of the technology (Cohen and others, 2012).

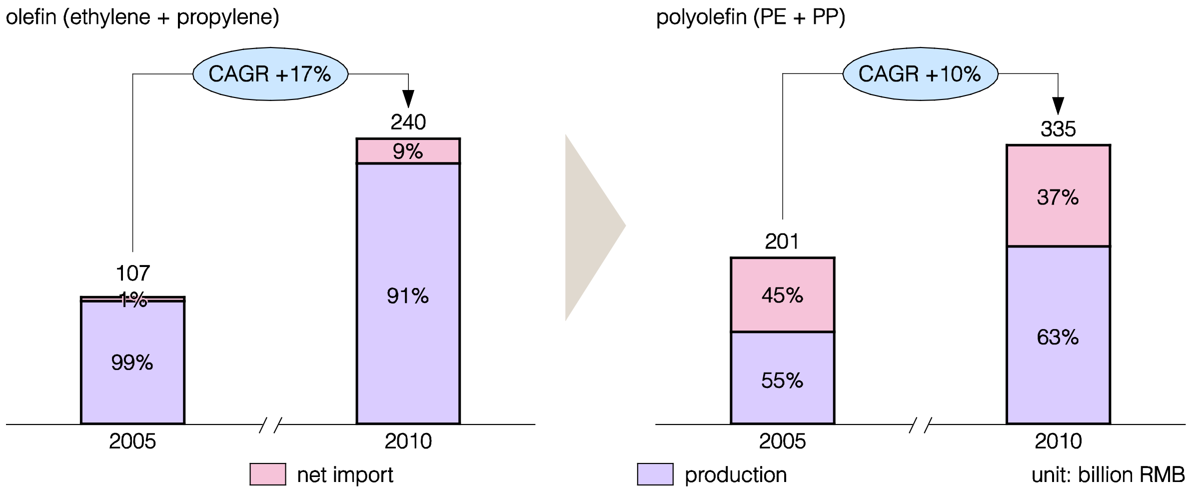

Figure 32 – China consumption value of olefin and derivatives (2005-10) (Cohen and others, 2012)

Cost estimates of coal gasification for chemicals was the subject of a report by Sciazko and Chmielniak (2012). According to Sciazko and Chmielniak (2012) coal is used as the basic feedstock in gasification plants that are currently operating and accounts for 61.6% of global gas production. Petrochemical industry by-products rank second (35.8%), and the remaining 2.6% of gas production is attributed to petroleum coke and biomass. For plants that are under construction and planned for start-up by 2016, the role of coal as the fuel will be maintained, and the share of gas produced from this raw material will increase to 79%. The main products of currently operating systems using gasification processes comprise chemicals such as ammonia, hydrogen and oxy-chemicals (46% of world gas productions), products of Fischer-Tropsch synthesis (30 %), power (16%) and gaseous fuels (8%). Chemicals will also be the main products of the plants that are under construction (72%).

Sciazko and Chmielniak (2012) carried out an in depth analysis of installations for gaseous and liquid fuel production based on coal gasification using commercially available technologies of coal gasification, gas cleaning and conversion and chemical synthesis. Systems for liquid fuels, hydrogen and methanol production were analysed in detail assuming three scenarios:

- basic (with no necessity to buy rights for CO_2 emission);
- reference (purchase 100 % of CO_2 emission rights at a price of 39 €/t); and

- prospective (assuming construction of CO_2 transport and storage facilities).

The analysis indicated that the most favourable option is the production of methanol, which shows economic effectiveness in all of the scenarios and, in the case of scenarios 2 and 3, gives the best results among the options analysed. The reason for this is related to low CO_2 emission, associated with the 'chemical sequestration', that is, the use of CO_2 for methanol synthesis. The economic attraction of producing hydrogen from coal is significantly more dependent on natural gas prices. Hydrogen production is economically feasible only in scenarios 1 (base) and 3 (prospective). Developments in coal-based hydrogen production/economy seem to be limited due to a lack of cost-effective storage technology and transport infrastructure. Currently, hydrogen from coal can effectively be used in chemical plants for the production of ammonia and fertiliser by substitution of the hydrogen produced from natural gas.

According to Richardson (2013), coal sells for 25 $/t in some of China's inland provinces with large coal reserves. Using this coal to produce poly olefins that can sell for 1500 $/t or more is a profitable proposition. In addition, on a variable cost basis, converting the coal to ethylene competes well with naphtha-cracking. If raw material prices rise by 10%, the variable costs of naphtha-based ethylene production increase by 20%, whereas coal-based costs rise by only 7%. However, logistical problems can be a significant impediment. Many CTO projects are located in central and western China, where the coal reserves are, yet the demand is mostly in eastern China, where the four provinces: Guangdong, Zhejiang, Guangxi and Shandong account for 50% of the said demand. This leads to an issue in transporting the final product. Richardson (2013) also highlights environmental challenges as a major barrier to investment. For instance, CTO conversion requires 15–20 t of fresh water to produce each tonne of olefins compared with 0.8–2.17 t of water needed for each tonne of crude oil processed through an oil refinery. Water resources are limited in the provinces of Inner Mongolia, Shanxi and Shaanxi, where many of the projects are located. Furthermore, high carbon dioxide emissions are another obstacle as the process generates a low of 7.1 t of CO_2 for every tonne of olefins produced and a high of 10.6 t. This is compared with 1.5–3.0 t of CO_2 per tonne of ethylene via naphtha cracking. Finally the recent NDRC rule of a minimum CTO plant capacity of 500,000 t/y leads to speculation that, as a result of the above, only 20% of the 6 Mt/y of CTO capacity due on stream in 2013-17 is actually viable (Richardson, 2013).

In summary, the coal-to-chemicals industry is capital intensive and dependent on not only the economics of scale but also availability of large amounts of coal and water. Forecast capital cost per unit capacity is shown in Figure 33 (Liu, 2012). The coal-to-chemicals industry continues to grow, however care must be paid to the appropriate use of resources to achieve the economic benefits whilst protecting the environment.

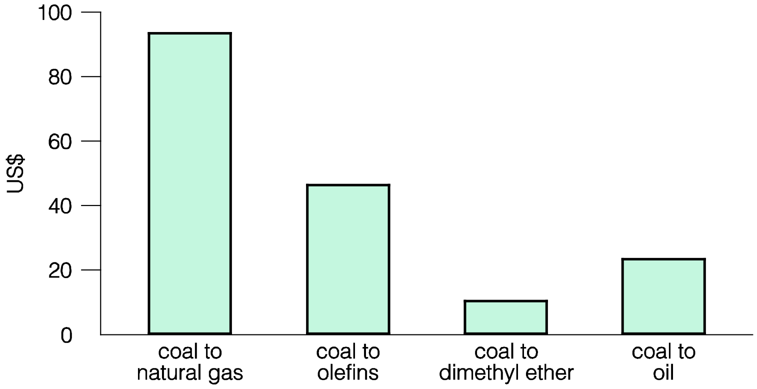

Figure 33 – New coal chemical industry forecast capital cost per unit capacity (US$ million/kt, US$ million/m^{3})

6 Conclusions

Society today, worldwide, depends on carbon-based materials used in daily life, work, transportation and recreation. Industrial chemicals and carbon-based materials such as basic chemicals, plastics and fibres are currently derived mostly from petroleum and natural gas. Materials and chemicals from coal are now recognised as an important, practical and profitable source and therefore are an area for future coal utilisation research and development. The proven large coal reserves and the aromatic molecular structures present in coals could be ideal feedstocks for the olefins, polymers and engineering plastics that have many applications and markets. However, the traditional source of coal chemicals, tars or liquids from by-product coke ovens, has steadily decreased in the last decades. So, although the opportunities are increasing for new applications and markets for coal chemicals, the traditional source of those chemicals continues to decline. The main issues facing the use of coal in chemicals include its structural complexity, processing difficulties, presence of many components in organic matrix at each stage of conversion, inorganic impurities, capital investments, processing costs and environmental impact. Furthermore, water consumption in coal conversion processes is high (converting coal to 1 t of chemicals requires 15–20 m^3 (3950–5300 gallons) of water) and therefore plays a major role in construction decision making.

The synthesis of many chemicals begins with a hydrocarbon source, frequently crude oil or natural gas. The high pricing and/or limited availability of these resources in some countries, mainly China, India and the USA, has made the use of coal a viable alternative. However, whilst the technology is developing rapidly in China and is expected to play a major role in the future in India, the use of coal as feedstock for chemicals is considered unlikely in the USA especially since the recent discovery, exploration and use of shale gas. Producing chemicals from coal increases energy security and diversity, and can be a profitable and reliable undertaking. From a market standpoint, although demand for chemicals has fluctuated over the last few years it is expected to grow worldwide and especially so in rapidly developing countries such as China and India.

Uses of coal include alumina refining, paper manufacture and chemicals and pharmaceuticals production. The number of chemicals that may be produced from coal is boundless and are not all covered in this review. However, main end chemicals from coal currently being developed and in demand include mono-ethylene glycol (MEG) dimethyl either (DME), olefins, acetic acid, formaldehyde, urea, ammonia, acetylenes such as vinyl chloride monomer (VCM), poly vinyl chloride (PVC), butanediol (BDO), vinyl acetate monomer (VAM), acrylic acid (AA), acrylonitrile (ACN) and naphthalene derivates. Coal-to-MEG is one of the major break-through processes to impact the chemical industry in recent years. A migration from conventional ethylene-based mono-ethylene-glycol (MEG) production to coal-based production could potentially lead to a shift in the global MEG market. Current coal-to-MEG capacity in China is approximately 1 Mt/y with forecasts of ~2 Mt/y capacity increase by 2015 and a potential of over 12 Mt/y by 2025.

Coal carbonisation is the process of converting coal into carbon or a carbon-containing residue through pyrolysis. It involves heating the coal to high temperatures in the absence of oxygen to distil out tars and light oils. The process is used to produce metallurgical coke for making iron in blast furnaces as well as other smelting processes. A gaseous by-product referred to as coke oven gas or coal gas is also formed along with ammonia, water, and sulphur compounds. Coke over gas is a valuable heating fuel. Other coal carbonisation by-products are usually refined to produce commodity chemicals. Gas separated from the tar has to be treated to remove substances such as ammonia, hydrogen sulphide (H_2S), light oil, and naphthalene. The most important components of a typical treated coke oven gas include hydrogen, methane, and carbon monoxide. Coal tar pitch and bituminous coal used for coke making are major feedstocks for coal-based carbon materials. It is forecast that heavy liquids from coal liquefaction and low temperature pyrolysis tars as well as coals of all ranks can become further feedstocks. Adsorbent carbons for water/air purification, medical applications and developing carbon molecular sieves would be the main uses of such feedstocks. Estimates show that coal used worldwide for the production of activated carbons and carbon molecular sieves was about 200,000 t/y and 3000 t/y respectively. Graphite and other advanced carbon materials offer a new market opportunity for coal. However, this would require the development of schemes to replace petroleum products thus adding significant value and creating demand for coal.

Gasification has been used in the chemical industry since the 1930s, typically, to produce methanol as well as chemicals such as ammonia and urea, which form the building blocks for nitrogen-based fertilisers and a variety of plastics. Methanol can be purified by distillation thus removing most of the impurities from the coal. It is typically converted to ethylene, propylene, acetic acid, DME and other chemicals. Processes to convert methanol-to-olefins (MTO) and methanol-to-propylene (MTP) have been developed and installed in recent years in China. The majority of operating coal-based, gasification plants are designed to produce chemicals and fertilisers.

There are currently few commercial coal-to-olefins (CTO) technologies: the MTO process and the MTP process. Technologies proven successful include the Dalian methanol-to-olefins (DMTO) technology (Dalian Institute of Chemical Physics of the Chinese Academy of Sciences), Sinopec methanol-to-olefins (SMTO) technology, The US Honeywell UOP/Norksk HYDRO MTO technology and the German Lurgi MTP technology. Four CTO facilities, using existing technologies, have been put into commercial operation in China. In addition, Companies in China are actively pursuing new technologies for the optimisation of catalyst production, reduction of water and coal consumption, improvement of production selectivity and yield. Geographically, China is the growth centre for chemicals from coal mainly due to the availability of low-cost coal in the country. This is especially so for methanol where annual growth averages >12% while in the rest of the world demand is growing at <3%. Studies forecast that China's methanol consumption will triple from 31 Mt in 2012 to 97 Mt in 2022.

Cost, capital and operating/maintenance, reliability, availability and safety are important factors in developing coal-to-chemicals facilities. Increasing process efficiency to produce more product over a period of time or per coal input helps defray high initial capital costs but reliability and availability can impact cost dramatically. For the production of some chemicals such as methanol, ammonia and acetyls, the economics of coal-to-chemicals appear favourable as existing facilities have been operating profitably for some time. The economics continue to improve with greater understanding of the conversion technologies. Increased availability, either through new materials or better maintenance methods, is also an area where research and development could lead to substantial improvements.

Finally, the non-fuel uses of coal involve utilising coal as a raw material and using chemical processes to turn it into gas, liquids, solid fuels and other chemical products. It has been used historically in the chemical industry since the 1950s. Numerous different products have coal or coal by-products as components including soap, aspirins, solvents, dyes, plastics, fibres (such as rayon and nylon), specialist products (such as activated carbon, carbon fibre and silicon metal). New technologies have been and continue to be developed that use coal as feedstock for the production of chemicals. The latest developments have seen coal chemicals moving to coal-to-dimethyl ether (coal-to-DME), coal-to-olefins (CTO) and coal-to-glycol (CTG). However, the uptake of these technologies is restricted by their high capital investment and technology requirements, the substantial risks involved due to limited knowledge of their performance, strict operating conditions and their uncertain economic viability. Companies considering such coal-to-chemicals facilities must weigh many factors, mainly the viability, profitability and environmental impact of such projects. In China, another important factor is whether the plants are to be located near the sources of coal or closer to where the final products will be used or distributed.

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