Research Programme of the Research Fund for Coal and Steel
Coal RTD

Project carried out with a financial grant of the
Research Programme of the Research Fund for Coal and Steel

Contract Number: RFC2-CT-2008-00006

REVIEW OF WORLDWIDE COAL TO LIQUIDS R, D&D ACTIVITIES AND THE NEED FOR FURTHER INITIATIVES WITHIN EUROPE

Contractors
IEA Coal Research Ltd, UK.
FuelConsult GmbH, Germany
Główny Instytut Górnictwa, Poland
Tallinn University of Technology, Estonia
Stredisko Pro Efektivni Vyuzivani Energie O.P.S., Czech Republic

June 2009

Contents

Abbreviations

bbl	barrel of oil = 42 US gallons ≈ 159 litres. 1 tonne of oil ≈ 7.33 bbl.
bbl/d	barrels per day
bp	boiling point
BRICC	Beijing Research Institute of Coal Chemistry
CCRI	China Coal Research Institute
CCS	carbon dioxide capture and storage
CCT	clean coal technology
CFR	Counter-flow Reactor
CRE	Coal Research Establishment (British Coal Corporation)
CHU-ISEP	continuous-hydrocracking unit, integrated solvent extraction plant
CTL	coal to liquids conversion technology
CTO	coal-to-oil conversion technology
CTSL	Catalytic Two-stage Process liquefaction process
DCL	direct coal liquefaction
DME	di-methyl ether
DT	Deutsche Technologie coal liquefaction process
daf	dry, ash-free
EC	European Commission
ECSC	European Coal and Steel Community
EDS	Exxon Donor Solvent process
EEC	European Economic Community
EIA	US Energy Information Administration
EU	European Union
EU-15	European Union of 15 member states (before last enlargement)
EU-27	European Union of 27 member states (since last enlargement)
FT	Fischer-Tropsch process
Gt	gigatonnes (thousand million tonnes)
GTL	gas-to-liquids
H-Coal	HRI (later HTI) Coal hydrogenation process
HTFT	high temperature Fischer-Tropsch process
ICL	indirect coal liquefaction
KAB	Kohleoel-Anlage Bottrop
LPG	liquefied petroleum gas
LSE	liquid solvent extraction
LTFT	low temperature Fischer-Tropsch process
Mt	megatonnes (million tonnes)
NEDO	New Energy and Industrial Technology Development Organisation (Japan)
NEDOL	NEDO coal liquefaction process
OECD	Organisation for Economic Co-operation and Development
PDU	process development unit
Pyrosol	Liquefaction process developed by Saarbergwerke AG
RFCS	Research Fund for Coal and Steel (European Commission)
SAS	Synthol and Advanced Synthol processes (SASOL)
Sasol	South Africa synthetic oil liquids company
SNG	substitute (or synthetic) natural gas
SRC	Solvent Refined Coal process
SSDP	Slurry Phase DistillateProcess (Sasol)
t/d	tonnes per day
t/y	tonnes per year
UCG	underground coal gasification
UK	United Kingdom
USA	United States of America
USDOE	US Department of Energy

List of Figures

List of Tables

1 Introduction

1.1 Background

The oil supply crises of the 1970s triggered major development programmes within Europe, the USA and Japan to establish technologies for the production of synthetic oil products from coal while South Africa, which already had an extensive coal to liquids (CTL) capacity, increased its capabilities further. Within Europe, various member states, the ECSC and the EC funded very significant technical research activities followed by financial support for various scale-up projects for the liquefaction and gasification of coal. An enormous amount of high quality scientific work was undertaken to understand and investigate various processes for the conversion of coal to liquid products. This was driven primarily by industrial organisations in Germany and the UK (the DT, Pyrosol and LSE processes respectively) but was supported extensively by industrial research institutes and universities throughout the European Union.

However, while these three developments were technically successful, they were not taken forward to the large demonstration and commercial prototype scale stage since at that time (late 1980s and early 1990s) the oil price was relatively low, security of supply of oil and natural gas was not a key political issue and, as such, the major funding requirements could not be justified. This change of emphasis was also reflected in the medium term guidelines of the ECSC and subsequently the RFCS programmes, as well as the EU Framework Programme, which downgraded any possible work on CTL apart from the production of hydrogen from coal, which was encouraged for other reasons than to support CTL development.

Indeed, over the last three decades, the EU-15 member states have reduced their dependence on coal and have transferred increasingly to natural gas as the basic general purpose fuel. At the same time, for transport and mobile applications, oil consumption has continued to rise despite the significant upward pressure on the price of crude oil. Even with the enlargement of the EU to 27 countries, which resulted in an upturn in indigenous coal use, the overall trend of increasing demand for imported gas and oil has continued as the newer member states adjust their fuel mixes to meet EU environmental standards, particularly for power generation applications.

Currently, oil supplies for Europe are dominated by the North Sea (UK and Norway), the Middle East, and Russia. Supplies of natural gas depend on the North Sea, Algeria, and Russia. It is envisaged that over the coming decades, the dependence on Russia for key supplies of both oil and gas will increase. At the same time, global demand for oil has been increasing significantly because of the economic development of China and India while oil exploration has also failed to keep up with production. This is reflected in the price of oil, which has increased steadily, albeit with fluctuations over a wide range (having peaked in mid 2008 at $147 per barrel, the price is currently close to $55 per barrel). The price of gas has also fluctuated widely but, as suppliers are pegging it to the oil price, it is no longer a cheap fuel.

The increasing dependence on Russia for natural gas supplies has already proved to be problematical from a security of supply perspective as Russia has used its primary supplier status to dictate terms to Ukraine, with knock-on effects for several EU Member States.

Thus, in summary, Europe faces a dilemma. Indigenous oil and gas reserves are limited; supplies are increasingly dependent on imports; prices are uncertain, but likely to fluctuate wildly, and at least one of the dominant suppliers shows a willingness to use its oil and gas for political purposes. Thus, there is an imperative strategic need for the EU to establish stable fuel supplies, which can provide insurance against the vagaries of the oil and gas markets. This is reflected in the Commission's policy to initiate greater renewable energy use, and to promote greater energy efficiency initiatives while also encouraging the development and deployment of near zero emissions coal fired power generation systems.

From this strategic perspective, the only primary fuel (apart from nuclear) which has the capacity and the infrastructure to meet this stability requirement is coal. Unlike oil and gas, coal is geographically widely distributed, with a reasonable number of countries involved in its international trade, which limits the likelihood of a monopoly supply situation (Minchener 2009). Also, international trade represents less than 15% of total world production. Most importantly, because of its large reserves, the price is likely to be more predictable than that of either oil or gas. At the same time, while Europe imports coal from a variety of sources, it still has large indigenous deposits of hard coal and lignite although, in Western Europe, much of the former is no longer economically extractable by conventional methods.

It is interesting to compare the current estimates of global proven reserves of coal, oil and gas, and to compare these with the corresponding resources. Proven reserves are the quantities of fuel still in the ground, which are assessed as being economically extractable using current technology and under current market conditions. Resources, by contrast, are the amount of fuel that may be present but the quantification is approximate and takes no account of either the technical or economic feasibility of extraction.

Figure 1 shows the 2005 fossil fuel reserves position. It is notable that coal, with reserves of over 900 gigatonnes (Gt) represents 64% of the reserves, with oil 19% and gas 17% (BP 2006). By contrast, if resources are considered, Figure 2 shows that coal rises to 95.5% at 18,000Gt, while oil and gas fall to 2.2 and 2.3% respectively (BP 2006). Ultimately, it is the reserves figure that dictates the level of supplies commercially available. However, the key factor here is that re-definition of resources to reserves occurs when the market is sufficiently attractive to warrant the necessary evaluation to prove up the deposits in the light of the technologies available for extraction and conversion, the costs involved, and the likely return on investment.

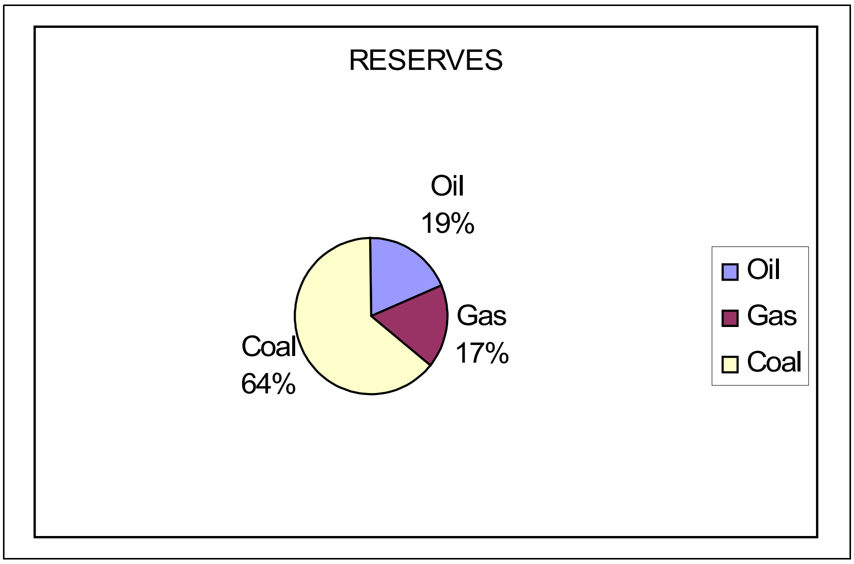

Figure 1 Global Coal, Oil and Gas Reserves 2005 (BP 2006)

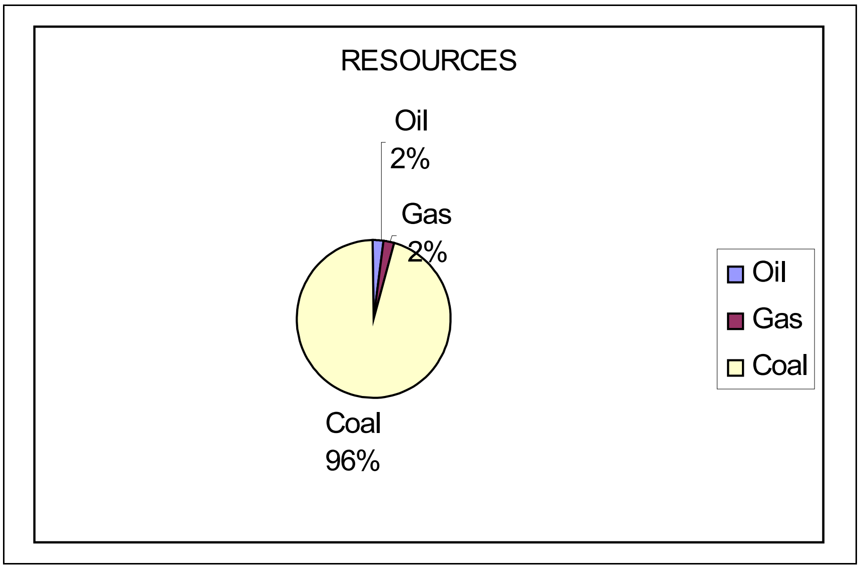

Figure 2 Global Coal, Oil and Gas Resources 2005 (BP 2006)

For oil and gas, these redefinitions have regularly been undertaken, but for coal, the supply position has been so relaxed that further proving and evaluation has not been needed. Even today, faced with increasing demand, coal supply limitations have not been due to either mining capacity or shortage of reserves, but to the transport infrastructure to the docks and onwards. While that position will change in the future, with the need to prove more reserves, the expectation is that there is considerable scope for the uprating of resources to reserves as coal prices rise. On a global basis, this covers not just the increased use of deposits already being mined but also the extraction of coal from deposits hitherto not exploited, including those in countries with as yet minimal mining activity.

A major pinch point for future fuel supplies is transport, for which demand shows no real sign of abating, with a continuing and expanding need for liquid fuels. The uncertainties in oil supply will continue to impact heavily on the transport sector, where no clearly viable alternative has yet been identified (not least since both biofuels and hydrogen involve significant use of fossil fuels). Consequently, the production of liquid fuels from coal offers a potentially attractive route to meeting this requirement, as one aspect of a balanced energy portfolio.

This position is reflected in the rapid growth of interest in CTL worldwide, with major engineering projects now underway in China and detailed feasibility studies being undertaken in the USA, while South Africa continues to upgrade its CTL production capacity. In Europe, there is a corresponding upturn in interest, particularly in the former Soviet Union satellite countries that are now members of the EU, such as Poland, Estonia and the Czech Republic, with several organisations now starting to reconsider the development and possible deployment of CTL processes. Therefore, it is important that the EC, the member state governments and EU industry are made fully aware of the status of CTL so that Europe can best deploy resources to take forward CTL technology, where appropriate, on a sustainable basis. The latter point includes consideration of various environmental issues which have arisen since the previous development work in the 1970s and 1980s.

Accordingly, this Accompanying Measure project, which is supported in part by the Research Programme of the RFCS, is designed to assist in achieving these overall needs.

1.2 Scope of the project

This project will:

- Consider the applicability of CTL within the European strategic context.
- Review CTL activities, past and present, including CTL itself and coal to hydrogen applications, the latter being a key part of the hydrogenation process within the liquefaction schemes.
- Ascertain possible future CTL R, D &D needs for Europe, building both on the global state of the art arising from work undertaken previously and the current worldwide activities including the planned and ongoing demonstration programmes in the USA and China respectively. For completeness, the current oil shale processing activities, particularly in Estonia, will also be considered.
- Review capabilities and expertise in EU universities to determine the possible impact if there is a need to implement new CTL R&D projects, with an emphasis on the current availability of suitably trained manpower.
- Consider the need for research and engineering training programmes to address identified shortfalls.
- Ascertain the capability and interest of EU industry should it need to implement larger-scale development and demonstration programmes and ultimately to build large CTL plant.
- Ascertain the benefits of seeking international cooperation on CTL R, D&D with stakeholders outside of Europe rather than limiting activities to EU member states.
- Promote and disseminate the results of these activities to EU stakeholders, such as technology providers and developers, and major proactive coal/oil shale producers and users, as well as appropriate technical institutes and universities. A particular focus will be on those EU nation states where CTL is potentially very relevant, i.e. various major coal and oil shale producing countries, such as Poland, the Czech Republic and Estonia. In those three cases, the dissemination process will include workshops in each of the three countries.

2 Applicability of CTL within the European strategic context

2.1 Security of coal supply

Europe has entered a new energy era, for which the European Commission has emphasised that the over-riding objectives of EU energy policy have to be *sustainability, competitiveness* and *security of supply*. For the EU energy industry, this offers a series of challenges, namely:

- Ensuring security of energy supplies on a sustainable basis
- Implementing technologies to achieve deep reductions in CO_2 emissions from fossil fuel power plants
- Maintaining EU industrial competitiveness to meet the global market challenge for advanced fossil energy power plants with integrated CCS

> The future energy needs of the enlarged EU will require the full range of available fuels to be utilised in an environmentally acceptable way. Such an approach is considered sustainable, as it will ensure the necessary diversity and security of supply provided that adequate environmental performance is achieved. Thus, fossil fuels will continue to provide a major proportion of the European energy supply over the coming decades. Coal has a major role to play in this EU energy mix, but it is faced with particular challenges in achieving environmental compliance. Consequently, it is important to determine the quantities of coal that (a) are available using current mining and utilisation technologies, and (b) could be available in the future should advanced extraction techniques become commercially proven, while also determining the coal's suitability for utilisation should technologies such as CTL be deemed strategically appropriate within the European context.

2.2 Indigenous solid fuel resources and reserves

Estimations of the amounts of natural resources such as coal, oil and gas that remain to be exploited are described by two terms *resources* and *reserves.* Reserves are sub-divided into two groups: *proven exploitable reserves*, and *indicative reserves*. Thus,

- Coal resources are broadly defined as the amount of coal actually present in a deposit, but the quantification is approximate and takes no account of either the technical or economic feasibility of extracting that coal.
- Proven exploitable reserves are those that are believed to be economically extractable using current technology and under current market conditions. Such an assessment is expected to take account of a coalfield's geological characteristics, probable seam thickness and quality, as well as the geological discontinuities such as faults and folding all of which affect the practical recoverability of the coal. As such, these reserves should have been thoroughly surveyed and their quantification well defined.
- Indicative reserves are those that have been less comprehensively explored and so are estimated with a lower degree of confidence than the proven reserves. They should be mineable (Figure 3), but it is not known how much coal will be *economically* exploitable (Kavelov and Peteves 2007).

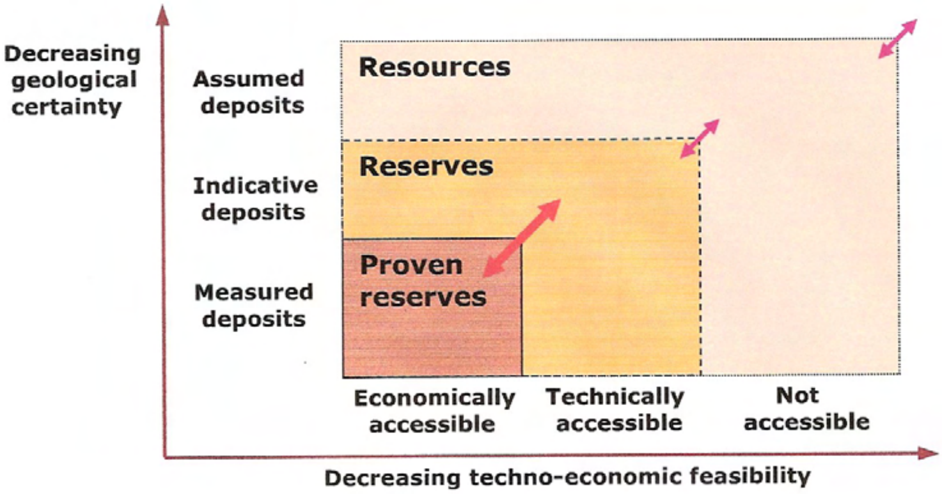

Figure 3 Depiction of resources and reserves (Kavelov and Peteves 2007)

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

The main quality parameter for coal is the carbon/energy content and so the logistics chains differ for hard coals and low rank coals. Global transportation of hard coals and some sub-bituminous coals is commercially worthwhile, while lower-grade coals (e.g. lignites and those with high impurity contents) must be used close to the coalfield as it is not economically viable to transport such coals any significant distance.

Within Europe there are considerable hard coal and lignite resources, but limited hard coal reserves. The lignite deposits are mostly located in Germany and in the Eastern member states. In the Western member states, coal production and, in most cases, utilisation have declined significantly, while in the eastern member states a similar decline has commenced although coal production and utilisation currently remain a major part of the energy mix.

Table 1 shows the main resources and reserves data for Europe together with recent annual production levels and hard coal imports. It is stressed that the reserves data comprise both proven and indicative reserves (see Figure 3). As the larger producers in the EU, the positions of the Czech Republic, Germany, Poland and the United Kingdom, and of Estonia as the focus of European oil-shale activities, are outlined below.

	Lignite + Brown Coal* (Mt)			**Hard Coal (Mt)**			
	Resource	**Proven and indicative reserve**	**Annual production (2006)**	**Resource**	**Proven and indicative reserve**	**Annual production (2006)**	**Annual imports (2006)**
Boznia-Herzogovena	3,994	2,767	5.1	-	-	-	-
Bulgaria	3,710	1,928	3.0	706	64	25.4	706
Czech Rep.	4,920	519	49.3	14,213	119	13.1	14,213
France**	-	-	-	99	-	-	99
Germany	77,200	40,800	180.4	230,000	23,000	21.9	230,000
Greece	6,800	3,300	65.8	-	-	-	-
Hungary	8,978	3,228	9.8	1,597	199	0	1,597
Poland	31,000	2,243	57.4	113,000	12,113	87.4	113,000
Romania	3,538	1,364	35.1	937	801	2.5	937
Serbia	-	15.926	36.5	-	-	-	-
Slovakia	1,000	70	2.2	-	-	-	-
Slovenia	616	110	4.7	-	-	-	-
Spain	354	354	8.2	4,519	1,156	11.7	4,519
United Kingdom	-	-	-	2,000	220	17	2,000
TOTAL	**142,120**	**72,619**	**457.5**	**367,053**	**37,672**	**179.0**	**367,053**
Other areas of EU interest							
Turkey	*3,147*	*534*	*62.0*	*1,039*	*860*	*3.5*	*1,039*
Ukraine	*****	*1,900*	*0.3*	*52,000****	*32,300*	*75.2*	*-*

* The calorific value of Lignite is assumed to be less than 12,000 kJ/kg, while that of Brown Coal lies between 10,000 and 20,000 kJ/kg

** Resources data taken from Euracoal, 2005.

*** Includes both hard coal and lignite.

Table 1 Resources, reserves and production/import data for hard coal and lignite within the EU sphere of interest (Euracoal 2008)

Czech Republic Coal is the Czech Republic's only significant indigenous energy resource, providing a stable contribution towards the country's energy security. There appear to be significant reserves of both hard coal and lignite (Euracoal 2004a). In 2006, total coal production was 61Mt, comprising 48Mt brown coal and 13Mt hard coal (MPO, 2008), while utilisation was 57.5Mt.

Germany Coal is an important part of Germany's energy consumption mix, meeting 24% of total energy needs in 2006, 5% by German hard coal (GVST 2007). Most of Germany's hard coal deposits are deep below ground and difficult to access. Their production is small in overall terms, but is subsidized and will remain so, though the level of subsidy is falling. In contrast, brown coal production is commercially viable without subsidies. Germany is the seventh largest coal producer in the world but, with internal production declining, it imported 46Mt of coal in 2007, of which 99% was hard coal (Euracoal 2008).

Poland From a European perspective, Poland possesses the largest internal coal reserves and its accession to the EU in 2004 significantly increased overall EU coal reserves and production. Poland was a major global supplier of hard coal until the political turnaround in the 1990s, associated with a growing market-economy, resulted in a contraction of its hard coal mining industry. Even so, coal currently dominates Polish energy supply, meeting about two thirds of the country's primary energy demand. Poland is unique in Europe in that almost all of its electricity (~96%) is generated from a combination of hard coal and lignite supplied from indigenous resources. Both are expected to retain a dominant role in the future, primarily for power generation and heat production, for which there is an extensive coal based infrastructure in the form of power plants, CHP facilities, and other coal-fired facilities (Mills 2007).

United Kingdom The UK has become the largest importer of seaborne steam coal in Europe. This represents a major change from its former position as a major coal producer prior to a near total collapse in coal mining. This arose due to decreasing internal coal consumption, following an uptake in the use of natural gas for power generation, the rationalisation of collieries in the run up to privatisation in 1995, a surge in low-cost imports and, more recently, the lack of commercial investment as mines reached the end of their economic lives (Euracoal 2004b). Although vast amounts of the UK's former hard coal reserves were sterilised due to the abrupt closure of working mines, the country still has significant coal resources, with at an estimated 220Mt of hard coal reserves (Euracoal 2008), both onshore and offshore in the southern North Sea. However, traditional mining methods are not suited to working offshore deposits, while the development and infrastructure costs of new mines for onshore deposits are not economical under the current economic conditions. Hence, these reserves will probably not be exploited until oil and gas supplies have declined to the extent that this coal is required on a strategic basis.

Estonia Estonia contains large deposits of oil shale. This is a sedimentary rock, which contains up to 50% of high-molecular polyfunctional organic compounds known as kerogen. Total resources are estimated at 5Gt, of which 1.5Gt are classified as mineable reserves. These comprise up to 2.8m thick horizontal layers that are at a depth of between 2 and 100m, interspersed with massive limestone deposits.

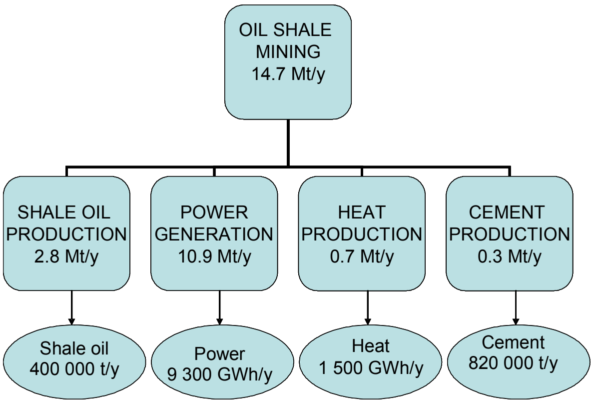

Figure 4 Material flows in the Estonian oil shale industry (Läänelaid 2009)

This shale is extracted by several companies, either from opencast workings (to a depth of 25m) or from underground mines. The shale is then either processed in retorts to produce oil and gas, used directly for power generation and industrial heating, or in cement production. Figure 4 shows the current situation in Estonia, in terms of extraction levels and relative uses (Oil Shale 2009).

The major industrial companies are:

- AS Narva Õlietehas, a subsidiary of Estonian Energy, which is a state-owned company engaged in the production, sale and transmission of electric and thermal power. This has included some international cooperation on oil shale utilization for oil and power production.
- Viru Keemia Grupp, which processes oil shale for production of fuel oils, oil coke and pitch, phenols, antiseptic wood impregnation oil and bitumen.
- The Kiviõli Oil Shale Processing Plan, which has interests in the production of shale oil and oil shale-based chemicals.

It should be noted that oil production from oil shale is also undertaken in Brazil, China, Russia while the USA and Australia have been involved in various research and testing activities.

2.3 Future projections

2.3.1 Global supplies and coal imports Global coal production in 2006 was close to 6.3Gt, comprising 5.4Gt of hard coal and 0.9Gt of lignite. For hard coal, this represented a 43% increase over the decade. At the same time, there has been a corresponding increase in the international coal trade, which, in 2006, amounted to 16% of the worldwide hard coal output. Steam coal exports grew by over 7% each year in the period 1999 to 2006 to reach 595Mt, while coking coal has remained relatively constant in the range 165-187Mt (Ritschel and Schiffer 2007).

According to long-term forecasts by the US Energy Information Administration (EIA), for a business as usual scenario, world coal consumption could increase by 74% over the period to 2030, with non-OECD countries accounting for 85% of that growth (EIA 2007). Over the same period, both the amount of coal produced for internal consumption and that to be traded internationally are expected to grow at a similar rate, with an emphasis on Asia (although such a projection is very sensitive to what assumptions are made about China and its involvement in the import/export market). It is stressed that this forecast was made prior to the global financial crash and short term growth in coal demand is expected to be severely limited. However, for the longer term, it is reasonable to expect a global recovery, at which point coal demand will increase broadly in line with previous projections. As such, the rate of growth in demand could remain in line with previous projections once that demand is triggered but the actual level of that growth will most likely be less than the 85% suggested, due to the short term problems.

The EIA projections for Europe suggest a relatively slow growth in overall energy consumption of 0.4% per year. Continued penetration of natural gas is expected in both the electricity and industrial sectors, and a growing use of renewable fuels is also foreseen for the region. Consequently, the EIA, in its reference case, suggests that annual coal consumption in Europe will decline by some 69Mt, which would still leave a significant market as the annual coal consumption in 2004 was some 530Mt (EC 2008). It is expected that, despite the availability of additional coal reserves in Poland and the Czech Republic, hard coal production will continue to decline as in many EU countries it is currently uncompetitive with imports (Energy Edge 2007). In many countries where hard coal production still exists, it is subsidised for socio-economic reasons, but the subsidies are gradually being phased out. In contrast, the central and eastern countries of Europe together with Turkey have significant reserves of readily accessible lignite, which can be worked with opencast methods that keep extraction costs low. Consequently, without subsidies, European lignite production is generally cost-competitive with imports of hard coal and so represents an important internally produced source of energy, which should be sustainable at current production levels for a long while. In 2004, lignite accounted for 47% of total coal consumption on a tonnage basis and 23% on a heating value basis.

Alongside demand, it is important also to consider the import supply possibilities. The current major suppliers into Europe are South Africa, Columbia and Russia. In the period to 2030, South Africa may be limited in its achievable level of exports while Russia may well reduce exports depending on its internal plans. Columbia appears to have plenty of extractable coal available for export. In the future, since worldwide demand will increase, the situation may well deteriorate. If these countries are to increase export production, then very significant investment will be required to establish new mines and supporting infrastructures. The EU's continued access to necessary import supplies could be dependent on such investments having been made. Thus, Europe will need to prepare carefully to ensure coal demand and supply requirements can be balanced. This has implications from a security of supply perspective. Further, it strongly suggests a need to determine whether there are technological advances that could lessen this dependence on imported coal since Europe has extensive hard coal resources, although these cannot currently be accessed economically.

2.3.2 Scope for increasing European indigenous reserves The reserves component of any mineable resource should increase over time as economic factors and technical improvements in extraction and use technologies render lower grade deposits more attractive. This will particularly apply to coal as the resources are so much greater than those of the competing fossil fuels, oil and natural gas.

Additionally, however, one technology, *underground coal gasification (UCG)*, has the potential to significantly increase access to coal in seams that are either too deep or too thin to be exploited by conventional mining techniques. In principle, UCG exploits the energy content of coal while avoiding the environmental problems at the surface associated with coal mining, disposal of mining waste and the subsequent coal combustion. Moreover, there are no methane emissions when this technology is used, unlike when coal is mined.

The UCG process involves injecting water/steam and air or oxygen into a coal seam. The injected gases react with coal to form a combustible syngas which is brought to the surface and cleaned prior to utilisation. The basic feasibility of the technique has been proven, but the development of a working system has proved more difficult. Recent work in the USA, Europe and Australia has concentrated on the exploitation of UCG in coal seams accessed using advanced guided drilling techniques (Coal Authority 2008). The main problems are borehole drilling, controlling the reaction within the seam and producing a gas of a consistent high quality. There also remains the need to fully evaluate the possible environmental impacts on underground aquifers and adjacent strata.

If UCG could be established on a commercial basis, it should prove possible to extract the energy from hard coal deposits that are currently considered as resources, such that the overall exploitable reserves of hard coal would be significantly increased. For lignite, there would be a corresponding benefit but the impact would be less as the great majority of such deposits are already considered as exploitable reserves. A feature of UCG that is of interest for the production of liquid fuels from coal is that the energy content of the coal is extracted as a syngas – essentially a mixture of CO and hydrogen. Once this has been brought to the surface, it can be used in a Fischer-Tropsch (FT) based plant to produce liquid fuels.

3 Overview of main CTL process routes and the impact of coal type

Coal is a solid with a high carbon content and a low hydrogen content, typically only 5%.

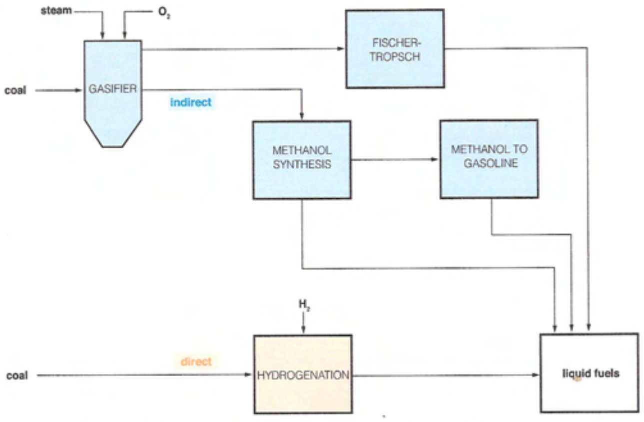

Figure 5 Principal process routes for the production of liquid fuels from coal (Couch 2008)

Transport fuels (gasoline/petrol, diesel and jet fuel) are currently derived overwhelmingly from crude oil, which has about twice the hydrogen content of coal. For coal to replace oil, it must be converted to liquids with similar hydrogen contents to oil and with similar properties. This can be achieved by removing carbon or by adding hydrogen, either directly or indirectly, while reducing the molecular size. Also during the process, elements such as sulphur, nitrogen and oxygen must be largely eliminated. Thus, the technical challenge is to increase the hydrogen/carbon (H/C) ratio in the product (Williams and Larson, 2003), and to produce molecules with the appropriate range of boiling points. There are two contrasting approaches to providing liquid fuels from coal by liquefaction, Figure 5, as described below.

3.1 Direct liquefaction

In direct coal liquefaction (DCL), pulverised coal is treated at high temperature and pressure with a solvent comprising a process-derived recyclable oil slurry (Figure 5). The large coal molecules are broken down into smaller molecules. Generally in DCL, the H/C ratio is increased by adding gaseous H_2 to the slurry of coal and coal-derived liquids. Catalysts can speed some of the required reactions, and the product is a liquid which is broadly comparable to a synthetic crude oil. Liquid yields in excess of 70% by weight of daf coal feed have been demonstrated for some processes, albeit under favourable circumstances. Overall thermal efficiencies for modern processes are generally in the range 60-70% if allowance is made for generating losses and other non-coal energy imports. The technology has yet to be proven at full commercial scale although several initiatives are now underway (see Sections 4 and 5).

There are two main variants of DCL, depending on whether or not the initial dissolution of the coal is separate from the conversion of the dissolved coal into distillable liquid products. Thus:

- a *single-stage* liquefaction process provides distillates via one primary reactor, or in a train of reactors in series. An integrated on-line hydro-treating reactor may be included to upgrade the primary distillates without increasing overall conversion.
- In contrast, a *two-stage* process provides distillates via two reactors or reactor trains, in series. The main function of the first stage is the coal dissolution, and it is operated either without a catalyst, or with only a low-activity disposable catalyst. The heavy coal liquids are hydro-treated in the second stage in the presence of a high-activity catalyst to produce distillable products (DTI 1999). Most two-stage direct liquefaction processes were developed in response to the oil price rises of the early 1970s, often as a development of earlier single-stage processes. Work was carried out in many countries, but few processes were developed beyond the laboratory scale and many were generically very similar.

Hydrogen is also needed to reduce the oxygen, sulphur and nitrogen present. These are removed as H_2O, H_2S and NH_3. A range of partially refined gasoline- and diesel-like products (as well as propane and butane) can be recovered from the synthetic crude by distillation. This provides a series of different temperature-range 'cuts', and each of the liquid products is made up of a mixture of different hydrocarbons appropriate to the boiling point range of the different components. These products tend to be highly aromatic, which can make them difficult to use as high quality transport fuels, although they can be rich in octane aromatics making a good gasoline substitute.

The range of liquid products produced by direct liquefaction depends on four major variables:

- the nature of the coal being processed;
- the solvent or solvent mix used;
- the process conditions, including temperature, pressure, residence time and catalyst;
- the number of reactor stages used, and the subsequent refining of the initial products.

3.2 Co-processing

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

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

Although some co-processing technologies have been developed to several tonnes/day or pilot plant scale, they have not been developed to the same degree as other liquefaction processes. The more important technology variants are outlined in Section 5.

3.3 Indirect liquefaction

Indirect coal liquefaction (ICL) is a high temperature, high pressure process (Figure 6), which comprises a gasification stage with syngas cleanup, followed by either Fischer-Tropsch (FT) or methanol synthesis. Oxygen blown gasification of the coal produces a syngas consisting mainly of CO and H_2, which can be modified as necessary by using the water gas shift reaction in which water and carbon monoxide react to form carbon dioxide and hydrogen, thus increasing the H_2: CO ratio. The syngas contains a number of impurities, including particulates, sulphur compounds (in particular H_2S and COS) and nitrogen, which are removed in a series of clean-up stages after which the CO_2 is separated. The cleaned syngas molecules ($CO+H_2$) are subsequently catalytically combined/rebuilt to make the distillable liquids. These can include hydrocarbon fuels such as synthetic gasoline or diesel, and/or oxygenated fuels, together with a wide range of other possible products.

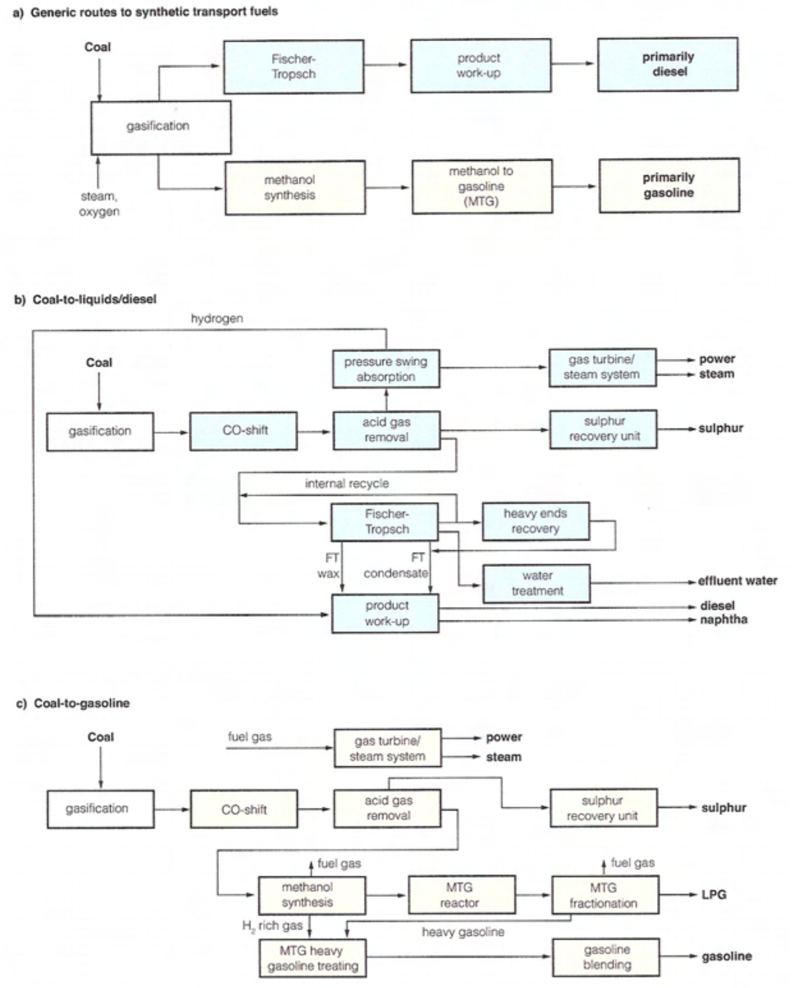

Figure 6 Flow diagram of the two generic routes to synthetic transport fuels using ICL (Radtke et al 2006)

There are two possible routes using ICL for the production of liquid transport fuels (Figure 6), either via FT synthesis from which, depending on the temperature and process conditions used, the main fuel product is generally diesel, or methanol synthesis where the main fuel product is petrol/gasoline (Radtke et al 2006).

For FT synthesis, there are two main operating modes:

- High temperature (HTFT) technology, which operates between 300–350°C to maximise the gasoline fraction; and
- Lower temperature (LTFT) technology, which operates in the range 200–250°C and maximises the production of diesel.

HTFT produces a more complex product slate than LTFT, and the gasoline produced contains considerable amounts of benzene and its derivatives, which are increasingly regarded as being undesirable in transport fuels. HTFT offers more possibilities for chemicals production and the large quantities of light hydrocarbons produced can be used to make a substitute/synthetic natural gas (SNG). The product distribution from FT synthesis can be estimated from thermodynamic considerations, but in practice there is a strong degree of empiricism as there are many competing reactions.

The route involving methanol synthesis was based on the discovery of shape selective zeolite catalysts in the early 1970s. Although it has not yet been proven at commercial scale, significant scale operations are being taken forward in China.

Linked to this is the production of di-methyl ether (DME), which involves de-watering methanol in the presence of a dehydration catalyst such as alumina. The production stages from a purified syngas are thus sequential. There are plans for a number of large scale plants worldwide, which may be built if the potential advantages of DME become more widely understood.

Although considerably more complex than DCL, indirect liquefaction has a number of advantages. Thus:

- the principal product from the first stage is a gas which leaves behind most of the mineral matter of the coal in the gasifier, apart from any volatile components;
- undesirable components such as sulphur compounds, are more readily cleaned out from the gas and removed;
- it is easier to control the build-up of the required products;
- there is good operational flexibility in that syngas made from any source (coal, natural gas, or biomass) can be used;
- the CO_2 produced can, in principle be captured for subsequent storage;
- the products from ICL are ultraclean, with near-zero aromatics and no sulphur. With minimal further refining it is possible to produce ultraclean diesel or jet fuel. In South Africa, Sasol has demonstrated that transport fuels produced from coal using ICL can match or surpass the accepted standards for oil-derived gasoline and diesel.

Also, each stage of the ICL process involves commercially proven components and the technology has been used in South Africa on a commercial scale for many decades. That said, much of the development of the FT stage has been on a trial and error basis (Davis 2005) and it has been suggested that the ‘art’ of FT reactor development has outpaced scientific and engineering understanding.

3.4 Hydropyrolysis

Pyrolysis is a simple method to convert coal into higher valuable fuels involving only a heating step to split coal into gas, tar and char. Devolatilisation is the first step in any thermal coal conversion process, so pyrolysis is a controlling step with an important influence on conversion rate and product formation. If the pyrolysis step is carried out in a hydrogen atmosphere (hydropyrolysis), while under pressure, chemical reactions can occur between the hydrogen and the free radicals in the primary coal decomposition products. The dynamic equilibrium between cracking and polymerisation, which compete with each other, determines product formation and quality, so, in principle, the process parameters, which influence the position of the equilibrium and thereby the product distribution, can be used to control the overall reaction and to increase the devolatilisation rate (Wanzl 2008a).

Because the chemical bonds in the macromolecular coal structure are relatively weak, the primary decomposition of the coal is a very fast reaction and can be completed within a few minutes if the coal is heated rapidly to the reaction temperature. Hydrogen can stabilise the primary carbonisation products and can also further crack the higher molecular coal fragments. This leads to significantly enhanced yields of volatiles and a shift in the product distribution compared to carbonisation in inert gas.

Pyrolysis and hydropyrolysis can be carried out by different methods. Reactor types which have been applied in technical development work are fixed bed, fluidised bed and entrained phase. The most important process parameters which determine the course of the hydropyrolysis reaction and the product formation are listed in Table 2.

Process design	Type and design of pyrolysis process Reactor type
Feed coal	Coal characteristics Pre-treatment of coal Impregnation with catalyst
Process variables	Temperature Hydrogen pressure Total pressure Particle diameter Heating rate of coal Residence time of volatiles Residence time of solids Ratio H_2 / coal

Table 2 Important process parameters in coal hydropyrolysis (Wanzl 2008a)

Hydropyrolysis is a relatively immature technology. During the early 1970s, the main focus was on fundamental studies while development work was generally at laboratory scale. The overall aim was to produce a partially hydrogenated oil which could be used as feedstock for the chemical industry and as motor fuel. However, in addition to oil, the other primary products are a high heating value gas and a char, which are of lower value. That said, the char could either be burned in power plants or gasified in order to produce a synthesis gas. Thus, hydropyrolysis of coal could be combined with combustion or gasification of the hydropyrolysis char, and offers the possibility of stripping the feed coal before combustion or gasification (Figure 7).

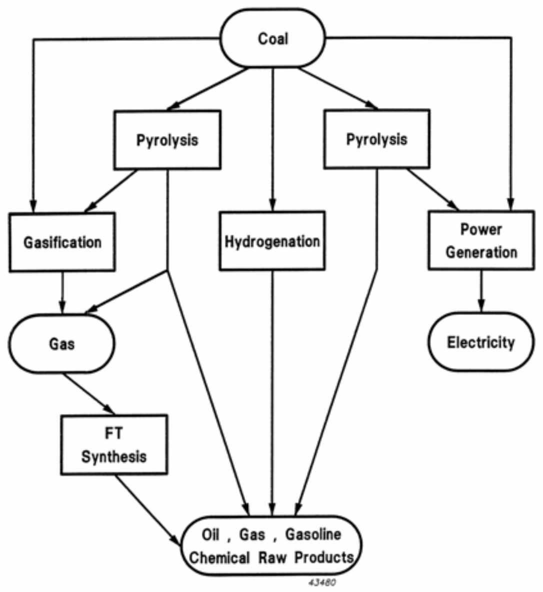

Figure 7 Hydropyrolysis as an approach for coal-to-liquids conversion (van Heek and Wanzl 1989)

3.5 Impacts of coal rank and composition on process options

Coal reactivity, and the presence and behaviour of both mineral matter and organically bound impurities, have substantial effects on some liquefaction processes, and on the liquids produced.

3.5.1 Direct coal liquefaction

For DCL, the products formed depend largely on what was there originally together with the dissolution and/or hydrogenation processes used. Thus the behaviour of a coal during DCL is governed by its rank (Shinn 1985), petrographic composition and the mineral matter present. Thus, high volatile (>35%) bituminous coals appear to be excellent direct liquefaction feedstocks, resulting in high oil yields and good product quality. The liquefaction behaviour of sub-bituminous coals and lignites differs from that of bituminous coals. Lignites tend to be more readily converted in moist mixtures of $CO + H_2$ rather than in hydrogen alone. Low-rank coals convert more slowly and incompletely than bituminous coals. They are more sensitive to solvent H-donor concentration, and require more severe reaction conditions to maximise yield. At the same time, although the total liquid yield tends to decrease with decreasing rank, the proportion of low-boiling distillates increases, which can be advantageous. Certainly, it has been shown that many sub-bituminous coals (such as low rank western USA coals and Australian brown coals) can provide suitable feedstocks.

In addition, it is important to consider the influence of coal properties on technical aspects of plant operation (Strobe et al 1981). In this regard, the most important characteristic coal properties are particle size, water content, amount and composition of mineral matter, content of the sulphur, nitrogen and chlorine species in the organic coal matter. The required particle size of the feed coal depends mainly on the process characteristics. On one hand, the particle size has to be low enough to ensure stability of the coal oil slurry, because coarse particles favour sedimentation while the valves of the high pressure pumps are very sensitive to oversize particles. On the other hand too high a proportion of very fine solid material is not desirable as this enhances significantly the viscosity of the coal oil slurry which causes high pressure drops and decreases the heat transfer in the heat exchangers. A typical particle size for hard coal as feed material is <0.2 mm.

The feed coal is usually dried in a combined drying and pulverising step. A high residual moisture in the coal which cannot be further reduced is disadvantageous as the resulting steam reduces the hydrogen partial pressure in the reactor volume. For hard coals 0.5-2 wt.-% moisture contents are attainable whereas for lignite 5 - 10 wt.-% has to be accepted. The mineral matter of the feed coal is an inert burden in the process and should be as low as possible, since they occupy expensive high pressure reactor volume without a contribution to the oil yield. Furthermore, they cause erosive material damages to the valves.

Within the organic part of the coal, the heteroatoms have varying impacts. Iron oxide is one of the most important catalytically active components of hydrogenation catalysts, which requires the conversion into the active species by sulphidation with hydrogen sulphide. Therefore, in coal hydrogenation, a sulphur content of the feed coal of >1 wt.-% is desirable. In contrast, the organic nitrogen can convert to ammonia and further to ammonium hydrogen carbonate and ammonium sulphide, which can lead to plugging and problems in plant operation. Chlorine from the coal is converted to hydrogen chloride and even with low chlorine contents in the coal of 0.1 wt.-%, this can lead in a short time to component corrosion unless the acid gas is neutralised by the addition of alkaline materials.

3.5.2 Indirect coal liquefaction

For ICL, the coal does not impact on the liquefaction process as once the syngas, consisting primarily of CO and H_2, has been produced, downstream processing does not depend on the coal rank. However, it does affect the performance of the gasifier, which provides the first major process stage (Collot 2006). When the selection of the gasifier for syngas production is considered, the important coal properties are caking behaviour and ash softening temperature. However, all coals, even those with higher ash contents, can be gasified without problems provided a suitable gasification process is selected (see Annex 1).

3.5.3 Hydropyrolysis

Coal rank, and by that its volatile matter content, is the main parameter which determines the attainable yields of liquid and gaseous products in hydropyrolysis. High volatile hard coals are the most suitable feedstock. Lower rank fuels like lignite and peat can also be used; however, but the nature of the liquids is less aromatic and the relative liquid product proportion is reduced since gas formation is enhanced.

3.6 Implications for EU indigenous coal utilisation

If Europe is to establish any CTL capability, it will be based on the use of indigenous coal sources. Until an innovative, cost-effective technique is established for extraction of the deeper hard coal deposits, such coal sources will be lignite and brown coal. The quality mix is in a range which is suitable both for ICL and in a significant part also for DCL. All lower rank coals should be suitable for hydropyrolysis. Ultimately, the choice will be dependent on the economics, which will be project specific.

3.7 Summary of CTL technologies

The processes resulting from DCL research are summarised in Table 3 (DTI, 1999). For ICL, the only significant process to date is that developed by Sasol.

ONE-STAGE DCL PROCESSES		
Technology	**Developer**	**Country**
DT, IGOR (Kohleoel)	Ruhrkohle AG and Veba AG	Germany
NEDOL	NEDO (New Energy and Industrial Technology Development Organization)	Japan
H-Coal	HRI, presently HTI (Hydrocarbon Technologies Incorporated)	USA
Solvent Refined Coal – SRC-I i SRC II	Gulf Oil	USA
Exxon Donor Solvent – EDS	Exxon Corporation	USA
Conoco Zinc Chloride	Conoco	USA
TWO-STAGE DCL PROCESSES		
Technology	**Developer**	**Country**
Catalytic Multi-Stage Liquefaction - CMSL	US DOE and HTI	USA
Catalytic Two-Stage Liquefaction - CTSL	US DOE and HRI (now HTI)	USA
Liquid Solvent Extraction -LSE	British Coal Corporation	UK
Brown Coal Liquefaction - BCL	NEDO	Japan
Consol Synthetic Fuel - CSF	Consolidation Coal Co	USA
Lummus Integrated Two-Stage Liquefaction - ITSL	Lummus Crest,	USA
Chevron Coal Liquefaction - CCLP	Chevron	USA
Kerr-McGee - ITSL	Kerr-McGee	USA
Mitsubishi Solvolysis	Mitsubishi Heavy Industries	Japan
Close-Coupled Two-Stage Liquefaction – CC-TSL	Amoco	USA
Pyrosol	Saarbergwerke	Germany
Supercritical Gas Extraction - SGE	British Coal Corporation	UK
Shenhua Process	Shenhua Group	China

Table 3 Direct coal liquefaction technologies

4 Review of European CTL R, D&D initiatives, past and present

Sections 4 and 5 provide an overview of the more promising and potentially credible R, D & D activities worldwide. Section 4 includes the previous EU activities, while Section 5 describes previous and new programmes in Australia, China, South Africa, and the USA. In the latter cases, significant large scale practical test programmes have either been undertaken, or are at the detailed engineering stage. Activities in India, Indonesia and Mongolia, which so far have only included studies and small scale experimental work, are not considered further.

4.1 European Commission and the member states

In Europe, during the mid 1970s, the development of coal liquefaction processes was first taken forward by industrial organisations in Germany and the UK (the DT, Pyrosol and LSE processes) and was supported extensively by industrial research institutes and universities throughout the European Union. This included development and assessment of various gasification options for the hydrogenation step. The ECSC and the EC provided very significant support for these technical research activities and scale-up projects, examples of which are listed in Table 4.

UK FOCUSED R&D ACTIVITIES		
PROJECT TITLE	**EC/ECSC CONTRACT No.**	**REPORT No.**
Improved coal liquefaction yields	7220-EC/852	EUR-14923-EN
Improvements to direct coal liquefaction		EUR-18247-EN
Chemical and physical valorisation of coal	7220-EC/117	EUR-10800-DE
Extended operation of the liquid solvent extraction process	7220-EC/829	EUR-10943-EN
Market potential of HTR modular reactors for high temperature processes		EUR-11635-DE
Optimisation studies on the liquefaction of coal	7220-EC/823	
Hydrogenating extraction of coal		EUR-12215-EN
Development of a computer package for DCL economics		EUR_12355-EN
The evaluation of cokes as filter aids in direct coal liquefaction		EUR-12257-EN
New hydrogen donors for direct liquefaction of coal;		EUR-12590-EN
Co-refining of coal and petroleum		EUR-12825-EN
New iron catalysts for direct liquefaction of coal		EUR-13043-EN
Co-refining of coal and petroleum		EUR-13168-EN
Hydropyrolysis of coal	7220-EC/207	EUR-14588-FR
Conversion of coal to liquid hydrocarbon distillates by hydrocracking	7220-EC-810	
Conversion of coal to liquids using supercritical extraction	7220-EC/8/805	
Solution of coal in supercritical solvents	7220-EC/8/809	
Production of distillate fuels and chemical feedstocks from coal	7220-EC/817	
Study of the solution of coal in solvents	7220-73/8/802	
Proceedings of EC Conf. on advanced transport fuels from coal	ECSC and EC projects	ISSN 0363-907X
Proceedings of EC Contractors meeting on production and utilisation of new energy vectors	ECSC and EC projects	ISBN 1-85333-161-9
Synthetic fuels from coal	ECSC and EC projects	EUR-11191-EN

GERMAN FOCUSED R&D ACTIVITIES		
PROJECT DESCRIPTION	**EC/ECSC CONTRACT No.**	**NATIONAL CONTRACT No.**
Feasibility study of an industrial coal hydrogenation plant		03E1242A
Optimisation of a combination of FT synthesis with coal liquefaction for production of motor fuels		03E3039A
Kohleoel-Project: Development of DT and IGOR; Kohleoel plant Bottrop		03E1158B; 03E1158E; 03E6323B; 0326323C; 0326552A
Development of the IG-Neu- and the Pyrosol liquefaction process of Saarbergwerke AG		ET1051E; 03E1050E; 03E1051Z; 03E1244A; 03E6161A
Hydrogenation of Rhenisch lignite		03E1087A; 03E1261A; 03E1417A; 0326524A
Development of a tubular hydrogenation reactor for catalytic high-pressure hydrogenation of hard coal and lignite		03E1270A; 03E1270B; 03E1270C; 0321270D; 0321270E
HTW-gasification studies	7220-ED/81, DIS-1897-98	
HTW PDU work	7220-EC/119 & 121, 7220-ED/051 & 027 & 077 &106	
Demo-plant in Berrenrath	LG/039/83/D; LG/4/84; LG/02/85; LG/07/86 &87; CT-92-001; 7220-EC/032; 7220-ED/069 & 075; SF-258/95; SF-263/97; 7220-C/040	
Development of the Texaco process for gasification of coal and hydrogenation residues		03E1217Z; 03E1263A
Prenflo-gasification pilot-plant in Fürstenhausen/Germany	LG/00018/83/DE, LG/00270/85/DE, LG/00354/87/DE, LG/00255/89/DE	
Prenflo-gasification demo-plant in Puertollano/Spain	SF/337/91/ES/FR, SF/00198/92/ES/FR, SF/422/93/ES/FR, SF/0002/94/ES/FR, SF/200/95/ES/IT/FR	
Entrained-flow gasification of hydrogenation residues in the VTA-gasifier	LG/00010/80/DE; LG/00020/84/DE	
Carbonisation of hydrogenation residues in a rotary kiln		03E-6104A; 0326617A

Table 4. Examples of EC/ ECSC and member states supported projects for UK and German CTL and associated R&D activities

4.2 Germany

The DT Process, (Deutsche Technologie) to which was subsequently added the Integrated Gross Oil Refining stage called IGOR+, is a development by Ruhrkohle AG and VEBA OEL AG of the Bergius or I G Farben process that was used at a commercial scale in Germany until 1945. The project development (project Kohleoel) spanned the period 1975 to 1993. It was financially supported from the start by the State Government of Northrhine Westfalia and also, from 1984, by the Government of the Federal Republic of Germany. The Kohleol project together with the complementary Saarbergwerke development (see below) were part of a national strategic initiative to promote national energy resources on the basis of domestic hard coal.

The process can achieve greater than 90% conversion when processing bituminous coals, with liquid yields in the range of 50-60% on a dry ash-free coal basis, Figure 8 (Wanzl 2008b). Coal is slurried with a process-derived recycle solvent and a 'red mud' disposable iron catalyst, then pressurised and preheated. H_2 is added and the mixture is passed to an up-flow tubular reactor, operating typically at 300bar and 470ºC. The specific coal feed rate to this reactor is in the range 0.5-0.65 tonnes/m^3/hour. Products from the top of the reactor pass to a hot separator. The overheads from this separator remain in the gas phase and are hydro-treated at a temperature of 350-420ºC in a fixed-bed reactor at the same pressure as the main reactor. The hydro-treated products are depressurised and cooled in two stages. The liquid product from the first of these stages is recycled to the slurrying step as part of the solvent. The liquid product from the second stage is routed to an atmospheric distillation column, yielding a light oil (C5 - 200ºC bp) and a medium oil (200-325°C bp) product. The bottoms from the original hot separator pass to a vacuum distillation column to recover distillable liquids. These are added to the hydro-treating reactor feed, and are subsequently largely recycled as solvent. The vacuum column bottoms consist of pitch, mineral matter, unreacted coal and catalyst, and in commercial operation would be used as a gasifier feedstock for H_2 production (DTI 1999).

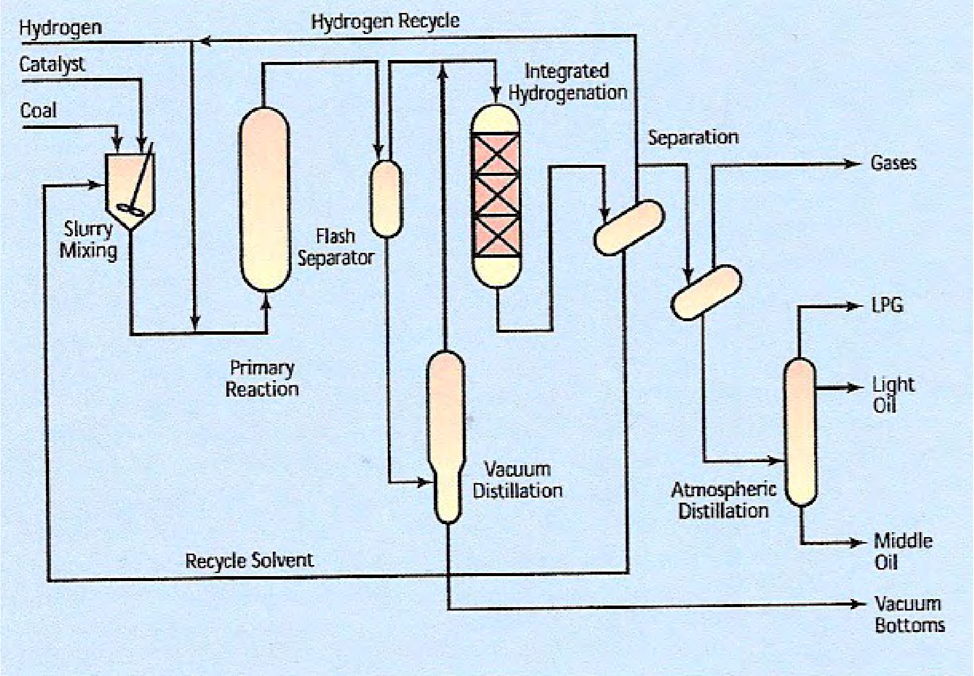

Figure 8 The DT Process (DTI 1999)

Development proceeded via a 0.2 tonne/day continuous unit at Bergbau-Forschung (now DMT) and a 200 tonne/day plant at Bottrop. The Bottrop plant operated from 1981 until April 1987, producing over 85,000 tonnes of distillate products from l66,000 tonnes of coal during approximately 28,000 operating hours. Thus, it has been stated the technology is demonstrated and ready for commercialisation, although no details of projected capital costs or overall process economics were made publicly available at the time. A feasibility study was carried out by Ruhrkohle AG and Veba Oel AG for a technical-scale hydrogenation plant for liquefaction of German hard coal for production of fuel oil and diesel as transport fuel. The plant was designed with a scale-up factor of 12.5 for a total coal throughput of 20,000 t-daf/d via four trains of 5,000 t-daf/d each. However, support was not forthcoming for this proposed scale-up of the technology and since then no further technology optimisation work has been supported, primarily due to the perceived problems of competing with low oil prices of the time.

In 1997, the China Coal Research Institute (CCRI) signed a two-year agreement with Germany to carry out a feasibility study for a 5000 tonnes/day demonstration plant. The suitability of sites for a liquefaction plant in Yunnan Province was investigated, including the potential market for products (EBR, 2007). However, the project did not proceed beyond the study stage due in part to a Government focus on progressing its own technologies (see China subsection).

Also in Germany, the Pyrosol Process was developed by Saarbergwerke (Wanzl 2008c). The intention was to enable the liquefaction of higher ash coals with a mineral matter content of up to 10 – 20 %. It was a two stage process, which comprised a mild hydrogenation process, with similarities to the DT process, to which was subsequently added a second stage hydro-pyrolysis step applied to the hydrogenation residue from liquefaction in the first stage with a reduced degree of conversion. A total distillate product yield of 55-60% on dry, ash free coal basis can be obtained. This product is lower boiling than that from most other processes due to the way in which it is recovered.

In the process scheme the coal slurry is prepared, heated and fed to the hydrogenation reactors. In a subsequent hot separator, the minerals, the unconverted coal and the low and non-volatile organic liquids are separated from the vapours and gases. The overhead flows through the intermediate separator where, by partial condensation at 300°C, an oil is obtained which is added to the coal slurry. The heat of the oil is used for direct exchange and contributes to the heating of the oil slurry. After the intermediate separator the product flow is led to the cold separator where distillation is used to recover the different oil fractions. The specific feature of the Pyrosol process is realised in the handling of the underflow from the hot separator which contains all remaining solids. While in the DT process the underflow is processed in a vacuum flash unit, in the Pyrosol process it is carbonised in a hydropyrolysis step.

Saarbergwerke began development of this two-stage direct coal liquefaction process in 1974, reaching a 6 tonne/day pilot plant that was operated between 1981 and 1984. By 1985, the process was sufficiently advanced for proposals to have been made to the German government for the construction of a million tonnes coal/year commercial demonstration plant. However, as oil prices decreased at that time, support was not forthcoming and in 1986 the 6-tonne/day pilot plant was finally closed down and dismantled.

While the German research and development programme was focused on DCL processes, Germany also has considerable gasification expertise, via Lurgi and Siemens, which is applicable to ICL processes. With regard to ICL, in 2006, the Syntroleum Corporation and Sustec Industries AG, a private company based in Switzerland, announced that they had entered into a project development agreement to jointly develop FT projects. They also indicated that the first project would be a nominal 3,000 bbl/d Syntroleum Fischer-Tropsch and Synfining unit as the first phase of a possible 20,000 bbl/d FT project at Sustec's Schwarze Pumpe industrial facility at Spreetal, Germany. This would include an expansion of the existing gasification capacity using Future Energy GSP technology which was originally developed by Sustec and its predecessor companies before being acquired by Siemens (RedOrbit 2006). It was announced that the pre-FEED engineering work and feasibility study would be completed by early 2007 to be followed by a decision on whether to proceed with the full project. However, no information is available about the realisation of these project plans

Finally, between 1977 and 1992, Germany via Bergbau-Forschung/DMT, was the lead partner for the IEA-Pyrolysis Project, with experimental support from the British Coal Corporation in the UK, together with the Technical University of Lund (LTH) and Chalmers Institute of Technology (CTH) in Sweden (Wanzl 2008a). The objectives of the project were to develop the technical and scientific basis for the optimisation of the thermal decomposition of coal into liquid fuels and basic chemicals, and to generate a data base for the design of pilot plants and for the assessment of the technical and economic feasibility.

This hydropyrolysis development was based on a two-stage reactor concept, which allows separate optimisation of the two primary steps of primary coal decomposition and subsequent treatment of the volatiles. The first step of coal decomposition uses an entrained phase reactor in order to achieve maximum yields of volatiles. As the char favours recombination reactions, which reduces the yield of liquid products, this solid is removed from the carrier gas at the outlet of the entrained phase reactor. The carrier gas with the volatiles is fed to a second reaction stage consisting of a thermal non-catalytic cracker which can be used to adjust temperature and residence time independently from the pyrolyser and thereby to optimise reaction conditions for the required product composition and quality.

The project work included extended experimental laboratory work on the influence of the different process parameters, the operation of a 1 kg/h PDU, and technical and economic feasibility studies. The test fuels included the whole range of coals from Germany and UK together with peat from Sweden. However, the techno-economic assessment indicated that while the oil products are attractive, the process would only be viable if a commercial use could be found for the significant quantities of char (the latter being 40% of the overall product slate). Consequently, this and other hydropyrolysis development programmes have stalled.

4.3 United Kingdom

Between 1973 and 1995, the Liquid Solvent Extraction (LSE) process was developed by the British Coal Corporation, Coal Research Establishment (CRE) as part of a national coal based strategic initiative.

Figure 9 shows a schematic diagram of the two-stage process. Coal is slurried with a process-derived recycle solvent, preheated and passed to a non-catalytic digestion step, which consists of two or more continuous-stirred tank reactors in series. These reactors operate at a temperature of 410-440ºC and a pressure of 10-20 bar, required solely to reduce solvent vaporisation. No H_2 is used in this step, but the solvent acts as a hydrogen donor, transferring up to 2% by weight of hydrogen to the coal. The digester product is partially cooled and filtered in a vertical-leaf pressure filter to remove unreacted coal and ash. The filter cake is washed with a light recycle oil fraction to recover product, and is then dried under vacuum. As the dried filter cake contains only a small proportion of residual non-distillable liquids; the process is relatively insensitive to the ash content of the feed coal or the extent to which it can be dissolved. In commercial operation, the filter cake would be gasified to produce H_2.

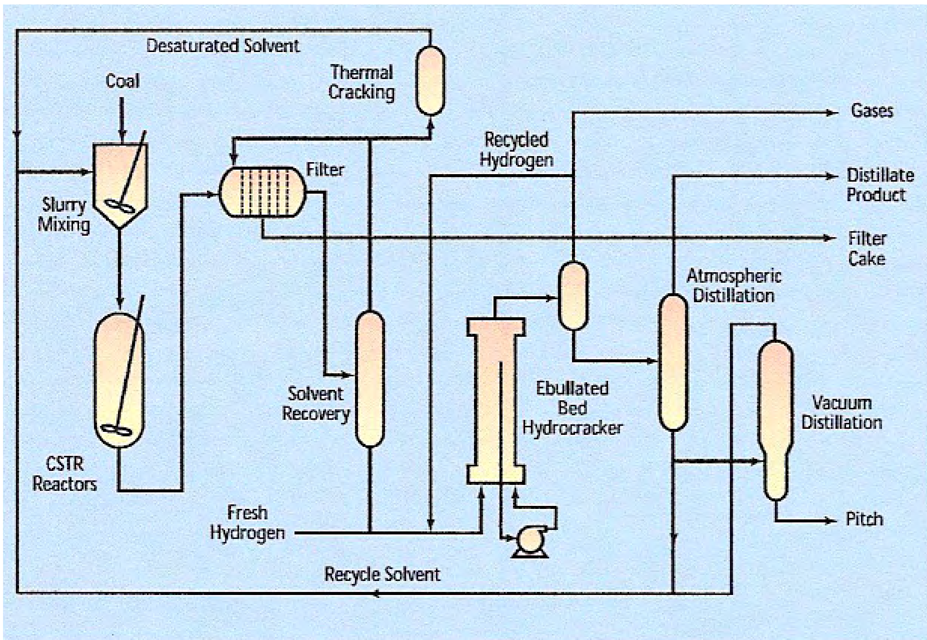

Figure 9 Schematic of the LSE process (DTI 1999)

The filtered coal extract passes to a distillation column to recover the light oil wash solvent and is then preheated, mixed with H_2 and routed to one or more ebullating-bed reactors in series. There is no inter-stage separation and the reactors operate at nominally the same conditions: ~200bar, 400-440ºC and a space velocity in the range 0.5-1.0 kg feed per kg catalyst per hour. The reactor products are cooled, depressurized and passed to an atmospheric distillation column to recover a distillate product. The cut-point of this column is adjusted to maintain solvent balance, resulting in a product that typically boils below 300ºC. The column bottoms are partially routed to a vacuum distillation column, used to control the level of pitch in the recycle solvent. The overheads from this column are recombined with the main atmospheric column bottoms stream and recycled as the solvent to the slurrying step.

The primary aim of the CRE work was to create and characterise various coal extracts after hydro-treatment, using a dedicated integrated solvent extraction plant together with a continuous-hydrocracking unit (CHU-ISEP). Alongside this key experimental facility, many aspects of liquefaction, such as catalyst selection and residue filtration, were first studied or screened on smaller equipment with the aim of confirming potential process improvements in recycle runs on the CHU-ISEP equipment. Between 1977 and 1986, over 30,000h of operation were achieved. In addition, secondary refining facilities were constructed, in which finished gasolines and diesels were prepared, tested and subsequently demonstrated in vehicles. This substantial programme of research was supported and partially funded by the European Economic Community (EEC) between 1974 and 1986. Alongside this, various specific R&D issues were partially financed through the research programme of the ECSC (Kimber 1996).

Following the technical success of the CRE activities, British Coal established a 2.5 t/d pilot plant, based on the two stage LSE process, which operated for four years at Point of Ayr, North Wales, UK. The EEC continued to provide part financial support and industrial input was provided by Ruhrkohle Oel und Gas GmbH and the Amoco Corporation. The ECSC also provided support for associated supporting R&D.

One of the major advantages of the LSE process is its ability to handle virtually any coal regardless of rank or ash content. The results from the operating programme showed that it would be possible to operate the process in an all-distillate product mode, removing the requirement for a vacuum column. At the laboratory scale, a significant proportion of saturated species could build up in the recycle solvent under certain conditions, reducing the effectiveness of the extraction step. However, in the pilot plant, solvent quality was maintained without the need for a separate, thermal cracking step. The total distillate product yield was in the range 60-65% (daf), most of which boils below 300ºC. That said, filtering to separate solids and liquids proved to be a difficult process step (Kimber 1996).

An outline design for a 65 t/d demonstration plant was produced in sufficient detail to allow a contractor to proceed directly to the detailed design stage. However, as with other major developments worldwide, the plant was not built because the low oil price and the perceived reduction in security of oil supplies concerns during the 1990s meant that the economic case could not be made (DTI, 1999). Consequently, the project team was disbanded and the equipment scrapped.

4.4 Poland

Poland has supported a programme of work on coal liquefaction since 1967, at the Central Mining Institute (CMI) in cooperation with other Polish R&D institutions, within the framework of a Ministry of Mining and Power Industry initiative. Based on a review of coal liquefaction research carried out elsewhere, and on the results of the Polish experimental programme, a two-stage method, similar to the US Consol CSF technology was selected. The work was carried out in a large-scale laboratory installation of capacity 120 kg/d and in a PDU of the capacity of 1,200 kg/d.

The drawbacks of the two-stage method, particularly in problems with the separation of unprocessed coal residue from the extract solution caused this work to be abandoned in the late 1970s, in favour of research on direct, one-stage, autocatalytic hydrogenation. This enabled the direct production of distillation products and the replacement of mechanical separation of solids by vacuum distillation. Steam coals with an ash content of about 20% and sulphur of up to 1.5%, were identified as the prospective feedstocks. This work was carried out at laboratory scale, large laboratory scale and in a PDU of capacity 2,000 kg/d of coal. The heart of the installation was a hydrogenation reactor with an external circulation system. No external catalyst was used. The catalytic functions were provided by the pyrite, contained in coal mineral structure. A schematic diagram of the direct coal hydrogenation process is shown in Figure 10 and the coal conversion and product slate are given in Table 5 (CMI 1993). In 1991, a process design was prepared for a pilot plant with a capacity of 200 tonnes of coal per day. However, the installation was not undertaken, mainly for economic reasons.

In 2006, a flow diagram was developed for a modified Coal Liquefaction Plant with an annual production capacity of about 1 million tonnes of diesel oil and gasoline, Figure 11, for which the basic technological parameters are shown in Table 6 (CMI 2006). The hydrogenation of the coal-oil slurry takes place in a reactor at 20 MPa and about 450^0C. Liquid hydrogenation products undergo atmospheric distillation into light oil and medium oil, which are further processed into gasoline and diesel oil. Heavy residues are processed by vacuum distillation under supercritical conditions with an organic solvent (Kerr-McGee method). Liquid products of the vacuum distillation of the post reaction residue form the compounds of the pasting oil. The coal hydrogenation residue containing unprocessed coal and ash is gasified with an additional amount of coal in a steam-oxygen mixture. Gaseous products of the heavy residue and coal gasification, with process gases from the hydrogenation and product refining are used for hydrogen gas production. No decision has yet been taken to commercialise the process.

No	Specification	Mass fraction
1	Coal conversion	71.9%
2	Light oil (boiling distillate C5 - 200^0C)	14.5%
3	Medium oil (boiling distillate 200^0C - 320^0C)	39.4%
4	Gases	11.3%
5	Semi-coke (ash-free)	28.1%

Table 5 Coal conversion and product slate of CMI coal hydrogenation process.

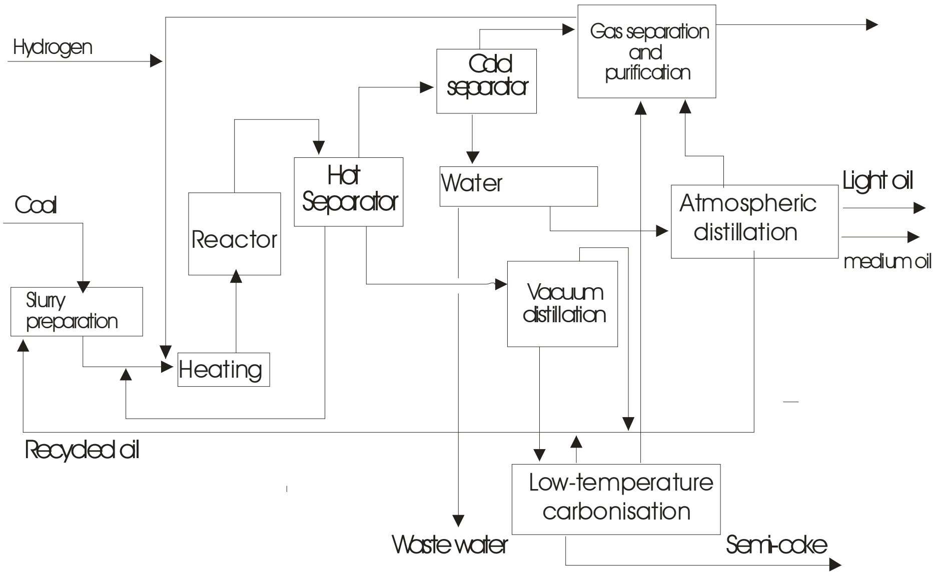

Figure 10 Central Mining Institute direct coal hydrogenation process

No	Specification	Production	Consumption
1	Products [t]		
1.2	Gasoline	0.27	
1.3	Diesel oil	0.05	
1.4	Sulphur	0.01	
1.5	Fuel gas	0.13	0.13
1.6	Liquefied gas	0.05	0.05
2	Raw materials [t]		
2.1	Coal, including:		1.23
2.1.1	Coal for hydrogenation		1.00
2.1.2	Coal for hydrogen production		0.23
2.2	Hydrogen (100%), including:	0.08	0.08
2.2.1	Hydrogen for hydrogenation	0.06	0.06
2.2.2	Hydrogen for liquid fuels production	0.02	0.02
2.3	Oxygen	0.39	0.39

Table 6 Basic technical parameters per tonne of coal for hydrogenation

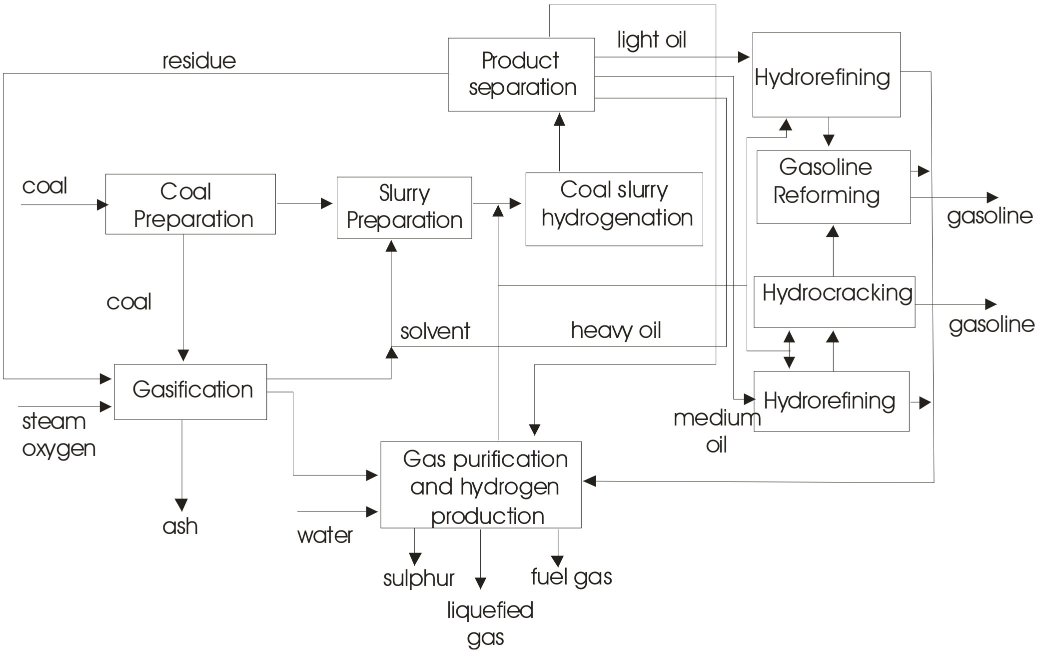

Figure 11 CTL process based on the Central Mining Institute concept (CMI 2006)

4.5 Estonia

While Estonia supports no R&D specifically in the coal-to-liquids area, the Government, as part of a strategic initiative, is supporting some projects relating to the development of oil shales via the Ministry of Education and Research. These are being undertaken by Tallinn University of Technology and run until end of 2014. They include:

- The development of new technologies for thermochemical processing of oil shale and blended fuels, which is examining the potential for liquefaction and upgrading of Estonian fossil and renewable fuels and fuel blends to achieve a more rational and appropriate utilization. The intention is to convert oil shale, peat, varieties of biomass and plastic wastes into non-conventional petroleum by using novel thermal dissolution, hydrogenation and co-processing methods.
- Environmentally friendly utilization strategy of oil shale processing solid wastes, which is designed to develop a comprehensive treatment approach for oil shale ash from various combustion and retorting facilities. The intention is to establish an overall strategy for recycling of different oil shale solid wastes, taking into account the composition and characteristics of initial material and marketing needs and value of product. There will be close international cooperation on the testing and industrial application activities.

5 Review of other international R, D&D initiatives

5.1 Australia

Australia is the world's largest coal exporter, but imports around 40% of its requirements for oil and oil products. It has huge coal reserves (over 79Gt out of the world current proven total of 1019Gt), including significant quantities of high quality hard coal in Queensland and New South Wales as well as brown coals in the Latrobe Valley in Victoria (IEA 2008). Several major proposals are currently being pursued although two are at a fairly early stage of development and no firm decisions have been made about plant construction.

5.1.1 Monash Energy Project The Monash Energy CTL project js supported by the Anglo Coal mining company and Shell. The concept is for an integrated CTL operation that includes a brown coal mine, a drying and gasification plant, carbon dioxide capture and storage and a FT plant for the production of transport fuels (IEA/CIAB, 2006).

The intention is that 1.2 tonnes of brown coal will produce 1bbl of high quality diesel, and, because the moisture in the coal will be recovered, overall water requirements will be much less than those for a comparable plant using other coals. Latrobe Valley brown coals are currently used for power generation, but because of their high moisture content (which is commonly around 60%), conventional power plants produce a disproportionate amount of CO_2. Converting the coal into liquid products could provide a more environmentally friendly usage route, particularly as the diesel produced would be considerably ‘cleaner’ than that produced from oil. The brown coal reserve in the Latrobe Valley is estimated to be 50Gt. Most of it is in relatively thick seams and is near the surface. It would therefore be capable of supporting several such plants over many years, and could provide the basis for moving into hydrogen production (Parker, 2007).

Anglo Coal has secured a site for the plant, and there are convenient offshore gas and oil fields less than 200 km away where the CO_2 can be used (possibly for enhanced oil recovery) and stored. The initial development would be for a plant producing 60,000 bbl/d of liquid products. Work is going on to assess the costs, and to refine the initial estimate of A$5 billion. Plant start-up is targeted for 2016, but further clarification is needed of the plant design details and the practicalities of CO_2 storage.

5.1.2 The Arckaringa Project Substantial deposits of sub-bituminous coal are located some 800 km northwest of Adelaide in South Australia. They were assessed in the 1980s and early 1990s for possible use for power generation; however, the cost/benefit calculations did not look sufficiently attractive. The total proven reserve is about 1.5Gt in three deposits with the main one being Wintinna where the coal has typically 38% moisture, 11% ash and 1% sulphur.

The opening of the Darwin to Adelaide railway (which passes through the deposits) has improved the logistics of development, and preliminary assessments are now being made of their possible use for a CTL plant. A pre-feasibility study has been completed, and the initial indications are encouraging. Altona Resources are in the process of raising the necessary funds to progress the project to the feasibility stage with costings that should be accurate to within ±10% based on an agreed plant flowsheet (Schrape, 2007). If the project proceeds, it would almost certainly be as a polygeneration plant with significant export of power in addition to the production of liquid fuels.

Current proposals are for a 10 Mt/y open cut mine to supply a CTL plant with two 15,000 bbl/d liquid product streams and 560 MWe of export power. In a second phase, a further 45,000 bbl/d capacity might be added, with an additional 840 MWe of power for export. In May 2008, Altona stated that it was "proceeding to the final stage of the Bankable Feasibility Study" for the project (Sourcewatch 2008).

5.1.3 Chinchilla In early 2000, Linc Energy carried out an underground coal gasification (UCG) trial in a block of coal 140 m deep. More than 35,000 tonnes of coal, in a seam 8m thick, were gasified producing some 80 million m3 of gas with a heat content varying from 4.5 to 5.7 MJ/m^3. The environmental footprint was encouraging as no groundwater contamination was discovered throughout the extended monitoring programme, and no subsidence was detected (Linc Energy, 2006).

The next stage in the project is to build a demonstration facility to produce a consistent UCG syngas, which will be used to produce liquid transport fuels via FT synthesis. This 5–10 bbl/d PDU is intended to prove the production of liquid fuels from a UCG operation. Unlike many other projects, the financing for the demonstration plant is in place, and construction is well advanced. It is reported that the underground gasification of a new block of coal has been started (Gasification News, 2007). Syngas production is being ramped up, and the PDU was scheduled to be commissioned during 2008. Linc Energy (Scandoil, 2008) will continue to operate and expand the Chinchilla demonstration facility for at least the next 3 to 4 years whilst commercial operations are developed.

The syngas-to-liquids demonstration plant has been designed in South Africa based on Linc Energy’s specifications after several months of R&D carried out at the University of Kentucky’s Centre of Applied Energy Research (CAER). At CAER a syngas with a similar composition to that produced from UCG at Chinchilla was used as the feedstock to determine the best catalyst to use (cobalt), as well as the operating temperatures and pressures applicable. Once the demonstration project is successfully completed, with an Environmental Impact Statement (EIS) in place, and the feasibility study finished, Linc Energy intends to raise the funds to build a 20,000 bbl/d commercial plant.

5.2 Canada

Canada, which contains significant coal, oil and natural gas reserves, also contains substantial bitumen deposits (known as tar or oil sands). The recoverable crude bitumen from Canada's tar sands is estimated to be 174 Gbbl, using current technology, making such reserves second only to the oil reserves of Saudi Arabia (Woynillowickz 2007). Other countries that have deposits include Venezuela, with similar quantities to Canada, the USA, Russia and several countries in the Middle East. However while it is possible to exploit these materials to produce oil products, at present it requires a greater amount of energy and in most instances it is more expensive than using conventional oil resources (Bentley, 2003).

Thus tar sands can be mined and the bitumen washed out of the mineral matter to be subsequently upgraded to a synthetic crude oil that can be refined. Alternatively, in appropriate locations, the injection of steam (or an alternative source of thermal energy) can be used to reduce the bitumen's viscosity to allow it to flow out of the reservoir. These processes can use more water and require larger amounts of energy than conventional oil extraction. That said, Canada does produce oil from a limited amount of its extensive deposits and the resultant production of oil is in excess of 1 Mbbl/d. Canada has also been active in developing co-processing techniques to process the bitumen.

Thus the Alberta Research Council for Co-processing**,** ARC, in collaboration with Canadian Energy Developments, originally developed the two-stage Counter-flow Reactor (CFR) process for upgrading tar-sand bitumen. Subsequently, the process was adapted to co-process sub-bituminous coals with bitumen. Incorporation of coal is said to increase distillable oil yields in comparison with those obtainable from bitumen alone. The process is unusual as it uses a CFR and, in place of H_2, uses CO and water in the first stage. The latter has been tested at a scale of 0.25 tons/day for co-processing and 5 tons/ day for bitumen alone. Coal is first cleaned by an oil agglomeration technique and then slurried with bitumen, water and a disposable alkali metal catalyst. The mixture is fed to the top of the counter-flow reactor, which operates at 380-400ºC and 87 bar. CO is fed to the base of this reactor and travels upwards, the shift reaction generating H_2. The high oxygen content of sub-bituminous coals is reduced by use of CO and steam and the process is claimed to be more effective and lower cost than the direct use of H_2. The second stage, in principle, consists of a second CFR reactor system operated at 420-480ºC/175bar. Either H_2 or CO/steam could be used in this stage. There is no recycle of product from the second stage. The conversion of the coal depends primarily on the coal characteristics, but conversions of up to 98% on dry, ash-free coal can be obtained in some cases. The overall product yield from the two stages is approximately 70% on the combined weight, dry ash-free coal and bitumen-fed.

In addition, CANMET developed a hydro-cracking process that was intended to break down heavy oils. This was established at a 5000 barrels (bbl)/day commercial scale at the Petro Canada Montreal refinery in 1985. A variation of the process was adapted for co-processing and was taken to 0.5 t/day pilot plant scale in a three-year R&D programme sponsored by Rheinbraun AG, Amoco Corporation and the Alberta Oil Sands Technology and Research Authority (AOSTRA). CANMET discontinued R&D in 1993. In the process, coal and a disposable coal-based catalyst are slurried with a petroleum vacuum residue or bitumen, mixed with H_2 and fed to a single-stage up-flow reactor. Typical operating conditions are reactor temperatures from 440-460ºC, pressures from 10-15MPa with feedstock coal concentrations of 30-40wt% (mineral matter-free basis). The reactor product is separated and fractionated to recover distillate products and an undistillable residue. The extent to which coal is converted is highly dependent on coal characteristics, but may be as high as 98% on a dry ash-free basis. The conversion of high-boiling material in the bitumen or vacuum residue may be up to 70%, depending on reaction severity. Overall net distillable oil yields of up to 80% on dry ash-free slurry feed are reported.

5.3 China

China has the world's third largest recoverable coal reserves, recently estimated at over 190 Gt (IEA 2008) but with rather limited oil and gas supplies. Oil consumption is outstripping domestic supplies and China is poised to overtake Japan as the world's second largest oil consuming economy after the USA (Skeer and Wang 2007). There is a clear strategic incentive for China to develop its own capacity for producing transport fuels and an obvious potential route is to use coal

China currently has the most active CTL programme in the world, with large scale ICL and DCL research and development programmes. The former includes both two-stage fixed bed FT synthesis and two-stage slurry/fixed bed FT synthesis processes. The Shanxi Coal Chemistry Institute has operated a 750 t/y pilot plant while the Yanzhou Mining Group Corporation in Shandong has operated a 5000 t/y pilot (Yu and others, 2007). Alongside this, the Beijing Research Institute of Coal Chemistry (BRICC) has undertaken some extensive work on coal characterisation for direct liquefaction. A 0.1 t/d (coal input) pilot unit has been used to test more than 100 Chinese coals, from which some 15 coals from ten mines have been identified as suitable for direct liquefaction. The most appropriate coals are sub-bituminous with low ash and high vitrinite contents. BRICC has also undertaken catalyst development (Xu, 2007).

These CTL developments are being undertaken in parallel with a number of coal to chemicals projects whose principal objective is the production of ammonia, polypropylene and polyethylene. In this context, China is acquiring considerable experience in the operation of gasifiers, using a variety of coals.

The leading industrial company that is taking forward the demonstration of CTL is the China Shenhua Energy Company Ltd, which is a very large enterprise with some 150,000 employees. The company has extensive coal production capacity (over 300 Mt/y by 2010) and significant coal-fired power generation capacity(30 GWe by 2010); it is one of four approved coal exporting companies, and is now the leading company for the production of chemicals and liquid fuels from coal. Shenhua is developing three process routes, DCL and ICL for transport fuels (and a range of other products), and methanol synthesis for olefins production. It has ambitious plans, with a target of 30 Mt/y output of liquid products by 2020 from eight projects (but see below).

5.3.1 DCL demonstration project Shenhua has a 6 t/d (coal input) direct liquefaction pilot plant in Shanghai, which has operated since 2004, and has provided the means for identifying and tackling potential scale-up problems. The experience has provided enough data to confirm the design basis for the first DCL demonstration plant, which uses a sub-bituminous coal (Xu 2007; Couch 2008). This has culminated in the recent construction of a DCL demonstration plant by the Shenhua Group, which will use 3.45 Mt of coal per year to make 1.08 Mt of liquid products including diesel oil, liquefied petroleum gas (LPG) and naphtha. The engineering work was completed on the first production line in Erdos of north China's Inner Mongolia Autonomous Region before the end of 2008 after which the Shenhua Group produced China's first barrel of liquid fuel from coal. This will be followed in 2009 by an extensive proving and demonstration programme.

The plant flowsheet is shown in Figure 12. The design has had to take into account the harsh local climatic conditions, including ambient temperatures ranging from –30°C to 40°C, with the likelihood of heavy sandstorms from time to time. Key design considerations included the environmental goals of zero wastewater discharge, minimal gaseous discharge, and the full use of residues.

The expected product slate includes:
- diesel, 715,000 t/y;
- naphtha, 250,000 t/y;
- LPG, 100,000 t/y;
- phenol, 3600 t/y.

In addition, there will be a slurry residue containing the mineral matter from the coal and high volumes of hydrocarbons. It is intended to use this as an alternative fuel to heavy heating oil. In order to make this transportable, it will be solidified on a steel belt which is cooled by underside water sprays. The belt will be sprayed with a release agent to prevent sticking, and the product will be discharged at approximately 90°C, well below its 150°C melting point. The solid flakes that are formed can be stored and transported for use in one of Shenhua’s power plants (Wu, 2007).

Shenhua has also publically declared that it will undertake a demonstration of CO_2 transport and storage for the CO_2 waste stream (Capture Ready 2009).

5.3.2 ICL demonstration plans Through its subsidiary, Shenhua Ningxia Coal Group, and together with Sasol, Shenhua is seeking to develop an 80,000 barrels per day CTL plant in the Ningxia Hui Autonomous Region (Greencar Congress 2008a). The partners have placed contracts with Foster Wheeler International Corporation and Wuhun Engineering Company to carry out an engineering feasibility study on the intended plant, to be located at Shenhua's Ningdong chemicals base (Greencar Congress 2008b).

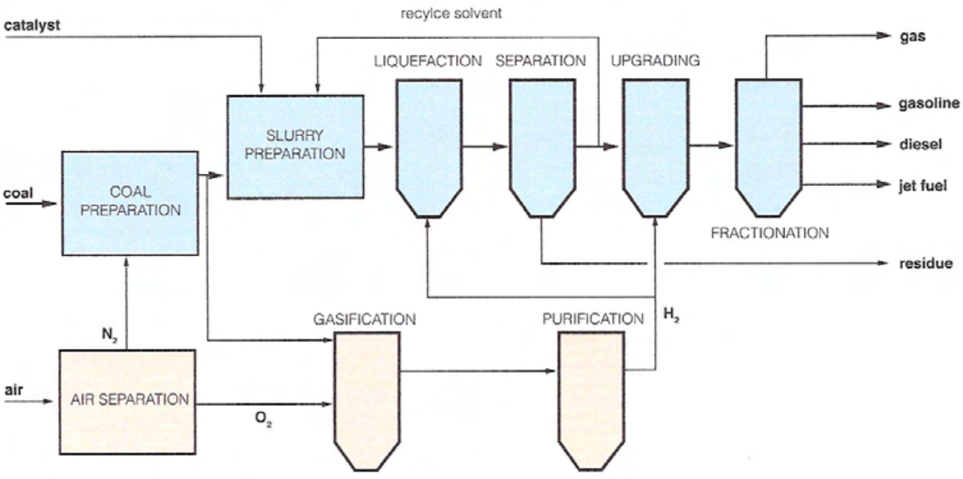

Figure 12 Shenhua DCL flowsheet for demonstration plant (Zhang 2007)

5.3.3 Government policy interventions It appeared that there might be a headlong rush to establish CTL projects in China once the DCL demonstration project was formally approved. However, the Government has taken several steps to prevent this from happening. First, in 2006, the State government raised the capital threshold for CTL projects to prevent small-scale projects from gaining financial support (People's Daily 2006). The government declared that it would not approve CTL projects with an annual production capacity below 3Mt, coal methanol and DME projects that are under 1Mt, and CTO projects under 600,000 tonnes.

As of 2007, five commercial-scale plants had been officially approved by the Chinese government for development and construction (Sun and Fletcher, 2007). These were:

- The DCL and ICL demonstrations of Shenhua noted above, together with a large-scale chemicals plant in Baotou, Inner Mongolia to produce olefins from coal, construction of which started in 2006. In addition, Shenhua has been pursuing indirect liquefaction in conjunction with Synfuels China, associated with the Shanxi Coal Chemistry Research Institute, Chinese Academy of Science. They are assessing the possibilities of building two 160,000 t/y ICL units at the Majiata site, one using low temperature FT synthesis for diesel, and the other using high temperature FT to produce gasoline, naphtha and chemicals. A further feasibility study had also been proceeding in conjunction with Sasol to determine the viability of an 80,000 bbl/d ICL plant at Yulin in Shaanxi Province. Each plant is expected to cost more than US$5 billion, and according to the Sasol news centre would be designed to be carbon capture ready (Sasol, 2006).
- The Yankuang Group is a major mining company, which intends to expand and diversify through the production of transport fuels and other chemicals on a substantial scale. It intends to build an ICL demonstration plant, in the Yulin area of Shaanxi Province, with the capacity to produce 1 Mt/y (of liquid products) using LTFT synthesis. Its cost is estimated at US$1.2 billion (Sun and Fletcher, 2007).
- The Lu'an Group intended to build a demonstration plant in Shanxi Province, which would produce 160,000 t/y of liquid products, based on ICL. The company had also entered into a strategic co-operation agreement with West Hawk Development of Canada for the further assessment of the possibilities for CTL (West Hawk, 2007). Some of the FT technology was developed by the Chinese Academy of Science (CAS). The cost was estimated at US$240 million (Sun and Fletcher, 2007).
- The Yitai Group intended to build a plant in Inner Mongolia of similar size to the Lu'an one, at an estimated cost of US$280 million (Sun and Fletcher, 2007). Its intended annual production was 110,000 tonnes of diesel, 38,000 tonnes of naphtha and 12,000 tonnes of LPG (Couch 2008).

However, in September 2008, the Government imposed further limitations when the NDRC ordered that all CTL projects, except the DCL and IDCL demonstrations involving the Shenhua Group in Inner Mongolia and the Ningxia Hui Autonomous Region, should be stopped (China Daily 2008). Additionally, the Ningxia plant was limited to 80,000 bbl/day rather than twice that capacity as intended originally. The rationale for this major cutback was that CTL is not yet a mature proven technology in China. Thus, it is still uncertain that the massive investment would be worthwhile in commercial terms as the capital intensive nature of CTL projects, coupled with the fact that many of the enterprises lack the management experience for establishing advanced technologies, means that there might be too great a risk to the overall wellbeing of the country, especially in times of a global financial crisis when oil prices have plunged from a peak of $147 per barrel in July to close to $55 per barrel in May 2009.

5.4 Japan

Japan, which has negligible indigenous fossil fuel energy resources, carried out an extensive CTL R&D programme during the 1980s and 1990s. The rationale for this was that the conversion of coal into liquid fuels would enhance stability for the supply of coal and coal based products from its Asian neighbours (NEDO, 2006). Both brown coals and bituminous coals were assessed.

5.4.1 The NEDOL process The R&D programme developed under the Sunshine Project, which continued until 2002, provided extensive experience on the operation of large pilot plants using a range of coals. Three routes were pursued for the liquefaction of bituminous coal:

- Solvolysis (where the solvent reacts with coal molecules to form new compounds, and there is bonding between,, or substitution of, certain radicals in the coal and solvent). This is particularly suited to the formation of light oils, and for thickening the circulating solvent;
- Solvent extraction, where some components of the coal selectively dissolve in a solvent,and hydrogen provides liquefaction under relatively mild conditions;
- Direct hydrogenation, where the liquid yield can be increased by the use of appropriate iron catalysts.

At the end of the 1970s, these three processes were incorporated into the NEDOL process by the New Energy and Industrial Technology Development Organisation (NEDO) (Figure 13). Subsequent development comprised nine coal characterization studies using a 1 t/d coal capacity PDU, which was operated for nearly 27,000 hours between 1989 and 1998 (NEDO, 2006). This was followed by operation of a 150 tonnes/day pilot plant at Kashima with continuous runs of up to 2000 hours. The applicability of the process was proven for a range of sub-bituminous and lower rank bituminous coals and it was possible to achieve 51% yield of light to medium oils, in a total yield of 58% on a dry ash free basis. The products are of relatively low quality, and require a substantial amount of upgrading to produce transport fuels or other high grade liquids.

In the NEDOL process, coal is ground with 2–4% by weight of a synthetic iron-based catalyst or with pyrite, and slurried with recycled solvent. The slurry is mixed with H_2, preheated and passed to the primary reactors, which are tubular up-flow vessels operating at 430–465°C and 15 - 20 MPa. The slurry residence time is about an hour, and the liquid phase residence time 1.5 - 2.5 hours. The products from this step are cooled, depressurised and distilled in an atmospheric column to yield a light distillate. The bottoms from the distillation column go to a vacuum column from which a middle and heavy distillate is produced, most of which is recycled to provide solvent, after passing through re-hydrogenation reactors (down-flow columns with packed beds of catalyst operating at 320–400°C and 10–15 MPa, with a residence time of about one hour). The products are depressurised at temperature and passed into a flash distillation vessel from which a hydrotreated naphtha product is taken off. The liquid product is recycled to the slurrying vessel to provide solvent. The bottoms from the vacuum column contain mineral matter, unreacted coal and catalyst, which in a commercial unit would be used as a gasifier feedstock for the production of H_2.

5.4.2 Brown coal liquefaction (BCL) Under intergovernmental co-operation between Australia and Japan during the 1980s, a 50 t/d pilot plant was built and operated, with continuous runs of more than 1000 hours. The feedstock was brown coal from the huge reserves in the Latrobe Valley in Victoria. These coals have low ash contents, but moisture contents are between 55 and 65%.

A yield of over 50% of oils was achieved (based on daf coal). Following extensive pilot plant operation between 1991 and 1997, the focus then shifted to R&D using a 0.1 t/day bench-scale continuous liquefaction test facility and related equipment to improve the reliability, economics and environmental compatibility of the coal liquefaction process. Based on the R&D results, it was concluded that it would be possible to increase the oil yield, improve the product oil quality and suppress scale formation in reactors with <1% catalyst addition (daf coal), compared to what had been achieved in the pilot plant.

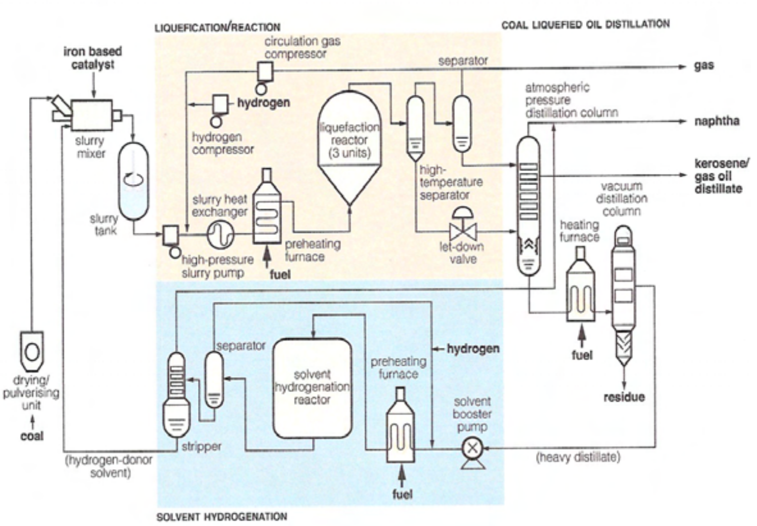

Figure 13 NEDOL process flowsheet for bituminous coal (NEDO, 2006)

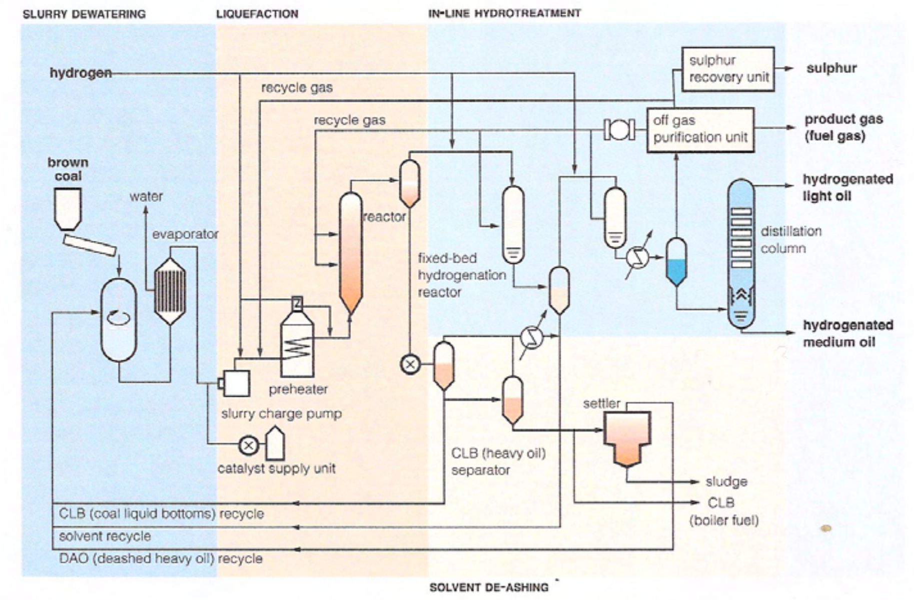

Figure 14 NEDO brown coal liquefaction process flowsheet (NEDO 2006)

The improved Brown Coal Liquefaction Process has four stages, as shown in Figure 14:

- Slurry dewatering;
- Liquefaction, using a highly active limonite catalyst to increase the yield of distillable oils. Limonite is a hydrous ferric oxide of variable composition, formed by the alteration of other iron minerals, such as the hydration of hematite or the oxidation and hydration of siderite or pyrite;
- An in-line hydrogenation process where the hetero-atoms (such as sulphur and nitrogen-containing compounds) are removed to obtain high quality distillable oils;
- Solvent de-ashing where the coal mineral matter and the heavy oils are separated, so that oils can be recycled and sludge removed for use as a low grade boiler fuel.

5.4.3 International cooperation In addition to working closely with Australia, NEDO has been able to advise both China and Indonesia about the appropriate conditions for DCL in their respective countries. NEDO has cooperated with CCRI in China, including a feasibility study for a 5000 t/d demonstration plant in China. Tests were carried out with a bituminous Yilan coal with predicted yields of 62%. The BRICC pilot unit in Beijing (see earlier section) for characterizing coals and process conditions was transferred from Japan. NEDO has also been prominent in sharing technology in support of the Chinese CTL programme.

5.5 South Africa

South Africa, with 49Gt of indigenous coal reserves but negligible oil and gas reserves, is the world leader in commercial scale CTL operations. South Africa has had a synthetic fuels industry since the 1950s, when Sasol Ltd (now a private company) was created by the South African government to reduce dependence on imported oil by making liquid fuels from coal (Steynberg 2006). Currently, Sasol can produce 150,000 bbl/d of liquid fuels and petrochemicals from coal via its indirect liquefaction process. The product slate is very diverse and includes more than 200 liquid fuels, pipeline gas, waxes, detergent range alcohols, solvents, petrochemicals, plastics, fertilizers and mining explosives, together with the marketing and mining of coal (Couch 2008).

Construction of Sasol's first synfuels plant at Sasolburg, then called SASOL One, started in 1951 and by 1955 this unit was producing petrol as well as its first range of chemicals. The OPEC oil-crisis of the early seventies together with the apartheid problems presented South Africa with the need to reduce dependence on expensive imported crude oil. This led to the construction between 1976 and 1980 of a second synfuels plant, SASOL Two, some ten times the size of SASOL One, at Secunda. The construction of SASOL Three, almost an exact replica of SASOL Two, commenced adjacent to the SASOL Two plant in 1979 and was fully operational in 1982. Subsequently the two plants were integrated (Steynberg 2006).

5.5.1 SASOL process technical details The Secunda process is shown in Figure 15, where it can be seen to be an extremely complex process to convert ~30Mt/y of low grade coal into syngas and then to various products via the indirect liquefaction route.

Synthesis gas is produced from coal using Sasol/Lurgi pressurised, oxygen-blown, fixed-bed dry bottom gasifiers. High ash content, high ash melting point coal is used to produce a high H_2/CO syngas to satisfy the demand for hydrogen in the FT synthesis. The volumetric demand for synthesis gas (consisting of some 58% H_2, 29% CO, 11% CH_4, 1% CO_2 and virtually no sulphur) has increased steadily over the years, resulting in continuous pressure to increase the production rates of individual units. During the late 1990s, the average gas production rates for these gasifiers were roughly 20% above the design capacity of 38,500 Nm^3/h.

After cooling, the gasification condensates yield co-products such as tars, oils and pitches. Other co-products, such as nitrogenous compounds, sulphur and phenolics are recovered as ammonia, sulphur, cresols and phenols respectively, with the pitch being converted into coke in the anode coke plant. The purified synthesis feed gas is then available for conversion through Sasol's various FT technologies, which at Secunda comprise the Synthol and Advanced Synthol (SAS) reactors.

After purification, the synthesis gas is sent to the reactors where the hydrogen and carbon monoxide react at moderate temperature under pressure in the presence of a fluidized, iron-based catalyst to yield a broad spectrum of hydrocarbons in the C_1-C_{20} range. This process is primarily used to produce liquid fuels. Hydrocarbons produced in the reactors are cooled in the plant, until most components become liquefied. Differences in boiling points are used to yield separate hydrocarbon-rich fractions and methane-rich gas. Some of the methane-rich gas (C_1) is sold as pipeline fuel gas, while the rest is sent to a gas reforming unit, where it is returned to synthesis feed gas by using pre-heated oxygen and superheated steam. Thereafter it is rerouted back to the reactors. The C_2-rich stream is split into ethylene and ethane. The ethane is cracked in a high-temperature furnace yielding ethylene, which is then purified. C_3H_6 or propylene from the light hydrocarbon gases is purified and is used in the production of polypropylene.

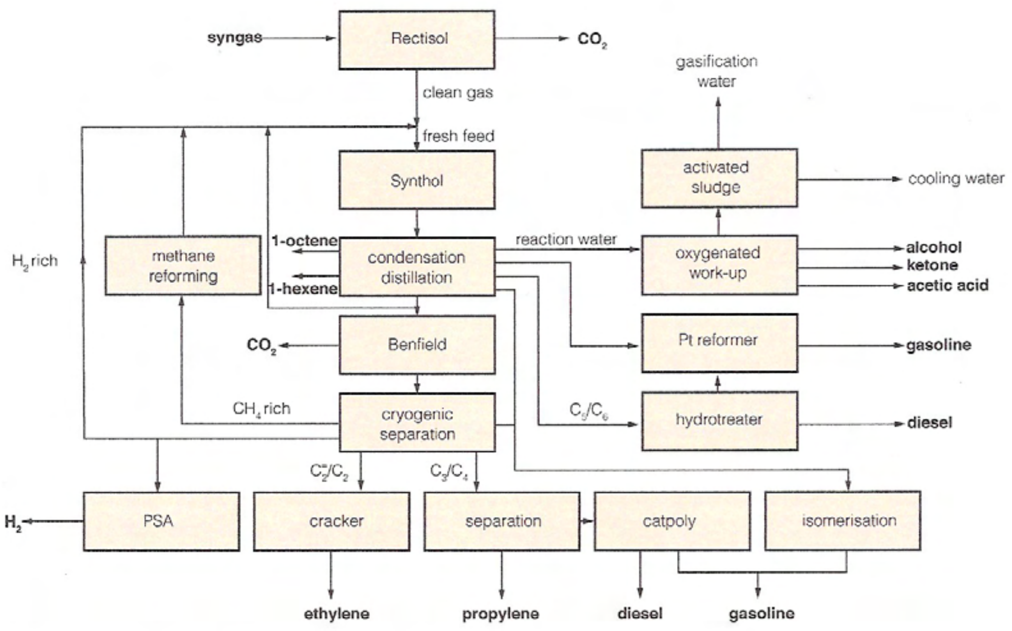

Figure 15 Process flowsheet for unit at Secunda (Steynberg 2005)

This stream also contains large quantities of olefins in the C_5 to C_{11} range. Alpha olefins pentene (C_5), hexene (C_6) and octene (C_8) are recovered, while the longer-chain olefins (C_7 - C_{11}) are sent to the fuel pool. The majority of this oil stream is routed to a refinery where, by using a range of standard refining techniques, liquefied petroleum gas, propane, butane, fuel oil, illuminating paraffin, petrol and diesel are produced.

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

The synfuels output from these HTFT plants is about 4.3 Mtonnes/year.

An alternative use for the synthesis gas from gasification is as in the SASOL 1 process. The synthesis feed gas is reacted at a lower temperature than in the SAS reactors, producing linear-chain hydrocarbon waxes and paraffins (Figure 16). Apart from hard wax, candle wax and specialty FT waxes, high-quality diesel can also be produced in this process. Residual gas is sold as pipeline gas, while lighter hydrocarbons are hydro-treated to produce pure kerosene or paraffin fractions. Ammonia is also produced and is sold as such or is used downstream to produce explosives and fertilizers. Sasol's strategy is to recover more and more of the higher-value chemical components in its product streams and to place them into lucrative chemical markets, thereby maximizing their value.

A new reactor, the Slurry Phase Distillate (SSPD) process, has also been established. In this process, preheated synthesis gas is fed to the bottom of the reactor where it is distributed into the slurry of liquid wax and catalyst particles. As the gas bubbles upward, it diffuses into the slurry and is converted into more wax by the Fischer-Tropsch reaction. The heat generated from this reaction is removed through cooling coils which generate steam. The wax product is separated from the slurry containing the catalyst particles. The lighter, more volatile fractions leave in a gas stream from the top of the reactor. The gas stream is cooled to recover the lighter cuts and water. The hydrocarbon streams are sent to the product-upgrading unit, while the water treated in the water recovery unit.

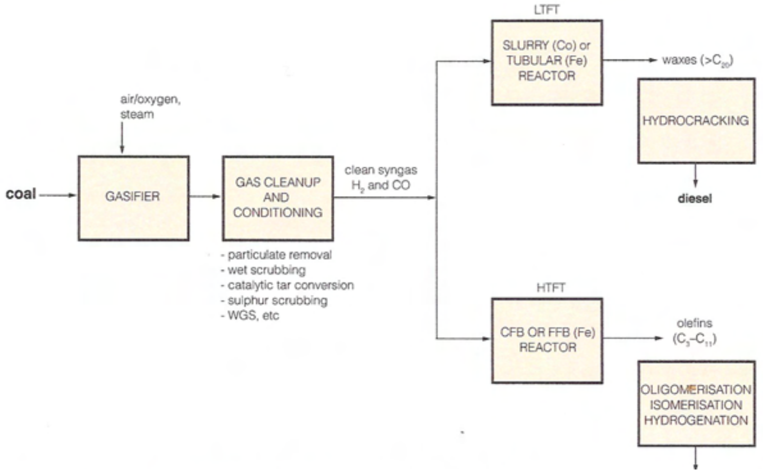

Figure 16 Process flow diagram for FT synthesis routes (Spath and Dayton 2003)

5.5.2 Overall commercial attractiveness The commercial success of Sasol as a private sector venture has been proven, albeit primarily within a domestic market context. This particular success in South Africa is due to a number of factors including the relatively cheap low grade coal, the provision of large capital investments while Government owned with (in retrospect) very fortunate timing, and the large capacity providing an adequate economy of scale to enable the recovery of significant quantities of co-products for high value chemicals.

Sasol is actively undertaking a pre-feasibility study for building another 80,000 bbl/d liquid fuels plant adjacent to the Secunda site. Provided there is enough coal nearby, the construction of such a plant would allow Sasol to benefit from the availability of experienced personnel on the adjacent site.

5.5.3 International cooperation and associated opportunities Preliminary studies have indicated that there are selected geographical regions throughout the world where the conversion of coal to liquid fuels and chemicals may be economically feasible. In such cases, Sasol is seeking to build on its experience and expertise by looking for opportunities where substantial deposits of low cost (possibly low grade) coal would support a CTL plant producing around 80,000 bbl/d, thus taking advantage of the potential economies of scale. This approach, however, means that any individual project size requires the investment of very large amounts of capital (of the order of US$5-6 billion) so that government guarantees relating to the value of production or other long-term support would be needed (IEA 2006).

The most promising options to date are in China, and Sasol is actively working with the Shenhua Group on several options at the 80,000 bbl/d plant scale. Sasol is also developing gas to liquids (GTL) technologies with a plant under construction in Qatar, with studies ongoing in Nigeria, Iran and Australia (Steynberg 2005), and with possible cooperation in India with the Tata Group (Couch 2008).

5.6 USA

Between 1976 and 2000, the US government supported a number of research and development projects for both direct and indirect coal liquefaction (Miller 2007). The first phase of this included the construction of relatively large-scale demonstration plants to assess the thermal/catalytic hydrogenation processes involved. This took place during the late 1970s and early 1980s, with a focus to develop and demonstrate the Exxon Donor Solvent (EDS), the HRI (H-Coal) and SRC-11 distillate fuels processes and the Solvent Refined Coal (SRC) process for boiler fuel. The H-Coal and EDS projects demonstrated the technical and engineering feasibility of DCL at the 200 t/d coal feed level, but many issues were not satisfactorily resolved. These included concerns over process yield, selectivity, product quality, and, ultimately economic potential.

During the 1980s and early 1990s, process improvements were demonstrated at bench and pilot plant scale. These Phase 2 processes used similar process equipment and unit operations so that there could be direct correlation for scale-up to the larger processes tested in Phase 1. Successes included the achievement of a substantial increase in distillable liquids yields for transport fuels, while the yields of the less valuable gaseous and non-distillable fuels were reduced. In addition, the liquid fuel quality was considerably improved, so that the primary product could be refined and distilled to meet the current specifications for gasoline, diesel and aviation fuel. Materials of construction and equipment designs were established to overcome the corrosion, erosion and fouling problems encountered previously (Burke and others, 2001).

Under Phase 3, broad based bench-scale and pilot plant process developments were included to overcome the technical and economic problems met in the earlier demonstration projects (Burke and others, 2001).

One important outcome of the US work was to demonstrate that DCL could be applied to a wide range of coals, and, in particular, to the large domestically available reserves of low rank indigenous coals.

5.6.1 The H-Coal® process This single-step process was developed by HRI (now Hydrocarbon Technologies Incorporated, HTI) from a commercial-scale route used to upgrade heavy oils. A 200 t/d pilot plant was built and operated at Catlettsburg , KY, USA in the early 1980s. This was adjacent to an oil refinery, and was able to take advantage of existing facilities for hydrogen production, sulphur recovery, wastewater treatment and laboratory and engineering facilities.

Coal is slurried with recycle solvent and accompanying solids which includes a mixture of hydrocracker products and various heavy distillates (Figure 17). Hydrogen is added and the mix is preheated and pressurised to 425–455°C and 20 MPa. It is passed through an ebullated bed hydrocracker where the catalyst is fluidised by the hydrogen gas and an internal recycle stream. The catalyst is either Ni-Mo or Co-Mo on an alumina base. The products pass to a flash separator from which the liquids in the overheads go to an atmospheric distillation column while the bottoms pass to a bank of hydrocyclones. From these, the bottoms stream goes to a vacuum distillation unit. Depending on the coal used, liquid yields up to 50% (dry basis) can be achieved (EBR 2007).

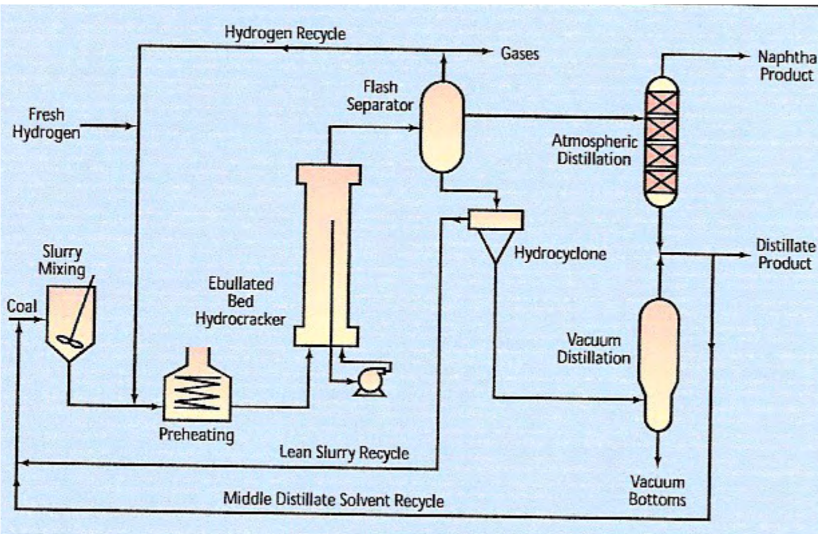

Figure 17 Schematic diagram of the H-Coal process (DTI 1999)

The pilot plant was designed for two modes of operation making either ‘syncrude’ or ‘fuel oil’. When producing fuel oil, it could handle up to 600 t/d of coal to produce heavy distillates and de-ashed residual products suitable for a boiler fuel. As with other processes, yields are dependent on the coal. Over 95% overall conversion can be obtained with suitable coals, with liquid yields up to 50% (dry basis).

Designs were subsequently prepared for a commercial-scale plant to be sited in the USA, but this was not taken forward. The design for the Shenhua direct CTL demonstration plant (see above) shows similarities to the H-Coal process although it uses an iron-based catalyst developed by CCRI and Shenhua.

5.6.2 The Exxon Donor Solvent Process (EDS) The Exxon Corporation started EDS process development in the 1970s and by 1980 had progressed to the construction of a 250 tonnes/day pilot plant in Texas, This unit was operated until 1982 and further supporting research continued until at least 1985, at which point development was discontinued. Typical liquid yields (including the liquids produced by Flexicoking) were ~36% for lignites, ~38% for sub-bituminous coals and ~39-46% for bituminous coals (all daf basis). These yields could be increased by recycling part of the vacuum bottoms stream to the slurrying step, although this was not tested on the 250 tonnes/day plant. Using this technique, yields of up to 47% for lignites, 50% for sub-bituminous coals and 60% for bituminous coals could be achieved. As a result the process showed relatively high specific capital costs and apparently uncompetitive economics.

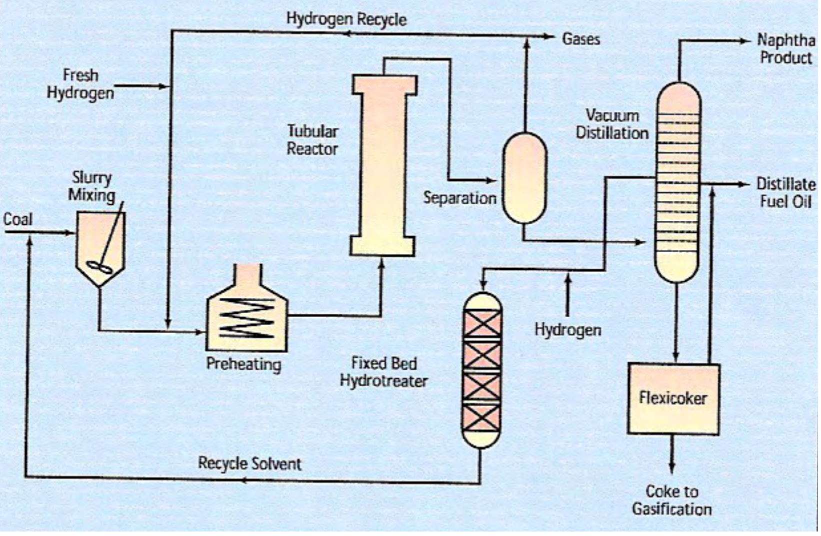

Figure 18 Schematic diagram of the EDS process (DTI 1999)

In the EDS process, coal is slurried with a distillable recycled solvent that has been rehydrogenated to restore its hydrogen donation capacity (Figure 18). This improves solvent effectiveness, and is the key distinguishing feature of the process. The slurry is mixed with H_2, preheated and fed to a simple up-flow tubular reactor that operates at 425-450ºC and 175bar. No catalyst is added. The reactor effluent passes to gas-liquid separators, from which the liquid product is fed to a vacuum distillation column. Naphtha and middle distillate products are recovered, although most of the middle distillate is recombined with the heavy distillate to form the basis for the recycle solvent. The vacuum column bottoms, containing the solid residues, are discharged and fed to a proprietary Exxon 'Flexicoker' unit. This combines pyrolysis and gasification steps to produce additional distillate product and a fuel gas, which would be used for H_2 production. Rehydrogenation of the recycle solvent is carried out in a fixed-bed catalytic reactor, using either nickel-molybdenum or cobalt-molybdenum on an alumina support. The reactor is operated at about 370ºC/110bar, although conditions are varied to control the degree of hydrogenation of the solvent and thus maintain its quality.

5.6.3 The Conoco Zinc Chloride Process In the late 1970s and early 1980s Conoco worked on the development of a process which uses molten zinc chloride to hydrocrack coal directly to give good yields of gasoline in a single step. This process is one of the very few direct liquefaction processes that is not a direct derivative of prewar technology. The process was taken to the 1 t/day pilot plant scale, although it operated for only a short period with limited success. Major metallurgical difficulties were experienced because of the highly corrosive nature of zinc chloride and other chloride salts that formed in the system. These difficulties remain, but if they could be resolved, this is one area in which further development might have the potential to make a significant improvement in liquefaction economics (DTI 1999).

5.6.4 The Catalytic Two-stage Liquefaction Process The Catalytic Two-stage Process (CTSL) was an extension of the H-Coal single stage process. It was developed at bench scale by HRI in the 1980s and scaled-up to 3 t/d PDU scale in the early 1990s. It was also demonstrated at the Wilsonville liquefaction test facility prior to its closure in 1992. The final operations at Wilsonville provided a well-defined base case for establishing process conditions, yields and product quality. The process subsequently evolved into a generic composite of much of the liquefaction development work funded by the USDOE in the 1980s and 1990s. It is shown in Figure 19.

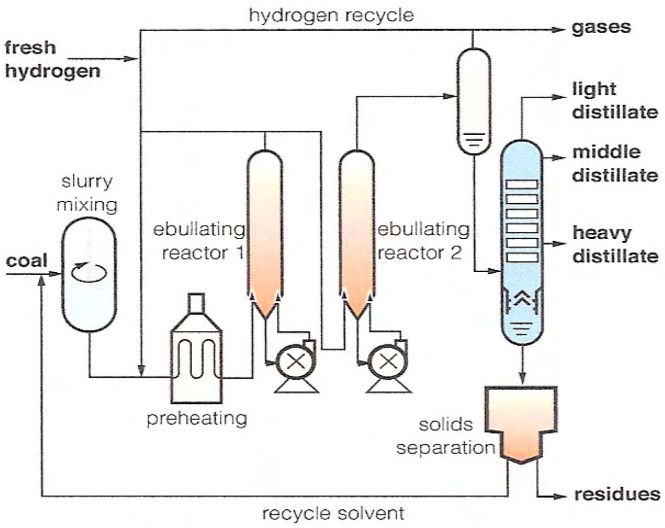

Figure 19 The CTSL two-stage process (DTI, 1999)

Coal is slurried with a process-derived recycle solvent, preheated, mixed with H_2 and fed to the bottom of the first of two fluid bed reactors where the catalyst particles are held in suspension by the upward movement of the liquid. The catalyst, Ni-Mo based and supported on alumina, is fluidised by an internal recycle in the reactor. The solvent acts as a hydrogen donor and makes the coal soluble by substantially breaking down its structure in the first reactor. This reactor also substantially rehydrogenates the solvent.

Typically, operating conditions of 400–410°C and 17 MPa are used when processing bituminous coals. With sub-bituminous coals, higher temperatures may be required to ensure this structural breakdown and the hydrogen donor effect becomes less important. In one process variant, a dispersed molybdenum or iron catalyst may be used in the first stage and the reactor products pass directly into the base of a second, fluid bed reactor, operating at the same pressure, but at a higher temperature (430–440°C). This reactor contains a supported catalyst, usually, but not necessarily, the same as in the first reactor.

After separation and depressurisation steps, the products from the second reactor enter an atmospheric distillation column, where distillates boiling up to 400°C are removed. The bottom stream from this column contains solvent, unreacted coal and mineral matter. The solids are removed by one of several possible techniques and the solvent is recycled to the slurrying step. In some process variants, only part of the bottom stream is routed to the solids removal step, resulting in the recycle solvent containing mineral matter and any dispersed catalyst that may have been used. The process is designed to operate without the need to remove a separate pitch stream as a product.

In addition, from 1985, HTI carried out test work on co-processing, treating it as a simplified version of the mainstream two-stage direct CTSL coal liquefaction process. It differs only in that there is no recycle solvent loop. Most work was carried out with lignites and other low-rank coals. Recent work includes the use of HTIs GelCat™ iron-based dispersed catalyst. Coal conversions of up to 91% (dry ash-free basis) have been reported. The conversion of heavy material in the petroleum residue varied from 80% to 90%, with overall distillable product yields in the range 77-86% by weight on the total feed.

The H-Coal, CTSL process and the associated coal/oil co-processing system that also uses the ebullated-bed reactor system are all now offered on a commercial basis by Axens.

5.6.5 Lummus Crest Co-processing This system was developed to a 0.25 tons/day PDU in the early and mid-1980s. It is a derivative of the Lummus ITSL process. A key feature of the process is that the petroleum heavy oil is hydrogenated prior to its use as slurrying solvent for the coal. This generates some hydrogen donor capability, increasing the extent to which the coal is dissolved and reducing repolymerisation and coking reactions.

Coal is slurried with the hydrogenated petroleum residue and reacted in an uncatalysed, short contact time reactor at a temperature of 430-450ºC and a hydrogen pressure of 140bar. The reactor products pass directly to the second stage LC-Finer ebullated-bed reactor, which operates at the same pressure and a temperature of 400-435°C, with a supported hydrotreating catalyst. As with many other co-processing options, the intention appears to be to integrate the process within an existing oil refinery. About 90% of the coal is dissolved in the first stage on a dry ash-free basis, with overall conversions approaching 95%. The overall conversion of heavy material in the petroleum residue is 70-80%. The total net yield of distillable products is in the range 50-55% on fresh feed.

5.6.6 More recent developments In the USA, there is again an upsurge of interest in CTL applications. Although there are currently no CTL production units in operation, there are a significant number of prospects being considered, as listed in Table 7.

Lead group	Partners	Location	Technology	Capacity (bbl/d)	Status
DKRW	Rentech GE, Exxon	Wyoming	ICL	18800	Design complete Construction, 2009
Rentech	KEC Parsons	Illinois	ICL	1800	Feasibility
WMPI	Shell, Sasol USDOE	Pennsylvania	ICL	5000	Design
ACCF		Illinois	ICL	30000	Feasibility
Alaska IDEA	CPC	Arkansas	ICL	80000	Feasibility
Peabody/Rentech		Massachusetts	ICL	10000-30000	Feasibility
Peabody/Rentech		Illinois Indiana Kentucky	ICL	10000-30000	Feasibility
Rentech	Adams County	Missouri	ICL	10000	Feasibility
Baard Energy	CEC	Ohio	ICL	35000-50000	Feasibility
Mingo County	Rentech	West Virginia	ICL	20000	Feasibility
Synfuels Inc	GE Halder Topsoe NACC, Exxon		ICL		Feasibility
Headwaters	Hopi Tribe	Arizona		10000-50000	Feasibility
Headwaters	NACC, GRE Falkirk Mining			40000	Feasibility

Table 7 CTL plants under consideration in the USA (Miller 2007)

It is stressed that despite the previous very extensive USDOE supported R&D for various DCL processes, all of the new prospects being considered are for ICL processes. This may be due to the greater flexibility in terms of product slate output, which would provide the plant owner with a more financially robust approach in times when oil prices might fall. At the same time, the USA now has considerable experience in the construction and operation of coal gasification units, which is the first step in the indirect CTL process. That said, the planned sizes of almost all the plants are far below the 80,000bbl/d scale that Sasol would recommend to ensure full economies of scale. The reasons for this are not clear.

These project proposals were listed in 2007 and so it remains to be seen how many will find finance and be taken forward in the difficult times of 2009 and beyond. Of very great significance in this context, are the US Government policy initiatives to support CTL deployment. Thus a number of investment initiatives and tax breaks have either been put in place or are under discussion in Congress. These include regulations governing a petrol excise tax credit, which would provide a much needed incentive to encourage the construction of CTL plants. In 2007, two senators introduced the Coal-to-Liquid Fuel Promotion Act, which would set the stage for large-scale production of transport fuels from coal through the provision of loan guarantees and tax credits for new CTL plants (Coal Age, 2007).

6 Environmental considerations

Should significant CTL operations be established, a number of environmental issues need to be considered (Irwin and others, 2007).

6.1 Indirect impacts

The first impact of using CTL technologies on a significant scale would be an increase in the amount of coal needed on a global basis. This would entail either

- an increase in coal mining, for which environmental standards are established including remediation requirements, or
- the introduction of underground coal gasification, for which environmental standards are not yet established since the technique is still at the development stage.

As the liquid products from CTL plants will generally have a higher energy density than the coal from which they are produced, it is probable that the CTL plant would be built at or near the mine, with the liquid products being transported either to a refinery or to the end users. Thus, pipeline or rail tanker transport over long distances would replace the transport of coal or the construction of power lines to take the power produced at a minemouth power plant. This can provide some environmental advantages.

6.2 Direct impacts - local emissions, effluents and residues from a CTL plant

For DCL plants, the exact nature of the by-products, and effective methods for their upgrading, treatment and safe disposal will depend both on the coal used, and the exact processing conditions. The practical considerations of effluent treatment have yet to be fully proven due to the absence of commercial plants. Encouraging indications appeared during the operation of the Kohleoel-Anlage Bottrop (KAB) which included the integration of product handling in the refinery and gasification plant. The results demonstrated the advantages of the IGOR concept. However, in the current climate, the performance of the large scale demonstration unit in China will be of critical importance in the near future.

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

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

In each case, Sasol has established rigorous procedures for meeting the appropriate environmental regulations. If ICL plants are established in other countries, there will be a need to ascertain that these procedures are adequate to meet local regulations.

6.3 CO_2 capture and storage issues

DCL plants will produce a concentrated stream of CO_2 from the hydrogen production unit while ICL plants will produce a similar stream from the processing of the syngas prior to FT synthesis. Also, as DCL operates with a significantly higher energy efficiency than ICL, it will have a lower specific CO_2 output.

Producing transport fuels from coal will involve a substantial increase in greenhouse gas emissions compared with possible oil based alternatives. However, as the CO_2 will be provided as a concentrated byproduct from both CTL processes, it will be highly suitable for direct transfer to CO_2 storage in geological formations or other mitigation processes. Where there is the opportunity for enhanced oil recovery (EOR) through CO_2 injection, then the sale of the CO_2 may provide a significant income stream that can more than compensate for the compression and storage of the CO_2. Where that option is not available, CO_2 storage will need to be in a saline aquifer, the additional costs of which will affect the economics of the operation.

For DCL processes, the exact form that the intended Shenhua CCS demonstration takes will be of considerable importance. For ICL processes, Sasol's corporate strategic policy is to ensure that any new CTL plants with which it is associated should at the very least be CCS ready. It is also likely, at least in Europe and Australia, that any application to establish a CTL plant would require the inclusion of some form of CO_2 mitigation. This might be either for immediate use or through the inclusion of capture ready measures within the process design.

6.4 Water usage

There are several major requirements for water in a liquefaction plant. Thus:

- process water is needed for
    - the steam feed to gasifiers to make up the hydrogen requirements,
    - water for use in the liquefaction processes,
    - wash water for syngas cleaning.
- steam may be required for the water-gas shift reaction;
- boiler feed water is needed to produce steam, and in many cases for on-site power generation;
- cooling water to remove heat at different stages, and in particular from the FT reactors where the highly exothermic reactions need careful temperature control.

In overall terms, CTL plants require substantial amounts of water, probably in the range of 5 to 10 bbl for each barrel of liquid products. Where lignites are the feedstock, these typically contain a large proportion of water, and if this is recovered, it can provide a significant proportion of the water that is needed. The Shenhua DCL demonstration plant is sited in an arid region of China, so the plant design includes a scheme to reuse water after suitable purification, to minimize the overall requirements.

6.5 The impact of coal-derived products

The transport fuels produced by CTL are generally environmentally superior to their petroleum-derived counterparts and should be capable of meeting all the requirements of clean air standards and regulations in most countries (Kaneko and others, 2001).

The synthetic transport fuels derived from ICL can bring significant benefits in terms of reduced vehicle exhaust emissions. With vehicle engines optimised to run on the CTL liquid fuels, emissions reductions, particularly of NOx and CO, are possible when compared with those from conventional fuels. This should result in improvements in local air quality, particularly in urban areas. FT diesel and jet fuel are pure paraffinic hydrocarbons and so avoid any environmental restrictions on use due to the presence of inherent aromatics and sulphur. There is also a substantial reduction of nearly 80% in particulate emissions (US GAO, 2007). There is also a reduction in CO_2 emissions since aircraft will have to carry less weight for the same amount of energy (de Kort, 2008).

These points have also been made by the Alliance for Synthetic Fuels in Europe (ASFE 2008), who have further pointed out that ICL fuels:

- can use the existing diesel and gasoline fuel distribution networks and be used in current engines;
- and could facilitate the development of a new generation of more efficient internal combustion engines, and further reduce vehicle pollutant emissions.

The benefits arising from the deployment of DCL products have yet to be quantified and much will depend on the experience gained from the operation of the Shenhua demonstration plant. Once again, work in this area was carried out in Europe during the 1980s based on plant operated by Saarbergwerke/ BASF and Ruhrkohle/Veba. This included the use of upgraded coal oil in a standard Mercedes car. The upgrading work at Veba was based on the syncrude from the KAB and demonstrated the feasibility of integrating DCL in a refinery using existing upgrading schemes to meet all requirements of German standards and regulations of the period.

7 Economic overview

In absolute terms, CTL will be expensive to build and expensive to run. Therefore, it will only be deemed worthwhile proceeding if concerns about the security of oil and gas supplies are such that substitute oil products via CTL can provide a level of reassurance at a price that is deemed worth paying. As with all 'insurance policies' this will always seem unnecessary until it is actually needed. Also, as with all insurance policies, under-investment or failure to pay the premiums will mean that benefits will not be paid out when they are needed.

CTL, by whichever route, is capital-intensive and therefore benefits substantially from economies of scale. Most studies on process economics have assumed that a full-scale commercial plant would produce 50,000-100,000bbl/day of liquid products (DTI 1999). Such a plant would process 15,000-35,000 tonnes/day of bituminous coal or up to double that amount of sub-bituminous coal or lignite.

Sasol have stated that their prerequisites for contracting with an organisation to proceed with a CTL FT plant would be assume a minimum plant size of 80,000 bbl/day, to take advantages of the economies of scale. At the same time, access would be needed for to up to 400 million tonnes of coal over the project lifetime. This would most likely be 'stranded coal' due to its low-quality or location, making it unsuitable for alternative applications, such as electricity generation.

Of equal importance would be the need for government support for the very large capital investments, on the grounds of improved energy security through decreased dependence on imported energy, and to shield developers from oil price volatility. In late 2006, the likely cost of such a plant was given as US$ 5-6 billion (Kelly 2006) with annual operating costs of some US$ 250 million.

In 2006, the IEA noted that for CTL to be competitive, a plant would need to have access to coal at less than 20 US$/t (IEA 2006). Although this is less than half of the current international price, over 80% of the world's coal is not internationally traded, and at least 30–40% of the world's coal is mined for less than 20 $/t - including most low rank coals. On that basis, at a steam coal price of 20 US$/t, CTL can be competitive with a crude oil price of under 40 US$/bbl, and the average production cost of synfuels would be about 50 $/bbl. There will be economies and cost reductions associated with the building of a series of CTL plants as operational experience is gained and the initial designs are copied and refined.

MIT examined the possible impact of including CCS on a CTL unit (MIT 2007). In broad terms, the capital cost of a synthetic fuels production facility would be around $53,000 per bbl/d of liquids output with no CO_2 capture. This would increase to $56,000 per bbl/d with CO_2 capture. This assumes a 20-year plant life, a three-year construction period, and a 15.1% capital carrying charge factor on the total plant cost, a 50% overall thermal efficiency for the FT plant, and a 95% plant capacity factor. Using these factors, the production cost of FT fuels is estimated to be 50 $/bbl without CO_2 capture (similar to the IEA estimate) and 55 $/bbl with CO_2 capture.

Coal Hydrogenation Plant units	**Investment costs**	
	M US$	**%**
General buildings	766	33.3
Hydrogen production unit	1071	46.6
Coal hydrogenation unit	255	11.1
Fuel production unit	208	9.0
Total investment costs	2300	100.0

Table 8 Modified investment costs structure for 1 Mt fuels per year plant.

In Poland, the investment costs for industrial coal hydrogenation plant were estimated in the 1970s and 1980s by GBSiPPW SEPARATOR (GBSiPPW SEPARATOR, 1981, 1987). In 2006, these estimates were updated at the Central Mining Institute, based on the indices of the cost of apparatus and equipment, and on indices of investment cost increases in the chemical industry (Chemical Engineering Archive 1979 – 2005). The investment cost for a plant of 1 Mt per year of coal-based liquid fuels, recalculated for 2006 is 2.8 billion US$ (± 30%).

Analysis of the investment costs structure showed that the cost of the hydrogen production unit is much higher than those of the coal hydrogenation and fuel production units. This is due to the assumed post-reaction residue separation by low temperature carbonization and hydrogen production in the Winkler reactor. An application of new technologies, industrially proven over the last twenty years, such as supercritical post-reaction residue separation and advanced gasification processes for coal and residue – based hydrogen production, should decrease the investment costs for hydrogen production.

Based on the literature (DTI, 1999) and material balance data, economic estimates for a modified concept of the Coal Liquefaction Plant CMI 2006 (CMI 2006) producing 1 and 3 million tonne of liquid fuels (gasoline and diesel oil) were prepared. The calculations were carried out for two coal price levels of 54 US$/t (Poland) and 20.5 US$/t (China). The modified investment cost structure for the 1 Mt per year plant is given in Table 8.

This analysis allows an evaluation of the impact of coal price and plant production capacity on the basic economic indicators of the plant (required product market price and required crude oil market price) to ensure that the required product price selling price can be met. The calculations were carried out for 2006 prices using simplified economic models based on indices given in DTI, 1999 (Table 9).

Installation capacity (Mt of liquid fuels per yr)	**1**		**3**	
Investment costs (M USD)]	2,300		4,515	
Coal consumption (Mt per year)	2.8		8.0	
Coal price (USD per tonne)	54	20.5	54	20.5
Required selling price (USD per bbl)	75.12	62.43	53.11	41.30
Required crude oil price (USD per bbl)	62.60	52.03	44.25	34.42

Table 9 Estimated economic indicators of coal-based liquid fuels production

As can be seen, the production capacity and coal price are key to the economics of a coal liquefaction plant. For a plant producing 3 Mt of liquid fuels per year, assuming a coal price below 54 US$/t, the required selling price for liquid fuels produced is within the range of prices met by refineries processing crude oil of the price level of 44 US$/bbl, while for a plant of capacity of 1 Mt of liquid fuels per year, the limiting crude oil price is 63 US$/bbl.

Production of 3 Mt of fuels per year would increase the share of coal – based fuels in the total fuel consumption in the transport sector in Poland. For example, the production of coal hydrogenation plant would cover 34% of the amount of engine fuels used by the transport sector in 2005. Assuming an annual increase in fuel consumption of 1%, the production level would satisfy 27% of the transport sector demand in 2030. This suggests that the development of such plant would strengthen the national energy independence in terms of engine fuels in a longer time perspective.

The key point is that the results of these various studies are consistent with each other and show that the production of liquid fuels from coal is broadly economic, given the range of oil prices to be expected over the coming decades. When the security of energy supplies is also taken into consideration, CTL to provide transport fuels becomes an attractive proposition providing that there is enough coal available to make sufficient quantities of the required fuels.

8 Possible future EU CTL needs.

This section examines the case for CTL application within Europe, whether R, D&D is necessary and, if so, how Europe might establish the expertise and experience to implement the appropriate programmes of work.

8.1 Geographical considerations

The international drivers for CTL are seen as (Kelly 2006):

- *Economics*: strong oil demand and rising real prices, versus (relatively) stable coal prices, mean the price gap in favour of coal will widen. To keep oil supply and demand in balance, significant growth will be required in unconventional oil production, which will include CTL
- *Energy security*: large coal reserves exist in Europe and in key industrial nations such as the USA, China and India, which will all be significant oil importers over the next 20 years.
- *Environment*: CTL produces low sulphur, high cetane FT fuels and CO_2 that can readily be stored, thereby responding to environmental regulations.

Most EU countries are showing an increasing dependence on oil and gas, and in many cases an increasing dependence on supplies from less than reliable sources such as Russia. To counter this situation, EU countries that might implement coal liquefaction must have ready access to large quantities of low cost coal, located close to the CTL plant, that are sufficient to last for a project lifetime of ~25-30 years.

Within Europe (Figure 20), many of the central and eastern countries have large, commercially proven lignite reserves but very limited oil and gas reserves. As such, all are possible candidates to establish coal liquefaction given the expectation of an economically-favourable crude oil price.

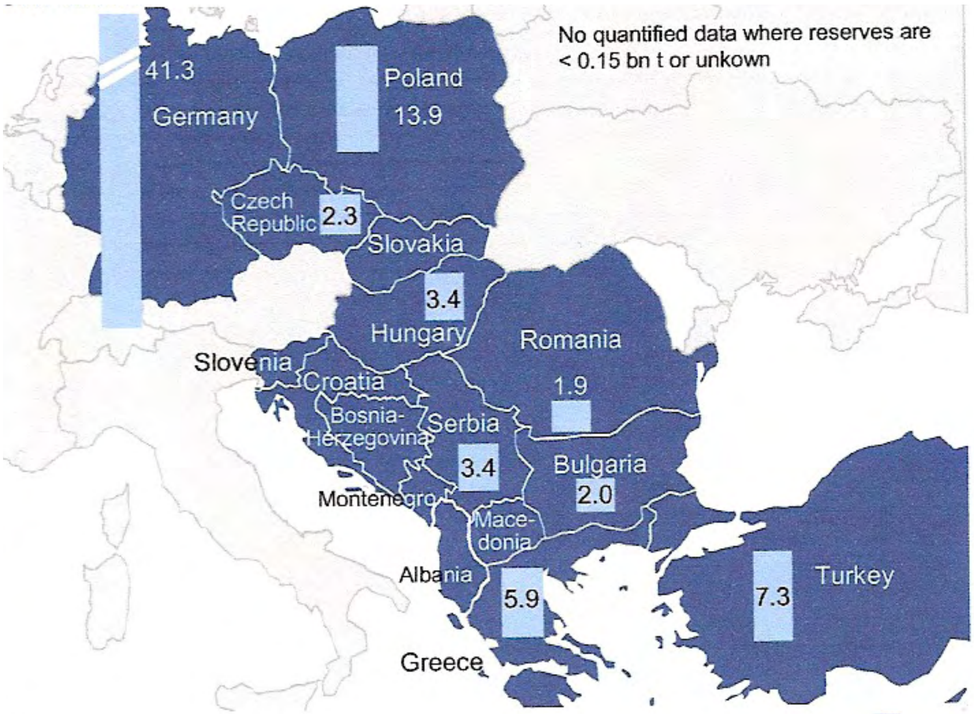

Figure 20 Indication of lignite reserves available in Central and Eastern Europe (Hartung 2006)
[Reserves given in billion tonnes on a 2005 basis]

It is stressed that the indicative reserves and resources comprise far greater quantities than the proven reserves and so it is likely that the quantities ultimately available for possible CTL use may be much higher. As discussed in Section 2, should techniques such as UCG be proved on a commercially viable basis then this will provide a major driver for uprating the proven reserves.

It is stressed that the geographical criteria for establishing UCG will be very similar to those for CTL. Thus UCG will need to be located near to large reserves of (in this case otherwise unmineable) coal in reasonably thick seams where the geology is environmentally friendly and the risks low. This suggests the lignite deposits of central and Eastern Europe as promising sites for combining CTL and UCG technologies.

When hard coals are considered, the picture is very different. With current mining technology, there are no viable sources of coal that could meet the CTL criteria set out above. However, if it assumed that UCG can be established on a commercially viable basis, then it might be possible to also set up CTL projects in

Germany and the UK. It should be noted that the Coal Authority recently awarded the UK's first UCG licence to Thornton New Energy Ltd, a subsidiary of BCG Energy Ltd. The company intends to combine the latest directional drilling techniques to allow it to create gas for electricity production from the vast deep hard coal reserves which still lie under Fife and the Firth of Forth (BCG Energy 2009).

8.2 Technical and economic considerations

The two CTL technology variants, DCL and ICL, each have certain potential advantages, as illustrated in Table 10. In both cases, various economic studies suggest that their outputs could be competitive with oil based products, although in the case of DCL processes there must be a significant element of uncertainty due to the immaturity of the technologies.

Indirect coal liquefaction is now a largely proven technology for the manufacture of useful liquid products for which the expertise and experience predominantly rests with Sasol. That company has declared a wish to establish the ICL technology outside South Africa and it must be presumed that any potential end-user would establish an associated training programme from Sasol alongside any purchase of the CTL process. As such, ICL deployment in Europe would be a purely commercial arrangement except where it could link conveniently to the development of underground coal gasification as the means to provide the synthesis gas for subsequent processing, which would require key developments to harmonise underground gas production to ensure a consistent syngas supply to the ICL process.

	Indirect Coal Liquefaction	**Direct Coal Liquefaction**
Advantages	• Ultra-clean products • Well suited for CO2 capture • Well suited for electric power co-production • May have lower operating expenses than direct conversion	• A conceptually simple process • Produces high-octane gasoline • Is more energy efficient than indirect conversion • Products have a higher energy density than those from indirect conversion
Disadvantages	• Conceptually more complex than direct conversion • Less efficient fuel production than direct conversion • Produces low-octane gasoline • Petrol products have lower energy density than those from direct conversion	• The products can have a high aromatic content • The diesel produced has a low-cetane number • The process may have higher operating costs than indirect conversion

Table 10 Advantages and disadvantages of direct and indirect coal liquefaction routes

For direct coal liquefaction, there are several promising processes and there could be merit in resuming their development to diminish the disadvantages while improving the overall process scheme and performance. Areas of interest, where Europe should have active expertise, might include:

- Better catalysts (conversion efficiency and lifetime)
- Improved process design via techno-economic modelling studies
- Improving understanding of the underlying science and engineering
- Investigating potential new process concepts, including part utilization of biomass and organic wastes with coal

The key additional factor, in the European context, is the possibility that underground coal gasification might provide a route to making currently unmineable coal supplies available as either producer gas (largely CO and H_2) or as H_2, while leaving the undesirable impurities and mineral matter underground, and allowing CO_2 to be captured efficiently for subsequent storage. In this event, liquid fuels could be produced directly by FT conversion without the need for the initial coal gasification stage, so reducing the add-on price penalty.

It is not appropriate to review UCG development in detail within this report, though UCG has the potential to unlock vast amounts of previously inaccessible energy in unmineable coal resources. However there are significant obstacles to be overcome before this is possible, many of which are associated with the fact that the process takes place deep underground in a context where it is difficult to monitor and control the conditions. Consequently, UCG requires a multi-disciplinary integration of knowledge from exploration, geology, hydrogeology, drilling, and of the chemistry and thermodynamics of gasification reactions in a cavity in a coal seam (Couch 2009).

UCG has reached the stage of "proof of concept", but different parts of the technology have been demonstrated/proved separately and each in unique circumstances (as is commonly the case with emerging coal technologies). That said, the single most important decision that will determine the technical and economic performance of UCG is site selection. The field trials undertaken so far are grouped into two main categories, namely those conducted at shallow depths, some in thicker seams, and those at greater depth in thin seams. To date, all that has been established is that given the right conditions, coals of different rank can be gasified underground. Ultimately, it will require a series of successful demonstrations, building on what has already been established, in different geological settings to establish where UCG can be safely carried out cost effectively at a commercial scale and without environmental damage.

Only now are the various steps being put together to establish UCG on a consistent and potentially commercial basis. There are large scale trials underway in China, Australia (Bloodwood Creek, Chinchilla) and South Africa (Majuba), with further pilot scale projects due to commence in the latter two countries later in 2009. The three operational projects in Australia and South Africa have reported successful firings and start- ups, and the results arising will be used to determine likely costs for scale-up activities. This should result in commercial-scale plants within four or five years, thereby providing greatly increased confidence in the technology (Couch 2009).

At the same time, the economics of both CTL and UCG operations will be strongly influenced by future requirements for CO_2 capture and storage. As with CCS, there is a need for regulatory harmonization and the need to ensure a positive public perception for these two potential technology introductions.

8.3 Technology demonstration issues

Ultimately, if the DCL route is pursued, there will be a need to demonstrate the technology in Europe, unless potential EU end-users decide to purchase a technology variant from China. For ICL, the possible link with UCG would also require some form of demonstration.

8.4 Capabilities and expertise at EU research institutes, universities and industry

In the 1970s and 1980s, many EU universities maintained CTL research equipment and undertook high quality research in support of the German and UK development programmes. With the demise of these developments, this skill base in universities has almost disappeared. The research teams have largely disbanded or have transferred to other fields; some have moved into related areas such as biomass conversion. Individual researchers with skills and experience in CTL can still be identified, mostly among senior staff with long memories, but they would need to be incentivised to re-launch CTL activities. A possible exception might be in ongoing work for catalyst development, which has been continued to support various gasification based projects.

Given the importance of the German and UK programmes in the European context, another telling blow has been the demise of both Deutsche Montan Technology and the British Coal, Coal Research Establishment. DMT now consults only on coal mining activities including health and safety, while CRE has been closed. In the process, their large coal conversion R&D programmes have been terminated, and the research staff have been dispersed. A number of the former staff members are still active in other areas, but, as with the universities, they would have to be incentivised to take up CTL activities again, and would probably only be willing to act in an advisory capacity. The equipment developed within the research institutes for CTL research has largely been disposed of or de-commissioned. Unless it has been transferred for use in other areas, it has probably been broken up or scrapped. One possibility is that it may have been switched for use on bio-refinery R&D.

The one bright spot is the continuation of work at the Central Mining Institute in Poland, which has maintained a certain momentum. These activities could provide a focus for future work, perhaps with advisors from UK and Germany being brought in to help on a part time basis.

In parallel with the decline in facilities and R&D commitment to coal liquefaction, and in common with other engineering and physical science based areas, a major shortage has developed throughout the EU in the availability of suitable graduate engineers and scientists. This is a problem in currently active coal based activities such as power generation, and is even worse for CTL - a technology that was effectively discontinued. It would take considerable effort to re-establish suitable training programmes. Fortunately, while experienced academic staff have transferred to other research areas, many of them are still employed in EU universities and could still be available to organise courses and training programmes.

In industry, there has been a similar run down in activities, though this has been moderated to an extent by the interest in CCS, which has high priority in some national research programmes and in the European Commission Framework R&D Programme. Pre-combustion carbon dioxide separation involves coal gasification and some parts of the industry are quite bullish about their ability to establish ICL as an extension of their IGCC processes. Large engineering firms can certainly design and build equipment for ICL systems in collaboration with SASOL.

8.5 International cooperation

It is clear from the discussions in Sections 4 and 5 that, while Europe effectively curtailed its coal-to-liquids R, D&D some 15 – 20 years ago, this has not been the case for the rest of the world. South Africa is the most obvious case in point with its large-scale development of the SASOL ICL process. Additionally, however, USA, China, Australia and Japan have all continued to invest in CTL technologies, and several of these are now approaching the pilot and demonstration phases. A number of these are taking the form of international collaborations.

9 Conclusions

Currently, there is a great deal of international interest in the possibility of converting coal to liquid fuels, especially for transport. This is due to

- the continuing uncertainties in the supply and price of oil when faced with the continuing and projected increases in demand – particularly from the developing economies
- the failure of oil reserves to expand to match this increase in demand
- the fact that global coal reserves are extremely large and widely distributed, with the consequence that coal supplies are likely to be more dependable, and the price less prone to wide fluctuations.

Thus, the production of liquid fuels from coal would

- greatly increase the availability and lifetime of liquid transport fuels
- reduce the uncertainties associated with wide oil-price variations
- increase the opportunities to use indigenous fuel reserves
- send a signal to oil producing countries regarding the maximum tolerable price ceiling.

In the European context, the situation is even more constrained by a high dependence on imported oil and gas, and by the vulnerability to outside events, as has been highlighted by the difficulties that arise when Russia cuts the supply of gas to the European gas distribution network. Thus, security of supply ultimately becomes an even more important driver than price. This implies that the developments needed to ensure fuel supplies (and particularly of liquid fuels for the transport sector) must be prioritised and sustained even if the short term economics look unfavourable. In this context, the production of liquid fuels from coal could have particular significance.

In terms of building a strategic level of CTL expertise, Europe has allowed itself to fall behind much of the rest of the world. This includes a shortage of process and engineering skills while it has also allowed its educational and R&D capacity to decline significantly. European industry has the ability to rectify this situation, but it will have to invest in expertise to establish the necessary skills base and experience, either by taking forward its own process demonstrations or through buying into various international initiatives. Likewise, the universities will have to regenerate the education and training, and R&D base. This will require active collaboration between the education, industry and government sectors (including the EC), and should be started soon while the remaining people with the necessary experience are still active.

Alongside CTL itself, underground coal gasification potentially provides an effective route for exploiting Europe's extensive indigenous coal resources by allowing energy extraction from otherwise unexploitable coal deposits. If the products from UCG can be integrated into an ICL plant, this then offers the prospect to provide gaseous and liquid fuels in a clean and effective way which would provide for stable prices, reduced dependence on outside suppliers, and a greatly enhanced security of fuel supplies. Thus, there is a case for UCG demonstration in EU, coupled with the production of liquid fuels by Fischer-Tropsch conversion, and excluding the DCL route.

With regard top DCL, there may well be some advantages that would justify the revival of a development programme in Europe. The way forward would need to be via collaboration with active demonstration programmes, which are currently only in China.

10 Recommendations

CTL has the potential to makes the maximum possible use in Europe of indigenous coal resources as part of an overall strategy to ensure security of fuel supplies within a sustainable energy mix. However, if that potential is to be realised, then it is necessary for Europe to reach the position where it has access to the necessary technology and expertise, covering both CTL, to most probably include CCS, and UCG.

In order to achieve that position, there is a need for a European wide initiative, which could best be led by the European Commission, within the context of the need to develop the European Research Area. This should include the need:

1. to explore the establishment of industrial scale ICL technologies in collaboration with SASOL. Co-development with either existing or planned IGCC and pre-combustion separation CCS R,D&D activities should also be encouraged so as to seek a near zero emissions solution. Such activities will need to be undertaken in regions of Europe that have access to large low cost deposits of lignite and brown coal.
2. to develop UCG technologies, either through stand-alone demonstration projects in Europe or by collaborating on either existing or planned demonstration projects outside of Europe. In the case of the former, there would be advantages if this development was undertaken in similar regions to those where any CTL plants are being established since there will be deposits of unmineable coal close to the large low cost deposits of lignite and brown coal referred to above.
3. to implement, following the successful development of UCG, the inclusion of a FT liquefaction plant as one of the post-gasification process trains in order to establish the viability of this option in terms of UCG and FT integrated operation.
4. to encourage the development of pilot and demonstration scale DCL plants (in Europe or elsewhere) in collaboration with USA, Australia, Japan and China
5. to establish supporting R&D, education and training programmes as a matter of urgency while some of the experienced academic and research personnel are still active. The objectives should be to develop expertise and to investigate possible process improvements for DCL processes.
6. to ensure that a European benchmark approach (similar to that for CCS) is established such that robust techno-economic assessment studies can be undertaken for all such projects on a consistent basis.
7. to encourage, for all the major process developments, strong EU industrial cooperation for the overall benefit of Europe.

11 References

ASFE (2008) Alliance for Synthetic Fuels in Europe. Available from: www.synthetic-fuels.org**.** (2008)

Bajura R A, Eyring E M (2005) Coal and liquid fuels. In: *Proceedings of the GCEP advanced coal workshop*. Provo, Utah, USA, 15-16 Mar, 2005. Morgantown, WV, USA, National Research Center for Coal and Energy. http://gcep.stanford.edu/pdfs 31 pp (March 2005)

BCG Energy (2009) Firth of Forth UCG. http://www.britishcoalgasification.co.uk/News-item1.html (February 2009)

Bentley R W (2003) Oil forecasts, past and present. *Energy Exploration & Exploitation*. **20**, (6); 481-491 (2003)

BP (2006) *BP statistical review of world energy – June 2007*. Available from: www.bp.com, BP Distribution Services, Surrey, UK, 45 pp (Jun 2006)

Burke F P, Brandes S D, McCoy D C, Winschel R A, Gray D, Tomlinson G (2001) *Summary report of the DOE direct liquefaction process development campaign of the late twentieth century: topical report*. DOE/PC 93054-94. Washington, DC, USA, Department of Energy.: http://www.osti.gov/energycitations/servlets/purl/794281-khohbO/native/794281.PDF, 154 pp (Jul 2001)

Capture Ready (2009) Shenhua to Introduce CCS into Its Erdos CTL Project. Captureready.com.: http://www.captureready.com/EN/Channels/News/showDetail.asp?objID=880. (26 Mar. 2009)

Central Mining Institute (1993) *Technologies of liquid fuels, coke and electrode binders production from semi-products of the hydrogenation process*. Final report of research carried in 1957-1990 at Central Mining Institute, Katowice, Poland (1993)

Central Mining Institute (2006) *Technical and economic assessment of a coal liquefaction technology implementation in Poland* . GIG, Poland (2006)

Chemical Engineering Archive (1979-2005) *Economic Indicators; Marshall & Swift Cost Index*, Chemical Engineering Plant Cost Index.

China Daily (2008) China's coal liquefaction craze cools off. http://www.chinadaily.com.cn/bizchina/ 2008-09/19/content_7043240.htm (19 September 2008)

Coal Age (2007) Coal-to-liquid fuel promotion act of 2007 introduced. *Coal Age*. **112**, (1); 5 (Jan 2007)

Coal Authority (2008) Underground Coal Gasification in the UK. Available from: www.coal.gov.uk/resources/ cleanercoaltechnologies/ucgintro.cfm Coal Authority, UK (2008)

Collot A-G (2002) *Matching gasifiers to coals*. IEACCC/65. London, UK, IEA Clean Coal Centre, 63 pp (October 2002)

Couch G (2008) Coal to liquids, IEA Clean Coal Centre CCC/132, ISBN 978-92-9029-451-1 (March 2008)

Couch G (2009) Underground coal gasification, IEA Clean Coal Centre (in press)

Davis B H (2005) Fischer-Tropsch synthesis: overview of reactor development and future potentialities. *Topics in Catalysis*. **32**, (3-4); 143-168 (Mar 2005)

de Kort G (2008) *Personal communication*. G M Global XTL Development, Shell Gas & Power, The Hague, Netherlands (28 Jan 2008)

DTI (1999) *Coal liquefaction*. Cleaner coal technology programme. Technology status report 010. London, UK, Department of Trade and Industry, 14pp (Oct 1999)

EBR (2007) *Commercialization of coal to liquids technology*. Energy Business Reports. Available from: www.energybusinessreports.com 80 pp (2007)

EC (2008) European Energy and Transport Trends to 2030 – 2005 update 2007, www.ec.europa.eu/dgs energy_transport/figures/trends_2030_update_2007/energy_transport_trends_2030_update_2007_en.pdf. European Commission, Directorate-General for Energy and Transport, ISBN 978-92-79-07620-6 (April 2008)

EIA (2006a) *Annual energy outlook 2006 – with projections to 2030*. DOE/EIA-0383 (2006). Washington, DC, USA, Department of Energy, 234 pp (Feb 2006)

EIA (2007) International Energy Outlook 2007, Available from: www.eia.doe.gov/oiaf/ieo/coal.html. Energy Information Administration/DOE, Washington DC, USA (May 2007)

Energy Edge (2007) Coal of the Future (Supply prospects for thermal coal by 2030-2050), EUR 22644, ISSN 1018-5593, Energy Edge Limited, UK (February 2007)

Euracoal (2004a) Czech Republic Analysis, Available from: www.euracoal.be/newsite/czech.php. Eurocoal (2004)

Euracoal (2004b) UK Analysis, Available from: http://euracoal.be/newsite/theunitedkingdom.php. Eurocoal (2004)

Euracoal (2005) *Coal Industry across Europe 2005*. Euracoal, Brussels (2005)

Euracoal (2008) Coal industry across Europe 2008: www.euracoal.org/pages/medien.php?idpage=406 (July 2008)

Gasification News (2007) Australia's Linc Energy starts UCG production at Chinchilla. *Gasification News*. **X**, (15); 7 (19 Sep 2007)

GBSiPPW SEPARATOR (1981) *Technical and economic analysis of coal-based liquid fuels production, Stage 4, v. 2; Direct hydrogenation process under moderate pressure*. Katowice, Poland (1981)

GBSiPPW SEPARATOR (1987) *Technical and economic analysis of coal-based liquid fuels production*. Katowice, Poland (1987)

GreencarCongress (2008a) Shenhua To Focus Solely on Ningxia Hui Coal to Liquids (CTL) Plant.: http://www.greencarcongress.com/2008/08/sasol-and-shenh.html (28 August 2008)

Green Car Congress (2008b) Sasol and Shenhua Contract Engineering Companies for China CTL Study http://www.greencarcongress.com/2008/10/sasol-and-shenh.html (23 October 2008)

GVST-Gesamtverband Steinkohle (2007) Steinkohle Jahresbericht 2007, www.gvst.de (Oct. 2007)

Hartung M (2006) From Mine to Wheel – the role of lignite-to-liquids in tomorrow's energy supply. *Coal-to-liquids, an alternative oil supply ? Workshop.* Paris, France, IEA (Nov 2006)

IEA (2006) *World energy outlook 2006*. Paris, France, OECD/IEA, 596 pp (2006)

IEA/CIAB (2006) *Coal-to-liquids, an alternative oil supply ? Workshop report.* Paris, France, IEA, 36 pp (Nov 2006)

IEA (2008) *Coal information – 2008 edition*. Paris, France, IEA/OECD, ISBN 978-92-64-04241-4, various pages (August 2008)

Irwin M W, Bowen B H, Preckel P V, Yu Z, Rupp J, Hieb F H, Mastalerz M (2007) *A feasibility study for the construction of a Fischer-Tropsch liquid fuels production plant with power co-production at NSA Crane (Naval Support Activity Crane)*. http://www.purdue.edu/dp/energy/pdfs/CCTR/CraneReportFinal-May2007.pdf, 67 pp (31 May 2007)

Kaneko T, Derbyshire F, Makino E, Gray D, Tamura M (2001) Coal liquefaction. *Ullmann's Encyclopaedia of Industrial Chemistry*. www.mrw.interscience.wiley.com Wiley-VCH Verlag GmbH & Co, 83 pp (2001)

Kavelov B and Peteves SD (2007) *The Future of Coal,* EUR 22744 EN, ISBN 978-92-79-05531-7, ISSN 1018-5593 Luxembourg: Office for Official Publications of the European Communities, European Commission, (2007)

Kelly RC (2006) CTL Projects – key issues and economics. Paper presented at: *Coal-to-liquids, an alternative oil supply ? Workshop.* Paris, France, IEA (Nov 2006)

Kimber GM (1996) A History of U.K. Coal Liquefaction, COAL R078, ETSU, Harwell. U.K. (Dec. 1996)

Läänelaid S (2009) *Personal communication,* Invent Baltics OÜ (March 2009)

Linc Energy (2006) Chinchilla pilot burn project. http://www.lincenergy.com.au/cpb.html (2006)

Miller C L (2007) Coal conversion – pathway to alternate fuels. In: *Proceedings of the EIA energy outlook modeling and data conference*. Washington, DC, USA, 28 Mar 2007, Available from: http://www.futurecoalfuels.org/documents/011907_miller.pdf, 19 pp (2007)

Mills S (2007) Prospects *for coal and clean coal technologies in the Czech Republic*, IEA Clean Coal Centre CCC/120, ISBN 92-9029-436-1 (January 2007)

Minchener A (2009) *Future coal supply prospects*. IEA Clean Coal Centre ESBN 978-92-9029-465-8 (March 2009)

MIT (2007) *The future of coal*. Available from: http://web.mit.edu/coal/ Cambridge, MA, USA, Massachusetts Institute of Technology. 192 pp (2007)

MPO (2008) Coal, Coke and Pellets in the Czech Republic in 2006, Available from: www.mpo.cz/dokument42846.html. Ministry of Industry and Trade, Czech Republic (9 Apr. 2008)

NEDO (2006) *Clean coal technologies in Japan*. Kawasaki, Japan, New Energy and Industrial Technology Development Organisation, 114 pp (2006)

Oil Shale (2009) Oil Shale Journal. Estonia Academy of Sciences. http://www.kirj.ee/oilshale. ISSN 1736-7492 (2009)

Parker D (2007) Brown coal to diesel a world first in scale. *The Australian*. www.theaustralian.news.com.au (28 Apr 2007)

People's Daily Online (2006) China reins in fast growth of CTL projects. Available from: http://english.people.com.cn/ 200607/29/eng20060729_287975.html (29 July 2006)

Radtke K R, Heinritz-Adrian M, Marsico C (2006) New wave of coal-to-liquids. *VGB PowerTech* **86**, (5); 78-84 (2006)

RedOrbit (2006) Syntroleum and Sustec Announce Joint Development Agreement for CTL Project. http://www.redorbit.com/news/entertainment/527471/syntroleum_and_sustec_announce_joint_development_agreement_for_ctl_project/index.html. (5 June 2006)

Ritschel W & Schiffer H-W (2007) World Market for Hard Coal, www.rwe.com/generator.aspx/rwe-power-cw/downloads/property=Data/id=503000/hard-coal2007.pdf. RWE, Germany (Oct. 2007)

Sasol (2006) Sasol and Chinese sign landmark coal-to-liquids agreement. www.sasol.com, News centre, 3 pp (22 Jun 2006)

Scandoil (2008) Linc Energy commits UCG project to South Australia. www.scandoil.com/moxie-bm2/carbon/politics_and_policy_carbon/linc-energy-commits-ucg-project-to-south-australia.shtml. Scandinavian Oil and Gas (November 2008)

Schrape C (2007) Arckaringa CTL and power – the right project at the right time for South Australia. In: *Proceedings of CTLtec 2007 – 4th forum on coal conversions technologies & investments*, Beijing, China, 14-15 Mar, 2007; CD-ROM, Singapore, Centre for Management Technology, 16 pp (2007)

Shinn J H (1985) The structure of coal and its liquefaction products: a reactive model. In: *Proceedings of the 1985 international conference on coal science*. Sydney, NSW, Australia, 28-31 Oct 1985. Rushcutters Bay, NSW, Australia, Pergamon Press (Australia), pp 738-741 (1985)

Skeer J, Wang Y (2007) China on the move: oil price explosion? *Energy Policy*. **35**, (1); 678-691 (Jan 2007)

SourceWatch (2008) Arckaringa Coal-to-Liquids and Power Project. Sourcewatch (2008). www.sourcewatch.org/index.php?title=Arckaringa_Coal-to-Liquids_and_Power_Project.

Spath P L, Dayton D C (2003) *Preliminary screening – technical and economic assessment of synthesis gas to fuels and chemicals with emphasis on the potential for biomass-derived syngas*. USA, National Renewable Energy Laboratory, www.nrel.gov/docs/fy04osti/34929.pdf, 142 pp (Dec 2003)

Steynberg A (2006) Commercial Experience in South Africa with Coal-to-Liquids and Coal-to-Chemicals. Paper presented at: *Coal-to-liquids, an alternative oil supply ? Workshop.* Paris, France, IEA (Nov 2006)

Steynberg A (2005) Overview of Sasol CTL and recent activities. Paper presented at a breakout session on coal liquefaction at *The Montana Symposium: Energy Future of the West.* Bozeman, MT, USA, 18-19 Oct 2005. Available from: http://www.energyfuture.mt.gov/sessions.asp, 22 pp (2005)

Strobel B O, Friedrich F, Kölling G, Liphard K G, Romey I (1981) Coal hydrogenation at Bergbau-Forschung. Erdöl und Kohle **34**, (9); 391-396 (1981)

Sun Q, Fletcher J J (2007) Coal to liquid development in China. In: *Proceedings of the 24th annual international Pittsburgh coal conference*. Johannesburg, South Africa, 10-14 Sep 2007, CDROM, 9 pp (2007)

US GAO (2007) *Crude oil: uncertainty about future oil supply make it important to develop a strategy for addressing a peak and decline in oil production*. GAO-07-283. Washington, DC, USA, US Government Accountability Office. http://www.gao.gov/new.items/d07283.pdf 76 pp (Feb 2007)

Van Heek K H, Wanzl W (1989) *Generation of liquid products from coal through pyrolysis and hydropyrolysis*. Erdöl Erdgas Kohle **105**, 30-36 (1989)

Wanzl W (2008a) *Hydropyrolysis – third way to liquid products from coal. In:* Schmalfeld J (ed.) Die Veredlung und Umwandlung von Kohle, p 175-237, DGMK, Hamburg, ISBN 978-3-936418-88-0 (2008)

Wanzl W (2008b) *Coal hydrogenation by DT technology. In:* Schmalfeld J (ed.) Die Veredlung und Umwandlung von Kohle, p 635-665, DGMK, Hamburg, ISBN 978-3-936418-88-0 (2008)

Wanzl W (2008c) *Pyrosol – A process for coal hydrogenation. In:* Schmalfeld J (ed.) Die Veredlung und Umwandlung von Kohle, p 687-691, DGMK, Hamburg, ISBN 978-3-936418-88-0 (2008)

WCI (2005) The Coal Resource – A Comprehensive Overview of Coal, www.worldcoal.org. World Coal Institute (2005

WEC (2007) Survey of Energy Resources, Available from: www.worldenergy.org/publications/ ISBN: 0 946121 26 5, World Energy Council (2007)

Williams R H, Larson E D (2003) A comparison of direct and indirect liquefaction technologies for making fluid fuels from coal. *Energy for Sustainable Development*. **V11**, (4); 103-129 (Dec 2003)

Woynillowickz D (2007) Tar sands fever! *World Watch*. www.worldwatch.org; pp 8-13 (Sep/Oct 2007)

Wu O (2007) Changing states. *World Coal*. **17**, (2); 34-38 (Feb 2007)

Xu Z (2007) *Private communication*. Beijing, China, Beijing Research Institute of Coal Chemistry, Deputy Director – Research Professor (12 March 2007)

Yu Z, Wu L, Li K (2007) Development of alternative energy and coal-to-liquids in China. In: *Proceedings of the 24th annual international Pittsburgh coal conference*. Johannesburg, South Africa, 10-14 Sep 2007, CDROM, (2007)

Zhang Y (2006) China's Development Strategy for Coal-to-Liquids Industry. *Coal-to-liquids, an alternative oil supply ? Workshop.* Paris, France, IEA (Nov 2006)

ANNEX 1

Overview of gasification development and applicability to CTL systems

Introduction

ICL, via either FT or methanol synthesis, requires the provision of a suitably conditioned CO/H_2-mixture known as synthesis gas or syngas. A number of processes have been developed to produce gas from coal, taking account of the very widely varying properties of mined bituminous and subbituminous coals, and also of the different applications for utilisation of the gas. For ICL, the syngas yield must be maximised while other possible gas components are avoided. Moreover, flexibility in coal feedstock is usually required, which limits the gasification options available.

Syngas production by gasification is a highly endothermic process, and the required energy is obtained by combustion of part of the carbon source. Also, syngas production and cleaning can be responsible for up to 70-80% of the total capital cost of coal liquids production, while the cost for synthesis is about 13-15% and for liquid processing 5-10%. Thus, the efficiency of the gasification step is the decisive factor in the overall process economics. Consequently, significant development work has been carried out on the development of coal gasification, both for CTL and other fuel related applications.

The three gasification options are described below. Entrained gasification is least sensitive to fuel characteristics and can provide a raw gas most suited to conversion into a syngas for ICL. The somewhat lower thermal efficiency of these high temperature processes as compared to fixed or moving bed gasification is often outweighed by simpler reactor design and operation. The third option, fluidised bed gasification, is only suitable for use with very reactive fuels, i.e. lignites or bio-derived fuels and certain waste materials. Only a detailed study will reveal which technology is the optimum choice in a given situation and environment. The three technology variants are described briefly below and, in the context of this report, the focus is on the production of syngas.

Fixed or moving bed gasification

Fixed bed (or moving bed) gasifiers require non-caking or weakly-caking lump coal in order to ensure good passage of the gasification agent (steam and oxygen) and the product gas through the reactor. Countercurrent fixed bed gasifiers achieve the highest energy efficiency and a complete conversion of the organic material of the coal into product gas. The need for lump coal with careful control of fines may require some preparation of the feedstock such as classifying and, maybe, briquetting. This requirement together with the limitation to coals with swelling numbers less than 2 can be a drawback in terms of coal availability. Another problem arises from the fact that the product gas from fixed bed gasifiers usually contains some methane and also some hydrocarbons which would cause problems in the subsequent methanol or FT synthesis. Hence, the gas cleaning procedure in fixed bed gasification for synthesis gas production is more complex than for some other gasification processes. The oldest and most widely deployed coal gasification process for syngas production is the Lurgi pressurised fixed bed gasification technology (Figure A1) (Reimert, 2008).

The Lurgi gasifier involves the gasification with steam and oxygen of lump sized, low or medium caking coals on a rotating grate at pressures of 20 to 30 bar. The countercurrent flow of gasification agent and fuel results in a high thermal efficiency of the reactor to produce a raw gas with heating values of 11 to 12 MJ/m³(STP). Depending on the feed coal characteristics the product gas contains 25 – 33 vol% of CO_2, 15 to 21 vol% of CO, 35 to 41 vol% of H_2 and 10 to 13 vol% of CH_4. For use as syngas, the methane must be removed. The high methane yield is, however, advantageous if the product is to be SNG. Furthermore, the raw gas contains tars mixed with dust, so a water quench follows the gas exit from the reactor. The tars are usually recycled on top of the fuel bed in order to mitigate dust elutriation and also to make some energetic use of the material which is otherwise barely useable. Well proven technology for raw gas cleaning and conditioning is available and a high grade product gas can be delivered for nearly any purpose.

Since the 1960s, the Lurgi process has been improved through increases in reactor size and components, extension of the feed coal slate to include low rank coals, and the use of air instead of oxygen as the gasification agent in order to make the process attractive for use in combined cycle power generation applications. In addition, the design has been modified for operation at up to 100 bar in order to increase the reactor throughput while at the same time increasing the methane content of the raw gas to be better suited for SNG production.

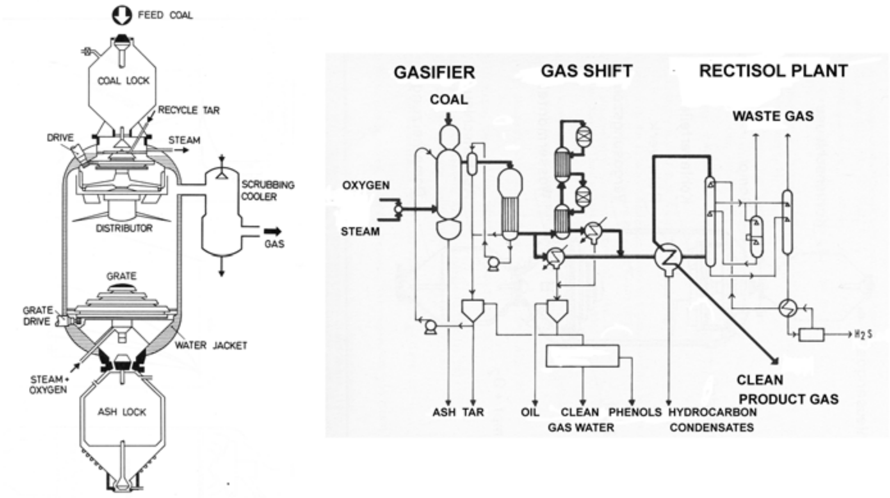

Figure A1 The Lurgi pressurised coal gasification process

The British Gas Corporation, in cooperation with Lurgi, developed a new design of the gasifier bottom in order to avoid the problems associated with rotating equipment in the fuel/ash bed, while simultaneously overcoming the limitation set by the ash softening temperature in the gasification zone. This resulted in the BGL slagging gasifier (Figure A2) (Kamka, 2005). The development was mainly undertaken in Westfield, Scotland, but later also in Germany. The sponsors included the EC and the former ECSC.

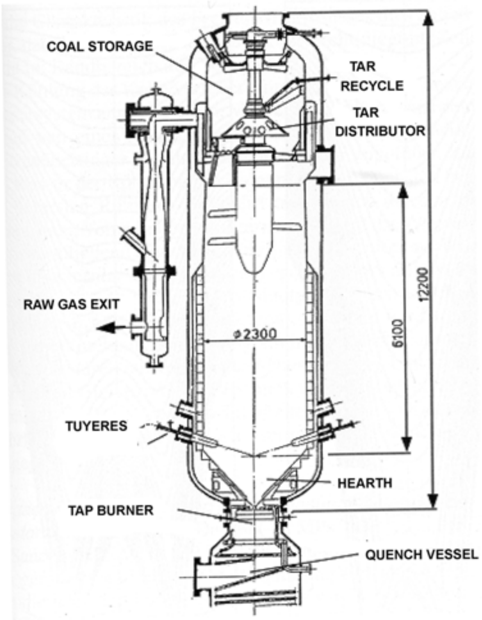

Figure A2 BGL Slagging Gasifier

The gasifier differs from the standard Lurgi reactor through:

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

It also operates at higher gasification temperatures than the standard Lurgi system and, hence, the CO/CO_2-ratio in the product gas is much higher and the methane content correspondingly lower. Typical gas compositions are 2 – 3 vol% of CO_2, 55 –60 vol% of CO, 25 – 28 vol% of H_2 and 6 – 9 vol% of CH_4.

The high temperature renders it possible to use less reactive fuels like cokes and certain carbonaceous residues. Furthermore, it provides for a better steam utilisation, and consequently, the amount of water that must be cleaned and processed is much reduced. Coal ash is converted into slag which forms a non-leachable glass on removal. This requires a low slag viscosity, which is obtained by adding fluxing agents, usually limestone or basic blast furnace slag.

The BGL slagger has not yet found as wide an application as the standard Lurgi gasifier but worked successfully in the SVZ Schwarze Pumpe (a central recycling station) in Germany to produce synthesis gas for methanol production and fuel gas for combined cycle power raising. The fuels were hard coals and lignite as well as various residues and secondary fuels made from waste. The process requires lump coal with a limited fines content. With non-caking coals, if the fines content (< 6 mm) is in excess of about 5 % there is a noticeable reduction in performance. However, with caking coals the particle size is less important as the fine coal forms a cake in the upper part of the reactor that is broken up by the stirrer. Fine coal can be briquetted or pelletised prior to feeding, or it can be fed though the tuyeres directly into the hearth (thereby converting the reactor partly into an entrained gasifier). However, all such measures increase the overall fuel cost. Like all slagging reactors, the ash content of the fuel has an important bearing on thermal efficiency, as the sensible heat of the slag cannot be recovered.

Fluidised bed gasification

Fluidised bed gasifiers have been successfully used in many installations for the conversion of highly reactive coals into syngas. The low reaction temperature (below the softening temperature of the fuel ash) renders the technology unsuitable for less reactive i.e. usually higher rank coals. The gasification reactor is particularly simple in design as it does not contain any moving parts and the ceramic lining is designed solely for heat insulation and erosion protection of the structural steel but is not attacked by molten ash. A drawback of fluidised reactors is the high elutriation of unreacted feedstock fines. The dust collected from the product gas thus requires recirculation into the gasifier or some other utilisation in order to ensure economic operation. The fuel conversion rate is, hence, markedly lower than for fixed bed (and entrained) gasifiers but can attain values of more than 90 – 95 %. The product gas still contains small amounts of methane (1- 5 vol.-%) and traces of hydrocarbons so a separation or conversion step for methane in gas clean-up is required if synthesis gas is the required product.

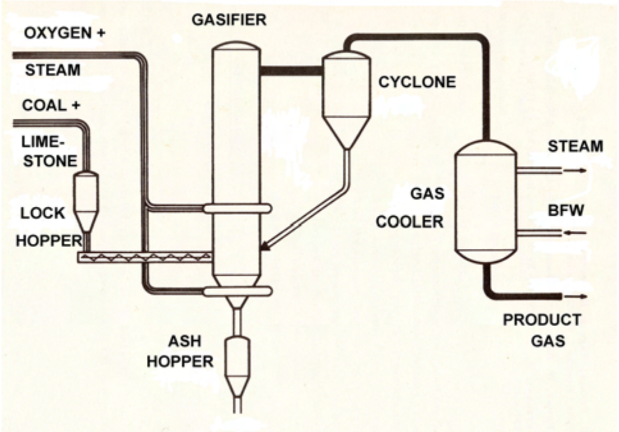

Figure A3 HTW process for fluidised bed gasification

The Rheinbraun HTW process is an example of a fully developed industrially proven gasification process for highly reactive carbonaceous fuels (Adlhoch, 2008). Much of the development work was supported by the German national government together with the EC and the ECSC.

Coal is fed into the bed using screw feeders, and is fluidised with the gasification agent, oxygen or air and steam. The bed operates at 800 C while the freeboard is maintained at a markedly higher temperature by adding more oxygen rich gasification agent. This post-reaction zone is essential as it provides for a high carbon conversion rate and simultaneously reduces the amount of hydrocarbons in the raw gas. The elutriated fines are separated from the gas flow by a hot cyclone and directly recycled into the fluidised bed. Rheinbraun used mostly dried lignite as the feed coal although other carbon containing materials like wastes were also successfully tested. Excess bed material is withdrawn via an ash discharge system consisting of a cooling screw feeder and a lock hopper system (Figure A3).

Entrained flow gasification

Entrained flow gasification is the most universally applicable technology. Gasification takes place in a flame and the fuel is introduced into the reactor either as a fine powder or as an aqueous slurry. The reaction temperature must be kept high in order to ensure complete gasification as the residence time in the gasifier is short. Hence, the ash melts and is withdrawn as a vitrified slag at the bottom of the reactor. This incurs a certain thermal loss and the thermal efficiency of entrained gasification is usually less than that of fixed bed dry gasification processes. The trade-off, however, is a simple reactor design and the wide variability in fuels that can be processed. Also, the high operating temperatures mean that even fuel of low reactivity can be processed and the product gas is free from hydrocarbons and methane. The technology is, thus, ideally suited for syngas production. However, the high temperature and the very aggressive coal slag require a high grade and expensive ceramic lining for the reactor. The key technology variants include Shell and Siemens (formerly GSP) and Krupp Koppers, all of which include dry feed systems, and GE Energy, which uses a slurry fed system.

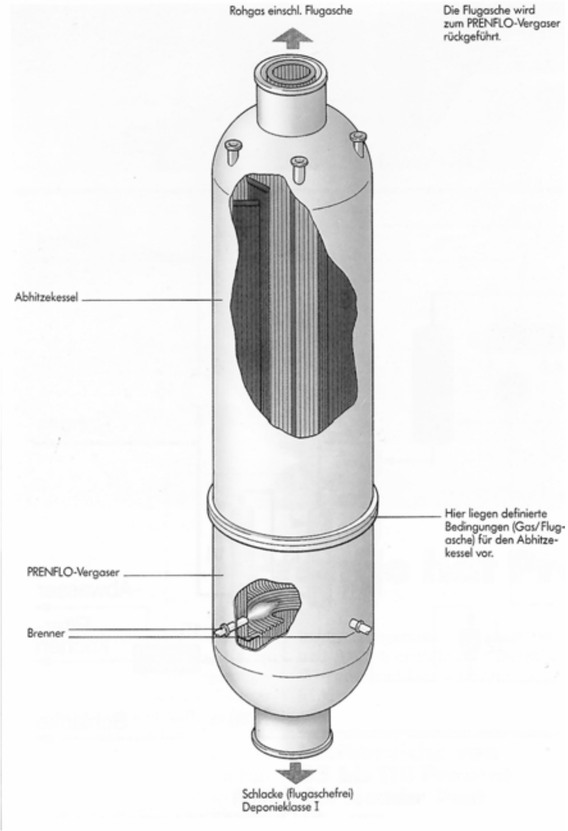

Figure A4 Prenflo Gasifier with radiation boiler

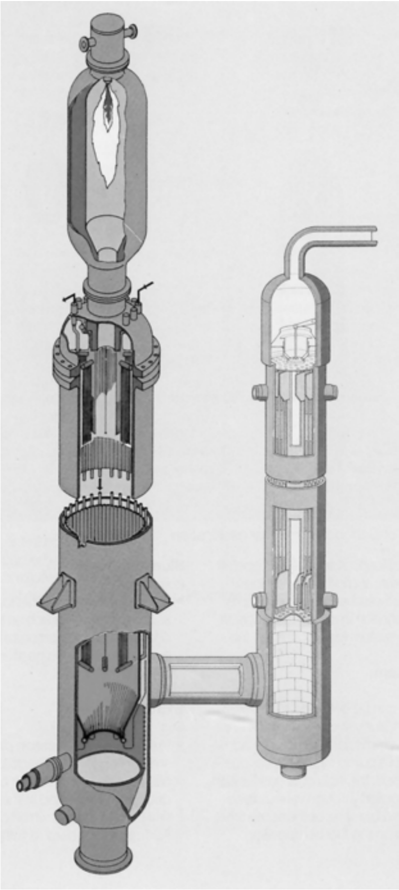

Figure A5 GE Energy wet feed entrained coal gasification

Development work was started in 1974 by Koppers GmbH who were later acquired by F. Krupp AG. There was cooperation with Shell BV of the Netherlands who contributed their expertise with pressurised mineral oil gasification while Krupp-Koppers provided know-how in coal technology and entrained gasification. The cost of the development was born by the firms alone. In 1983 both parties concluded their agreement. In 1987, Shell built a demonstration plant in Deer Park, USA, and the process was then named Shell Coal Gasification Process (SCGP). In 1993, using this technology, the 250 MW$_e$ IGCC plant was built at Buggenum in the Netherlands, with support from the EC.

Following further development with support from the German Government, Krupp-Koppers established the Prenflo process, which then was used for the 300 MW_e IGCC plant in Puertollano, Spain. This demonstration project received EC financial support.

The SCGP and Prenflo processes are quite similar in that they operate with dry powdered fuels and the reactors are equipped with four burners arranged in one plane and firing from opposing directions. The slag is withdrawn at the bottom and the hot raw gas passes into a radiation boiler at the top of the water jacketed gasification chamber (Figure A4). After leaving the radiation boiler the raw gas is quenched with recycled cold gas before entering into a convective waste heat boiler (van der Ploeg, 2005; Bonn, 2008).

The gas produced contains 60 to 68 vol% of CO, 24 to 29 vol% of H_2, 0.5 to 6 vol% of CO_2 and some 5 to 7 vol% of N_2 (from the pneumatic fuel transport). It is virtually free of hydrocarbons including methane. The H_2/CO-ratio can be readily adjusted to any required value using the shift reaction. The processes were successfully tested with a very wide slate of fuels including (dried) lignites and petroleum coke. Recently, several large gasification plants using Shell gasifiers have been built in China, delivering synthesis gas for ammonia or methanol production.

The Gaskombinat Schwarze Pumpe (GSP) (Schingnitz, 2008) process was originally developed to handle lignites with fairly high salt content. The gasifier was dry fed with down-fired burners and the raw gas was quenched with water immediately under the gasification vessel in order to treat the corrosive gas components. The GSP activities were first acquired by Future Energy GmbH and subsequently by Siemens Power Generation. The latter organisation has received orders for a few large units in China for industrial applications.

The GE-Energy process (Figure A5) is the only process with a wet fuel feeding system. Hard coal is fine ground and mixed with water to form a slurry that can be pumped to the head of the reactor where it is injected with oxygen. The oxygen oxidises the carbon to CO and provides the heat of reaction for the water gas reaction with steam formed out of the slurry water. Although the wet fuel incurs a significant thermal penalty for the efficiency of the process, the reduced handling risks with coal dust at pressure compensates for this to some extent. Many units were sold for industrial applications in the USA and more recently some have been sold to China. The technology has also been used on two IGCC demonstration projects in the USA (McDaniel, 2002).

References to Annex 1:

Adlhoch W (2008) Hochtemperatur-Winkler-Verfahren, in: J. Schmalfeld, (Ed.) Die Veredlung und Umwnadlung von Kohle, DGMK, Hamburg 2008, ISBN 978-3-936418-88-0

Bonn B (2008) Prenflo-Verfahren, in: J. Schmalfeld, (Ed.) Die Veredlung und Umwnadlung von Kohle, DGMK, Hamburg 2008, ISBN 978-3-936418-88-0

Kamka F, Jochmann A (2005) Development and Satus of BGL Gasification, Int'l. Freiberg Conf. On IGCC and XTL Technologies, June, 16-18, 2005

Mc Daniel J E (2002) Tampa Electric Polk Power Station IGCC Project Final Report DE FC 21-91 MC27363, http://www.tampaelectric.com/data/files/PolkDOEFinalTechnicalReport.pdf

Reimert, R (2008) Festbettvergasung, in: J. Schmalfeld, (Ed.) Die Veredlung und Umwandlung von Kohle, DGMK, Hamburg 2008, ISBN 978-3-936418-88-0

Schingnitz M (2008) Gaskombinat Schwarze Pumpe-Verfahren, in: J. Schmalfeld, (Ed.) Die Veredlung und Umwnadlung von Kohle, DGMK, Hamburg 2008, ISBN 978-3-936418-88-0

Van der Ploeg R, van den Burg R, van den Born I (2005) Shell Coal Gasification Process for Power and CO2-Capture, Int'l. Freiberg Conf. On IGCC and XTL Technologies, June, 16-18, 2005