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A review on coal to liquid fuels and its coal consumption

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Abstract

Continued reliance on oil is unsustainable and this has resulted in interest in alternative fuels. Coal-to-Liquids (CTL) can supply liquid fuels and have been successfully used in several cases, particularly in South Africa. This article reviews CTL theory and technology. Understanding the fundamental aspects of coal liquefaction technologies are vital for planning and policy-making, as future CTL systems will be integrated in a much larger global energy and fuel utilization system.

Conversion ratios for CTL are generally estimated to be between 1-2 barrels/ton coal. This puts a strict limitation on future CTL capacity imposed by future coal production volumes, regardless of other factors such as economics, emissions or environmental concern. Assuming that 10% of world coal production can be diverted to CTL, the contribution to liquid fuel supply will be limited to only a few Mb/d. This prevents CTL from becoming a viable mitigation plan for liquid fuel shortage on a global scale. However, it is still possible for individual nations to derive significant shares of their fuel supply from CTL, but those nations must also have access to equally significant coal production capacities. It is unrealistic to claim that CTL provides a feasible solution to liquid fuels shortages created by peak oil. For the most part, it can only be a minor contributor and must be combined with other strategies.

Keywords

Coal-to-liquids, synthetic fuels, conversion ratio, peak oil mitigation

1. Introduction

The oil price has risen dramatically over the last few years. The price of oil reached \$100 per barrel in January 2008, before rocketing to \$147 barrel in July 2008. After the dramatic price collapse in late 2008, oil prices have now recovered to over \$60/barrel, still an historic high. In summary, there are few signs of a return to the \$20 per barrel that was a typical price in the 1990s and continued oil dependence is environmentally, economically and socially unsustainable [1]. Peak oil concerns, resulting in imminent oil production limitations, have been voiced by various studies [2-5]. This has resulted in renewed interest in alternative fuels for the future.

Alternative liquid hydrocarbon fuels can be obtained from various feedstocks, ranging from solids to gases. Coal-to-Liquids (CTL) is a technology based on the liquefaction of coal using three basic approaches; pyrolysis, direct coal liquefaction (DCL) and indirect coal liquefaction (ICL) [6]. Gas-to-Liquids (GTL) and Biomass-to-Liquids (BTL) are related options, based on feedstock other than coal. Generally, synthetic fuel properties can be made almost identical to conventional petroleum fuels.

CTL is one of the more reasonable approaches for alternative liquid fuels, having already been technically and commercially established. The U.S. Department of Energy report *Peaking of World Oil Production: Impacts, Mitigation, and Risk Management* [7], the National Petroleum Councils report *Facing Hard Truths about Energy* [8] and other studies, expect significant future use of CTL as a way to lessen the impact from declining conventional oil supply.

1.1. Historical overview

CTL is an old technique, developed at the beginning of the 20th century and has recently attracted attention once more. Historically, it helped to fuel the German military during two world wars. CTL provided 92% of Germany's air fuel and over 50% of their petroleum supply in the 1940s [9]. South Africa developed CTL-technology in the 1950s during an oil blockade and CTL now plays a vital part in South Africa's national economy, providing over 30% of their fuel demand [10].

The best known CTL-process is Fischer-Tropsch (FT) synthesis, named after the inventors Franz Fischer and Hans Tropsch from the Kaiser Wilhelm Institute in the 1920s [11]. The FT-synthesis is the basis for ICL technology. Friedrich Bergius, also a German chemist, invented direct coal liquefaction (DCL) as a way to convert lignite into synthetic oil in 1913 [11]. Karrick [12] invented a low temperature carbonization process in the USA around the 1930s, as a way to produce smokeless fuel and liquids from oil shale.

CTL-technologies have steadily improved since the Second World War. Technical development has resulted in a variety of systems capable of handling a wide array of coal types. However, only a very small number of commercial enterprises based on generating liquid fuels from coal have been undertaken, most of them based on ICL-technology. The most successful is the South African company Sasol, originally created as a way to protect the country's balance of payment against the increasing dependence on foreign oil [10, 13]. A new DCL plant has recently become operational in China, possibly marking the beginning of a new era.

1.2. Aim of this study

The theory and technology behind CTL are reviewed. Understanding the fundamental aspects of coal liquefaction technologies are vital for planning and policy-making, as future CTL systems will be integrated in a much larger global energy and fuel utilization system. As a result, future CTL development will be affected by existing infrastructure and systems. In our overview, we attempt to point out some likely paths for CTL development and indicate possibilities and limitations. Based on various assumptions about the future, we will project a number of outlooks regarding dominating CTL-technology in the future.

This study also compiles various assessments of CTL conversion ratios. Furthermore, an empirical coal consumption estimate is made using Sasol, the world leading commercial CTL enterprise, as a reference case. This is compared with other estimates as a simplistic “*sense check*”, aimed to investigate how well future outlooks agree with practical experience. The derived conversion ratios are also used to estimate future coal consumption as a function of CTL-capacity.

The annual decline in existing crude oil production has been determined as 4-7 Mb/d [14]. Similar production volumes would be challenging to offset, either partially or in full, by new CTL-projects. However, we overview some CTL forecasts and discuss their potential for counteracting a decline in oil production from a global perspective. Most especially, the required coal tonnage will be discussed to determine the feasibility of a large scale CTL-industry as a peak oil mitigation strategy.

2. Basic chemistry of CTL

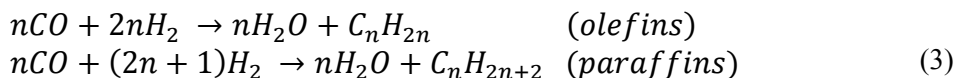
The basis for all types of CTL-syntheses is a carbon source combined with a hydrogen source, such as steam. Chemical reactions between carbon and other compounds will eventually fabricate hydrocarbon molecules of the desired length. The original Fischer-Tropsch (FT) process was described by Formula 1.



Carbon monoxide can be produced by gasification of coal or another carbon rich compound. The necessary reaction energy is applied by adding oxygen or steam (Formula 2).

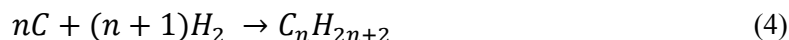


The resulting mixture of carbon monoxide and hydrogen is usually called synthesis gas (syngas). It is used to construct hydrocarbon chains of different lengths using condensation and a suitable catalyst. Generally, the FT-process yields two types of products, described by two different reactions (Formula 3).



The type of resulting products depends on the catalysts used and the reactor operating conditions. Olefin-rich products with n in the range 5-10 (naphtha) can be used for making synthetic gasoline and chemicals in high temperature FT-processes. Paraffin-rich products with n in the range of 12-19 are suitable for making synthetic diesel and waxes in low temperature FT-processes.

The Bergius-process is the basis of DCL. Splitting coal into shorter hydrocarbons, resembling ordinary crude oil is done by adding hydrogen under high pressure and temperature, thus eliminating the need for a gaseous middle stage (Formula 4).



2.1. Catalysts

Both Bergius- and FT-processes use different catalysts to aid the chemical reactions. Common catalysts are transition metals such as iron, ruthenium or cobalt. Transition metal sulphides, amorphous zeolite and similar compounds have also been utilized. In general, catalysts have a large impact on process efficiency as well as influence over the resulting products. Many catalysts are notoriously sensitive to sulphur-compounds or other substances, which requires special treatment and separation techniques to avoid catalyst poisoning.

Much research has been made on different catalysts for CTL-processes and in many ways some of the greatest chemical challenges can be found in the right choice of catalysts and the optimization of their performance. Closer discussions on catalysts used in CTL have been done by others [15-18].

2.2. Other process problems

Liquefaction can also be affected by the different properties of the coal feedstock. Different types of coal have different properties, requiring compatibility between CTL-reactor design and coal feedstock.

Hydrodynamic problems can be caused by thermal fragmentation of coal, when the coal particles are shattered into smaller grains capable of clogging gas outlets and causing other unwanted disturbances. Drying coal and reducing moisture will lower the probability of thermal fragmentation.

Caking occurs due to the plasticity of coal and causes coal particles to meld into larger cakes, leading to pressure drops and channel burning, severely reducing the performance of the CTL-reactor. Mixing high caking coals with low caking coals creates a more manageable overall caking probability.

High ash coals will call for a gasification design capable of removing large ash concentrations without loss of performance. Practical CTL-design can be found for all forms of coal [19]. Consequently, suitable designs are essential for obtaining good performance.

3. CTL technology options

Experience from many different types of coal to liquid fuel conversion techniques exists, while only some have been commercialized and proven feasible by industry. CTL-technology is an old concept that has to be fused with modern processes and machinery to be able to fulfil the economic and environmental constraints of today.

Existing technological infrastructure from conventional crude oil processing and gas liquefaction can provide synergistic effects reducing costs and necessary research. Research on synthetic fuels from non-coal feedstock exists in several places, where coal is too expensive or impractical to acquire for example. In theory, FT-synthesis can be used to create liquid fuels from very unconventional feedstock as long as hydrogen and carbon are available. For instance, carbon dioxide, carbon monoxide and other combustion exhaust have been used as feedstock in patent applications [20].

3.1. Pyrolysis

The oldest method for obtaining liquids from coal is high temperature pyrolysis. Typically, coal is heated to around 950° C in a closed container. The heat causes decomposition and the volatile matter is driven away, increasing carbon content. This is similar to the coke-making process and accompanying tar-like liquid is mostly a side product.

The process results in very low liquid yields and upgrading costs are relatively high. Coal tar is not traditionally used as a fuel in the transportation sector. However, it is used worldwide for manufacturing roofing, waterproofing and insulation products and as a raw material for various dyes, drugs and paints.

Mild temperature pyrolysis uses temperatures of 450-650 °C. Much of the volatile matter is driven off and other compounds are formed through thermal decomposition. Liquid yields are higher than for high temperature pyrolysis, but reach a maximum at 20% [21]. The main product is char, semi-coke and coke (all smokeless solid fuels). This technique has mostly been used to upgrade low-rank coals, by increasing calorific value and reducing sulphur content.

The Karrick process is a low temperature carbonization process that also yields liquids [12]. The main product is, however, semi-coke. The tar liquids produced require further refining before they can be used as a transportation fuel.

In summary, pyrolysis provides low liquid yields and has inherently low efficiency. Furthermore, the resulting liquids require further treatment before they can be used in existing vehicles. A demonstration plant for coal upgrading was built in the USA and was operational between 1992 and 1997 [21]. However, there is little possibility that this process will yield economically viable volumes of liquid fuel. Consequently, further investigation and analysis of coal pyrolysis is not undertaken.

3.2. Direct coal liquefaction (DCL)

This process is built around the Bergius-process (Formula 4), where the basic process dissolves coal at high temperature and pressure. Addition of hydrogen and a catalyst causes “*hydro-cracking*”, rupturing long carbon chains into shorter, liquid parts. The added hydrogen also improves the H/C-ratio of the product.

Liquid yields can be in excess of 70% of the dry weight coal, with overall thermal efficiencies of 60-70% [22, 23]. The resulting liquids are of much higher quality, compared to pyrolysis, and can be used unblended in power generation or other chemical processes as a synthetic crude oil (syncrude). However, further treatment is needed before they are usable as a transport fuel and refining stages are needed in the full process chain. Refining can be done directly at the CTL-facility or by sending the synthetic crude oil to a conventional refinery. A mix of many gasoline-like and diesel-like products, as well as propane, butane and other products can be recovered from the refined syncrude.

Some smaller pilot-plants and testing facilities have provided positive results. In 2002, the Shenhua Group Corporation, the largest state-owned mining company in China, was tasked with designing and constructing the world’s first DCL commercial plant in Inner Mongolia Autonomous Region [24], which recently became operational.

3.3. Indirect coal liquefaction (ICL)

This approach involves a complete breakdown of coal into other compounds by gasification. Resulting syngas is modified to obtain the required balance of hydrogen and carbon monoxide. Later, the syngas is cleaned, removing sulphur and other impurities capable of disturbing further reactions. Finally, the syngas is reacted over a catalyst to provide the desired product using FT-reactions (Formula 1).

Alteration of catalysts and reaction conditions can create a wide array of different products (Figure 1). For instance, methanol is one possible product that can be produced directly or further converted into high quality gasoline via the Mobil process in additional stages [25]. In general, there are two types of FT-synthesis, a high temperature version primarily yielding a gasoline-like fuel and a low temperature version, mainly providing a diesel-like fuel [26]. More details on FT-synthesis via ICL-technology have been discussed by others [6, 26].

Sasol in South Africa owns the only commercial-scale ICL plants currently in operation with well established and proven technology and together with a lot of operational experience [10]. In total, Sasol has over 50 years of experience of ICL and has produced over 1.5 billion barrels of synthetic oil during its existence [21]. A number of different ICL-technologies have been developed by Sasol, the oldest ones date from the 1950s and was used to late 1980s. Today, advanced technologies from the 1990s are utilized, including the Sasol Advanced Synthol High Temperature FT-synthesis and the Sasol Slurry Phase Distillate Low Temperature FT-synthesis [13].

Synthesis gas				
Heat & power generation <ul style="list-style-type: none"> • IGCC • CCS-systems 	Synthetic natural gas <ul style="list-style-type: none"> • Methane • Gas substitution 	Hydrogen <ul style="list-style-type: none"> • Hydrogenation • Hydro-cracking • Ammonia Synthesis • Urea • Fertilizers • Nitric acid • Nitrogenous compounds • Fuel-cell fuels 	Synthetic oil <ul style="list-style-type: none"> • Raw distillates • Refinery upgrading <ul style="list-style-type: none"> • Gasoline • Diesel • other fuels • Naphtha cracking <ul style="list-style-type: none"> • Ethylene • Propylene • Alpha olefins • Lube oil base stock • Speciality waxes 	Methanol & Alcohols <ul style="list-style-type: none"> • Gasoline • Diesel fuel • Ethylene • Propylene • Oxo-chemicals <ul style="list-style-type: none"> • Formaldehyde • Methyl amine • Chloromethanes • Acetic acid • DME • Fuel-cell fuels

Figure 1: Possible uses of synthesis gas from ICL. Based on [8]

3.4. Comparison of DCL and ICL

The main candidates for future CTL-technology are DCL and ICL. In essence, DCL strives to make coal liquefaction and refining as similar to ordinary crude oil processing as possible by creating a synthetic crude oil. By sidestepping the complete breakdown of coal, some efficiency can be gained and the required amount of liquefaction equipment is reduced.

Coal includes a large number of different substances in various amounts, several unwanted or even toxic. Some substances can poison catalysts or be passed on to the resulting synthetic crude oil. Ever-changing environmental regulations may force adjustment in the DCL process, requiring it to meet new regulatory mandates, just as crude oil processing has to be overhauled when new environmental protocols are introduced.

In comparison, ICL uses a “*designer fuel strategy*”. A set of criteria for the desired fuel are set up and pursued, using products that can be made in FT synthesis. Many of the various processes will yield hydrocarbon fuels superior to conventional oil derived-products. Eliminating inherent noxious materials in coals is not just an option; it is a must to protect the synthesis reactor catalysts. Far from all ICL-derived products are better than their petroleum-derived counterparts when it comes to energy content or other characteristics. However, all ICL fuels are inherently clean and virtually free from nitrogen, sulphur and aromatics, generally giving lower emissions when combusted [27-28].

Comprehensive comparison between DCL and ICL has been performed by other studies [22, 29-30]. In general, it is not easy to compare them directly, as DCL yields unrefined syncrude while ICL usually results in final products. ICL has a long history of commercial performance, while DCL has not. Consequently, the economic behaviour of a DCL-facility has only been estimated while ICL-analyses can rely on actual experience.

3.5. System efficiency

It is widely believed that DCL is more energy-efficient for making liquid fuels than ICL, justified by the simplicity of DCL's partial breakdown compared to the complete coal reconstruction used in ICL. Several other features, like environmental impact, flexibility and reliability of process, should also be taken into account for a more complete systematic view of the technology options.

The estimated overall efficiency of the DCL-process is 73% [31]. Other groups have estimated the thermal efficiency between 60-70% [21, 30]. SHELL estimated the theoretical maximum thermal efficiency of ICL to 60% [32, 33]. The overall efficiency of ICL (making methanol or di-methyl-ether) is 58.3% and 55.1% [30]. Tijmensen et al. [34] give an overall energy efficiency of ICL of about 33-50% using various biomass-blends. Typical overall efficiencies for ICL are around 50%. Detailed well-to-wheel analysis of energy flows for ICL diesel has been done by van Vliet et al. [35]

Caution must be exercised in making efficiency comparisons, because DCL efficiencies are usually for making unrefined syncrude, which requires more refining before utilization, and ICL efficiencies are often for making final products. If the refining of DCL products is taken into account, some ICL-derived fuels can be produced with higher final end-use efficiency than their DCL-counterparts [30]. It is also sometimes unclear, whether the extra energy needed for process heat, hydrogen production, and process power is included in the analyses, making efficiency comparisons even more delicate.

3.6. Process requirements

CTL requires more than coal to produce usable fuel. Heat, energy, catalysts and other chemicals are necessary to maintain functioning production. Water is a vital part of the process, either as hot steam or as a feedstock for hydrogen production. Water for cooling and the boiler must also be provided, and for a larger plant the amount of water consumed can be very large indeed. Water consumption is approximately equivalent for DCL and ICL. The water consumption for a 50 000 b/d facility with American coal would be in the region of 40 000 to 50 000 cubic meters per day [36]. Therefore, water availability is an essential factor to be considered during placement of CTL-facilities. Grinding of coal and mixing it with water are another process steps that will consume energy and water.

The DCL-system requires hydrogen to crack the coal into syncrude. This hydrogen is the most costly part of the DCL-system. High efficiency designs often acquire hydrogen from steam reforming of natural gas, but DCL-systems can also be modified to produce hydrogen from coal by so-called water-gas-shift-reactions. Necessary process heat for obtaining syncrude is usually provided by coal.

ICL utilizes huge amounts of steam to break down coal into syngas, requiring substantial energy input. Treatment and purification of the syngas is necessary for protecting the catalysts. This usually involves gas cooling and different separation stages, all necessitating additional energy. However, some of this energy can be produced from sulphur and other compounds separated out from the syngas in the recycling processes. Some ICL-configurations actually generate more electricity than they consume by converting excess heat into electricity [30].

Finally, DCL or ICL refining and product upgrading requires additional heat, energy and hydrogen. This extra energy requirement is up to 10% of the energy content of the syncrude and can also be provided by coal. Additional energy must be also provided to reduce GHG and other emissions, if environmental concerns are to be taken in to account.

3.7. System costs

The capital cost of a facility is usually the largest cost, with operation/management costs coming second. The coal costs are usually around 10-20%, varying due to local supply, quality etc.

ICL-plants in the US provide break-even crude oil-prices in the range of 25 to 40 US\$ per barrel, dependent upon environmental measures (such as CO₂-capture) undertaken [30]. Older and more modest studies claim break-even crude oil-prices around US\$35 per barrel [37]. Liquid fuel costs for a Chinese DCL facility have been estimated at around US\$24/barrel [38]. The development of coal prices and the economic situation in recent years has influenced break-even prices. The most recent study of CTL costs available, suggests a break-even price of 48-75 US\$/barrel [39]. Expected costs for ICL and DCL do not seem to differ much and can be assumed as virtually identical. Table 1 gives some estimated costs for construction in the USA of three different capacities.

The DCL-facility in Inner Mongolia in China has an overall cost in the order of US\$4 billion [41]. Sasol and China were planning two additional 80 000 b/d ICL-plants in Shaanxi (650 km west from Beijing) and Ningxia (1000 km west from Beijing), with US\$5 billion as estimated capital cost per plant [42]. Currently, only two projects are approved and the Chinese National Development and Reform Commission suspended all other CTL-projects in September 2008 [41].

Table 1: *Estimated costs of CTL-industries in the US. The costs for emission reductions are not included, nor are government grants and funding. Source: [40]*

	One 20 000 b/d plant	One 80 000 b/d plant	One Mb/d Industry
Capital investment	\$1.5-\$4 billions	\$6-\$24 billions	\$60-\$160 billions

3.8. Emission properties

The low sulphur content of CTL products compared to petroleum-derived fuels is a common trait for both DCL and ICL, which comes from the necessity to protect catalysts from poisoning. Aside from this similarity, emissions and combustion characteristics of DCL and ICL fuels differ. Comprehensive analysis of emission characteristics of synthetic and conventional fuels have been compared by others [43, 44].

DCL products are typically rich in polycyclic aromatics and heteroatoms [45-48], while ICL has lower aromatics content. High temperature FT-synthesis yields branched products and contains aromatics, whilst these are virtually absent in low temperature FT-synthesis [49]. Recently, environmental regulation trends have moved towards limiting the aromatic content in transportation fuels [30], giving the advantage to ICL-fuels.

Toxic trace metals and inorganic compounds, such as cadmium, selenium, arsenic, lead and mercury, can be passed on to the final fuel product in both DCL and ICL-processes. In ICL-systems, removal of mercury and other metals is generally trivial

and inexpensive [30]. For DCL, however, it will be more complicated and more costly, but not impossible.

Cetane and octane numbers also differ, resulting from the chemical properties of the various products. ICL gives diesel of a high quality, which is mostly due to the dominance of straight-chain products. However, low densities are a problem for ICL products, but this can be mitigated by blending [48]. General differences of final products are summarized in Table 2. Typical properties for specific ICL-distillates can be found in Leckel [48].

Table 2: Typical properties of DCL and ICL final products. Modified from: [49]

	DCL	ICL
Distillable product mix	65% diesel, 35% naphtha	80% diesel, 20% naphtha
Diesel cetane number	42-47	70-75
Diesel sulphur content	<5 ppm	<1 ppm
Diesel aromatics	4.8%	<4%
Diesel specific gravity	0.865	0.780
Naphtha octane number (RON)	>100	45-75
Naphtha sulphur content	<0.5 ppm	Nil
Naphtha aromatics	5%	2%
Naphtha specific gravity	0.764	0.673

Both DCL and ICL fuels emit large amounts of carbon dioxide compared to ordinary petroleum-derived fuels. However, there are methods for reducing or even neutralizing emissions without raising production costs drastically. Substantial differences exist between DCL and ICL technologies with regard to the potential and cost of greenhouse gas emission mitigation [30].

Vallentin [39] concludes that DCL generates about 90% more CO₂ than conventional fuel on a well-to-wheel basis. This is in agreement with other studies, but if reduction measures are implemented, the emissions could be reduced to no more than 30% extra compared to conventional petroleum fuels [30].

ICL-technology generates approximately 80-110% more CO₂ emissions compared to conventional fuels, if the CO₂ is vented [30, 39]. However, there are ICL-system configurations where H₂S+CO₂ co-capture/co-storage can reduce emissions [30]. Well-to-wheel analysis has shown that even with CCS, CTL production chain emissions are higher than for petroleum-derived fuels, mostly due to emissions from mining [35].

In summary, CTL fuels can improve emission characteristics and reduce transportation emissions of sulphur, aromatics, NO_x and particles compared to conventional fuels [43]. However, there does not seem to be much potential for CO₂ emission reductions if the full supply chain is analysed for either DCL or ICL.

3.9. Infrastructure

Industrialized countries have generally discarded DCL technologies for making synthetic fuels and focused more on ICL or GTL [30]. Consequently, DCL-systems generally require new technology, with the important exception of the H₂-production [30]. Scaling up current DCL plants to a globally significant fuel industry is a daunting task, but not impossible if proper investments and developments are pursued.

In comparison, commercialization of ICL-technology began in 1934 [48], and have been continuously redesigned and developed ever since. ICL-systems only require a relatively small amount of new technology as most components are already established. Similarities exist with GTL-technologies and the chemical industries based on syngas derived from gasification [48], making future ICL-developments easier. This common technical ground and experience provides a solid base for expansion into new ICL-projects. Realizing those and scaling up existing capacity could still prove to be a significant challenge.

In conclusion, the existing support infrastructure for ICL seems stronger than for DCL. Worldwide gasification capacity indicates that supporting gasification solutions are common for producing chemicals, but FT-fuel is increasing its share [50]. However, DCL can provide important new feedstock for refineries, as conventional crude oil begins to become scarce in the wake of peak oil.

3.10. Transition properties

CTL-systems must also be able to cope with an uncertain future. Stricter environmental regulations, increased demand for liquid fuels, energy and electricity together with energy security questions are important factors that can greatly impact any technology. Williams and Larson [30] has attributed to DCL poor prospects for making high quality diesel, which makes it an unsuitable candidate for energy efficient end-use technologies. Furthermore, fuel flexibility, such as being able to blend the coal feedstock with biomass, tar sand or waste material, is also an advantage worth considering. FT-synthesis also generates naphtha as a by-product, which can be a valuable feedstock for the chemical industries and allowing for further business opportunities [35].

One possible future outcome is the so-called “*hydrogen society*”, where hydrocarbon fuels are phased out and replaced with hydrogen fuel cells. If the hydrogen scenario is taken into account, major differences can be seen. DCL consumes hydrogen during cracking stage and it is impossible to obtain pure hydrogen in the DCL-process. In comparison, ICL can produce hydrogen and the modifications needed to switch production from hydrocarbons to hydrogen are relatively minor [35].

Methanol, ethanol or other similar fuels are other alternative fuel possibilities with acceptable efficiencies [51], resulting in other transitions. Methanol, DME and many other fuels can more easily be produced by ICL than DCL. However, DCLs similarity to conventional petroleum processing should not be overlooked as it can provide a means mitigate shortages in conventional crude oil without having to construct entirely new systems for new transportation fuels. Syncrude from DCL does offer the possibility of prolonging the life and usability of current infrastructure as conventional petroleum supply decreases.

Another possible future is based on electrification and the corresponding transition will be from hydrocarbon fuels to electricity. Anthropogenic climate change mitigation strategies requests reductions or eliminations of CO₂ emissions, which favours CCS-technology. The CCS-capable power plant design known as Integrated Gasification Combine Cycle (IGCC) has many similarities to ICL-technology and is one of the flagships of future clean coal technology [52]. In comparison, DCL lacks any strong connections to future coal-fired power generation. The IGCC-concept combined with ICL can generate various fuels, chemical products, heat and electricity at the same time

and this would make it possible for coal to play a major role in a climate and otherwise environmentally-constrained world [30].

4. Summary and future outlook

The two candidates for CTL are DCL- and ICL-technologies; the fraction of liquids obtained from pyrolysis is simply too small and of too low quality. Energy-efficiency differences exist, but if end-use is taken into account these differences will decrease and become relatively minor. Fundamental characteristics do not favour any of the approaches, and feasibility is largely dependent on the future society and energy system that CTL should be integrated into.

ICL-fuels, especially ICL-diesel, are generally cleaner and can outperform many DCL-fuels and conventional fuels in terms of emissions. It is also easier to implement CCS and GHG emission reduction in ICL-plants compared to DCL. In essence, ICL-technology will generally put the coal energy system on a track more dedicated to environmental concern, while DCL does not offer this possibility to the same extent.

ICL offers more variable systems, capable of producing many more products than DCL-systems, especially in polygeneration designs [30]. The existing infrastructure supports further ICL-developments to a much larger extent than DCL. Furthermore, ICL is capable of dealing with more future outcomes and has generally better transition properties. In comparison, DCL is a less flexible transition technology with stronger ties to the present conventional fuel system layout. However, this can also be an advantage as DCL can be used to maintain existing infrastructure as conventional crude oil becomes increasingly scarce.

There is some interest in CTL-technology around the world, especially in China. However, all but two CTL-projects were recently suspended [41]. The objective was initially to produce 10 Mt annually of crude oil equivalents by 2010 from domestic coal and CTL-technology and total output was expected to rise to 30 million tons of crude oil equivalents by 2020, approximately 16% of Chinas present crude oil production [53]. Currently, China is reconsidering this plan and the future path remains uncertain.

The Alliance for Synthetic Fuels in Europe (ASFE) is a collaboration of DaimlerChrysler, Renault, Royal Dutch Shell, Sasol-Chevron, Volkswagen and Toyota, trying to promote GTL, BTL and CTL-technology development in Europe. ASFE [54] sees synthetic fuels as a vital part of developing a less polluting vehicle park together with creating energy security that enables transportation in to the future. However, the actual number of CTL-projects in Europe is low. Mostly small scale or laboratory scale projects in liquefaction chemistry.

Recent interest in CTL-technology has grown as a reaction to increased American dependence on imported oil. Several major American coal companies have expressed interest in CTL-technology or created blueprints and studies for CTL-plants [55, 56]. The US military has expressed concern over the dependence on foreign oil and studied alternatives derived from CTL or possibly BTL [57, 58]. Feasibility studies and evaluation programs are being pursued, but no full scale program has yet been implemented. Uncertainty about the cost and performance of CTL plants, uncertainty about the future course of the oil price and CO₂ emission properties are three major obstacles for future development [48].

5. Coal consumption of CTL

The consumed amount of coal in CTL is often overlooked or just briefly discussed in many studies. Conceptually, coal is a finite resource and this puts limitations to the amount of fuels that can be produced by liquefying coal. Practical details regarding coal supply, such as accessibility, transportation and production will impact CTL feasibility.

Many estimates of coal consumption by CTL have been performed in the literature. Couch [22] and Malhutra [59] state yields of approximately 3 barrels of unrefined syncrude per ton of bituminous coal for DCL, with less efficiency for low rank coal. The Monash Energy CTL project aims to produce liquid fuels, using 1.2 ton lignite per barrel [60]. Milici [61] gives conversion ratios of 1.3-1.8 barrels per ton bituminous coal, also mentioning lower yields for lower coal ranks. National Petroleum Council [8] has compiled other American yields and gives conversion rates ranging from 1-2 barrels/ton of coal. However, liquid yield comparisons are tricky, as yield is dependent on the chosen technical system, the coal type used, system borders and many other factors. Despite differences in methodologies, all estimates of CTL-coal consumption end up at approximately the same figures.

Sasol can be used to establish an empirical estimate of the coal consumption of CTL, since they are the world's leading CTL-producer. The Secunda site consists of two CTL plants with a combined capacity of 150 000 b/d and “*more than 40 million tons of coal per year*” is consumed [10]. In 2003, the South African synthetic fuel industry consumed 24% of all coal produced in South Africa [62], since Sasol's CTL facilities are the only producer of synthetic fuels in South Africa, this must also reflect their coal consumption (Figure 2). South African coal production was 238 Mt that year [63], and consequently, the coal consumption of the CTL sector was 57 Mt. All South African coal is classified as bituminous [63].

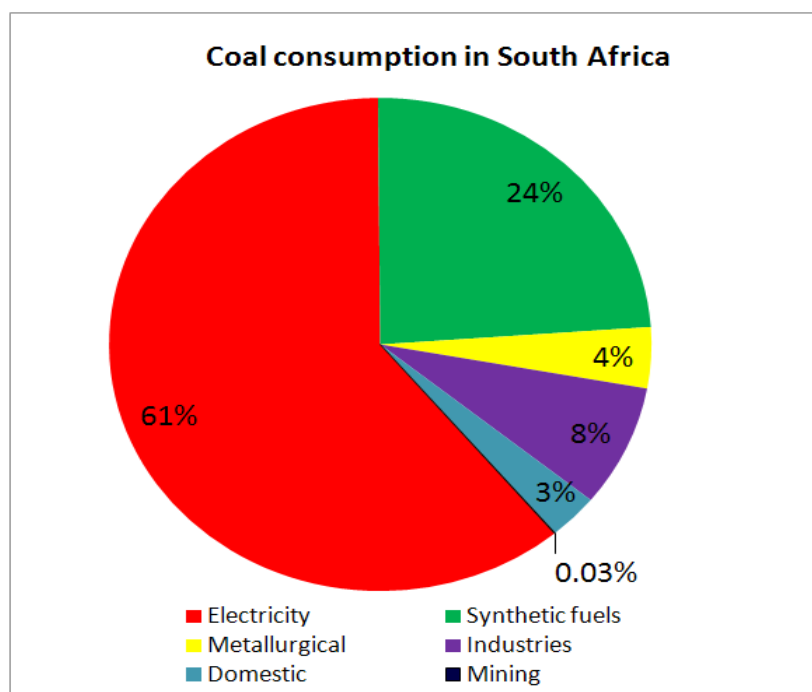


Figure 2: South African coal consumption in 2003 divided into parts.

Using 40 Mt as a lower limit and 57 Mt as an upper limit for Sasol coal consumption, one can compute that one barrel of synthetic fuel consumes 0.73-1.04 tons of bituminous coal, i.e. a conversion ratio of 1-1.4 barrels/ton coal. This agrees with the estimates of other studies, but tends to be in the lower range. Differences between technical and Sasol-derived estimates reflect disparities between theory and practice. Suboptimal conditions, losses, leaks and similar are unavoidable parts of reality, especially when performed on a large industrial scale. Including coal quality issues, refining and further treatment, also makes it reasonable to expect lower yields. Hence, the empirical Sasol conversion ratios are deemed reasonable. Similar conversion efficiencies are also realistic for future large scale CTL-industries, especially since ICL is the more likely future CTL-technology development path.

5.1. Coal consumption in various CTL-forecasts

Any CTL production forecast must be related to coal consumption. Some CTL forecasts do not mention corresponding coal consumption, while others present estimated consumption volumes. We will use the Sasol-analogy and compare with other studies as a simple “*sense check*”, to investigate how well estimates agree with practical experience.

Outlooks that present CTL as a mitigation or even a solution to the problem of declining conventional oil supply will be closely inspected. For instance, the National Petroleum Council [8] presents a number of production forecasts, where the main message is that peak oil can be partially solved by substantial CTL-development in the USA. We intend to quantify what required coal volumes are needed to offset decline in existing crude oil production. This sheds some new light on the discussion of future CTL potentials and requirements. Furthermore, it is also useful information for policy makers when planning for the future, as the achievability of replacing oil with derivatives of another finite resource on a large scale can be disputed if sustainable development is the ambition.

Hirsch et al. [7] assumed annual future construction of 5 CTL-plants, each with a capacity of 100 000 b/d. No coal consumption figures or conversion ratios are given. Using Sasol experience, corresponding increase of annual coal consumption is 133-190 Mt. This is equivalent to ~2.5% the world production of coal for 2007 [64]. This is a significant increase, but probably doable if proper investments are forthcoming.

The National Coal Council [64], also mentioned in [8], foresees a production of 2.7 Mb/d by 2025 and presents 430 Mt as the corresponding coal consumption, which equals a conversion ratio of 2.3 barrels/ton coal. Using Sasol experience, coal requirement would be 700-1000 Mt, almost twice as much as the National Coal Council assumes. In conclusion, the National Coal Council's estimate is optimistic when compared to actual experience, and will probably require a dramatic increase in process efficiency and improved technology or use of high quality coals with excellent liquefaction properties.

The National Petroleum Council [8] also present a CTL forecast of 5.5 Mb/d by 2030 with corresponding coal consumption of 1439 Mt, originally performed by the Southern States Energy Board [65]. The conversion ratio is 1.4 barrels/ton, in agreement with Sasol experience, but it should be noted that the consumption figure from Southern States Energy Board [65] is leaning toward the optimistic side. Using the Sasol model,

estimated coal consumption becomes 1466-2100 Mt, which is more than the entire current coal production of the US [63]. In summary, we can conclude that this CTL-forecast is entirely unrealistic, since it is not feasible to divert all coal to new CTL facilities, or to double the US coal output in 20 years [66, 67].

The Annual Energy Outlook 2007 (AEO2007) Reference Scenario features a CTL production of 2.4 Mb/d globally and 0.8 Mb/d in the USA [68]. No coal consumption figures are provided for global CTL production, but the USA CTL industry is estimated to consume 112 Mt, which equals conversion ratio of 2.6 barrels/ton coal. It should also be noted that coal consumption for CTL has decreased 50% in AEO2007 compared to AEO2006. Applying the Sasol model, estimated annual coal consumption would be 213-304 Mt, which is twice as much as the EIA assumes. It should be remembered that a significant share of American coal is subbituminous coal, i.e. more low-ranking than the South African coals that Sasol utilize. In essence, the EIA must be assuming that future American CTL-industry will be twice as efficient as Sasol. Given the fact that Sasol is a world leading CTL-enterprise, the EIA assumption seems very optimistic and only vaguely justifiable.

The Annual Energy Outlook 2009 (AEO2009) has reduced US CTL production in the Reference Scenario to only 0.26 Mb/d by 2030 [69]. The coal consumption presented is only 24.6 Mt, which would equal a conversion ratio of 2.9 barrels/ton. Corresponding coal usage would be 68-95 Mt, using the Sasol model. Although the expected CTL capacity has been reduced, the conversion ratio has increased compared to earlier estimates and is even further away from the real numbers. We can only conclude that the conversion ratios used by EIA seem extremely high and lack any real counterpart. The EIA seems to be using purely theoretical values, rather than sound numbers derived from practical experience.

AEO2007 [68] foresees a global CTL-production of 2.4 Mb/d in the reference case, and this would annually consume 640-912 Mt of coal. This is equivalent to around 12% of the current world production of coal. AEO2009 [69] has lowered the global CTL/GTL-production to only 1.6 Mb/d, without showing individual contributions to this figure. The reduction is justified by concern for CO₂ emissions. The global CTL-production in AEO2009 would require something in the range of 400-500 Mt coal annually, using the Sasol model.

Annual decline in existing crude oil production is around 4-8%, equivalent to an annual production decrease of 3-7 Mb/d [14]. Such massive volumes are theoretically possible to produce, but would require astronomical investments regardless of the chosen technology. Related coal usage would be 782-2555 Mt, using the Sasol model. Such vast volumes of coal cannot be realistically liquefied just to offset a single years decline in existing world oil production. Consequently, it must be asked whether the investment and the coal itself can be used more efficiently in ways other than CTL and if other mitigation strategies should be preferred.

These findings also have repercussions for future climate policies, as several of the Intergovernmental Panel on Climate Change (IPCC) emission scenarios [70], used for projections of temperature increases and anthropogenic emissions, depict significant contribution from CTL in the future. In the dynamic technology scenario group (A1T), liquid fuels from coal are assumed to be readily available at less than US\$30/barrel with prices falling even further. The environmentally B2 scenario family sees CTL production

costs decline from US\$43/barrel to US\$16/barrel. Details on conversion ratios are not given, nor related coal consumption volumes.

As an example, the B2 Message scenario gives a global CTL production of 32 Mb/d (71.8 EJ) in 2100, which is more than the 23.2 Mb/d (52 EJ) derived from oil production in the same year. Equivalent coal consumption would be 8342-11680 Mt, using Sasol conversion ratios, and still very extensive even if better efficiencies were reached in the future. The world coal production is given as 300 EJ in 2100, meaning that 24% goes to CTL. Can so much coal be really produced and diverted to CTL in a realistic case or should some emission scenarios be revised? Either way, more details should be shown regarding assumed conversion ratios, technologies and other factors.

In summary, we find that many forecasts or scenarios do not discuss CTL coal consumption or conversion ratios in any detail. In some cases, actual numbers are given but they are often very optimistic compared to practical experience or peer-viewed literature. Our “*sense check*” seems to indicate that several CTL outlooks have poor agreement with practical experience and empirical data. Scenarios and guidelines for future planning should not be use such vaguely justified numbers or assumed conversion ratios.

5.2 Coal consumption summary

Using the empirical Sasol estimate and estimates found in the literature, it is possible to establish four different conversion ratios. We have chosen to set the low conversion ratio at 1 barrel/ton, the mean value at 1.5 barrels/ton and the high estimate at 2 barrels/ton. This is in agreement with both Sasol empirical data and other studies. The technical CTL-conversion ratio is assumed at 3 barrels/ton coal, based on Couch [22] and Malhotra [59]. The results are summarized in Table 3 and 4. The approximate coal consumption for an arbitrary CTL-capacity is shown in Figure 3.

Table 3: Summary of forecasted CTL capacities and their estimated coal consumption

Scenario	Capacity	Ann. consumption [Mt]			
	[Mb/d]	Low	Mean	High	Tech.
Sasol Synfuel	0.15	54.8	36.5	27.4	18.3
Hirsch	0.50	182.5	121.7	91.3	60.8
NCC 2025	2.60	949.0	632.7	474.5	316.3
SSEB 2025	5.50	2007.5	1338.3	1003.8	669.2
EIA US Ref 2007	0.80	292.0	194.7	146.0	97.3
EIA US High 2007	1.70	620.5	413.7	310.3	206.8
EIA Global Ref 2007	2.40	876.0	584.0	438.0	292.0
EIA US Ref 2009	0.26	94.9	63.3	47.5	31.6
4% Decline	3.00	1095.0	730.0	547.5	365.0
8% Decline	7.00	2555.0	1703.3	1277.5	851.7

Table 4: Summary of forecasted CTL capacities and their estimated coal consumption in 4 cases as shares of world coal production in 2007

Scenario	Capacity [Mb/d]	Share of world coal production 2007			
		Low	Mean	High	Tech.
Sasol Synfuel	0.15	0.86%	0.57%	0.43%	0.29%
Hirsch	0.50	2.85%	1.90%	1.43%	0.95%
NCC 2025	2.60	14.84%	9.89%	7.42%	4.95%
SSEB 2025	5.50	31.39%	20.93%	15.69%	10.46%
EIA US Ref 2007	0.80	4.57%	3.04%	2.28%	1.52%
EIA US High 2007	1.70	9.70%	6.47%	4.85%	3.23%
EIA Global Ref 2007	2.40	13.70%	9.13%	6.85%	4.57%
EIA US Ref 2009	0.20	1.48%	0.99%	0.74%	0.49%
4% Decline	3.00	17.12%	11.41%	8.56%	5.71%
8% Decline	7.00	39.95%	26.63%	19.97%	13.32%

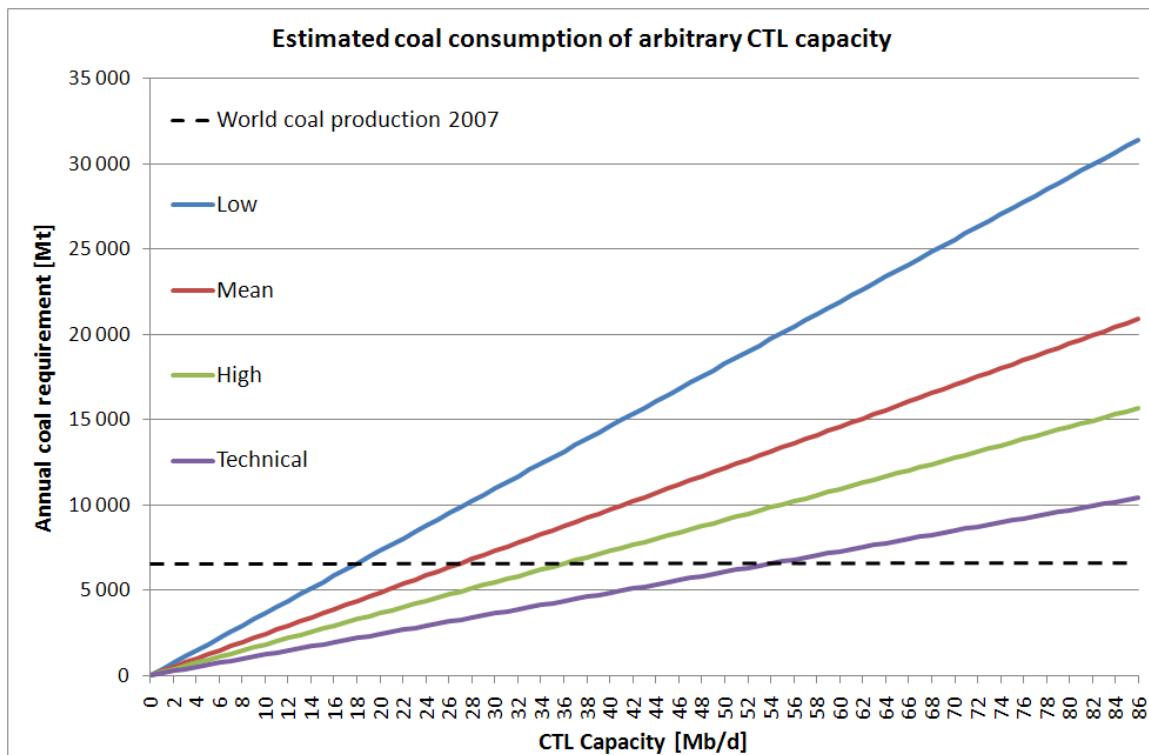


Figure 3: Estimated coal consumption as a function of CTL capacity for 4 different conversion ratios ranging from 1-3 barrels/ton. Current world coal production can be converted to 17-54 Mb/d, depending on assumed conversion ratio. However, practical experience indicates that the low or mean cases are the most realistic.

Conversion ratios are of significant importance as current world coal production can give everything from 17-53 Mb/d in equivalent CTL-capacity (Figure 3). However, empirical experience from Sasol indicates that realistic conversion ratios are in the order of 1-1.5 barrels/ton coal. This puts a strict limitation on future CTL capacity imposed by

future coal production volumes, regardless of other factors such as economics, emissions or environmental concern.

Future CTL production will ultimately be limited by coal production and the share that can be diverted to liquefaction. How large this share can become is dependent on alternatives and priorities, but assuming that 10% of world coal production can be diverted to CTL, the contribution to liquid fuels supply will be limited to only a few Mb/d (Figure 3). This prevents CTL from becoming a viable mitigation plan for liquid fuel shortages on a global scale.

However, it is still possible for individual nations to derive significant shares of their fuel supply from CTL, but those nations must also have access to equally significant coal production capacities. The worlds coal reserves are unevenly distributed with the vast majority located in a small number of countries [63]. Combined with the fact that most coal is consumed in the same country as it was produced due to unfavourable long distance transportation properties, the number of countries that can sustain significant CTL projects in the future becomes quite limited.

6. Conclusions

ICL seems to be the more likely option for future CTL-projects, based on its higher flexibility, better environmental capabilities and stronger supporting experience and infrastructure. Furthermore, the fuel properties seem to benefit ICL compared to DCL, especially if end-use efficiencies are considered instead of just process efficiencies. Estimated costs between the two system types seem similar and do not favour either approach. However, more meticulous economic studies are required for a comprehensive discussion but the lack of commercial DCL experience is problematic.

Estimates for coal consumption of coal liquefaction have been presented in many studies [8, 22, 59, 61]. A pragmatic estimate can be derived from the Sasol experience, and used as a complementary approximation in addition to more purely technical assessments. This estimate is further justified by the likelihood of ICL as the primary candidate for future large scale CTL-industries. The differences between coal consumption estimated from Sasol experience and other assessments are small. Generally, CTL conversion ratios are in the order of 1-2 barrels/ton coal.

Comparing empirical coal consumption estimates and conversion ratios with various CTL forecasts gives a reasonable agreement, even though EIA [68] and SSEB [65] show significant optimism without more than vague justifications. In general, many future CTL scenarios assume conversion ratios much higher than Sasol, thus resulting in significantly lower coal consumption. This bias might be a case of questionable optimism or perhaps even a result of wishful thinking. Another possible explanation is that certain parts of the process, for instance heating process water and producing process heat, have been omitted.

In our compilation and analysis, we find that the coal consumption is a major factor for CTL feasibility. Significant CTL production requires equally significant coal production and resources. We anticipate that only a few countries or regions can realistically develop a large scale CTL industry. Effectively, CTL will be limited to the dominating coal reserve holders that can divert shares of their production to liquefaction.

The US has the world's largest coal reserves and has been subjected to many CTL feasibility studies and projects. In 1980, Perry [71] pointed out that the construction of a synthetic fuels industry will be very costly and will provide only a small amount of increased energy independence. This situation has obviously not changed as Couch [22] states that replacing only 10% of the US transport fuel consumption with CTL would require over US\$70 billion in capital investments and about a 250 Mt of annual coal production increase. Achieving required increases in coal production has been deemed questionable by other studies [66, 67]. Correspondingly, Milici [61] concluded that the US coal industry only could handle liquefaction of 54-64 Mt coal annually without premature depletion of the coal reserves, and states that attempts to replace all oil imports would deplete the national coal reserves by 2100. The resulting volumes of synthetic fuels are insignificant compared to the present and expected demand.

World oil production currently stands at more than 80 Mb/d [63]. The total cost for replacing a significant amount of the world's oil production by CTL would be astronomical, regardless of the chosen system approach. Necessary investments for a large CTL industry are evidently colossal, but the greatest issue lies perhaps in coal consumption. Coal will account for a large part of the costs, and with the required volumes being vast, accompanying changes in coal price and additional costs of increasing coal feedstock production will greatly affect the future economics of CTL. This is a topic that deserves more attention in future studies.

In addition, the social and environmental impacts of large scale development of CTL must be considered. The political challenge of becoming very reliant on such a carbon dioxide-intensive fuel as coal is a major obstacle for many countries where greenhouse gas emissions are an important issue. Even if CCS and/or low emission CTL-technologies are implemented, the vast required coal amounts will create serious environmental impact due to mining. Obtaining public acceptance, and later political acceptance, for CTL might become challenging because of its unavoidable environmental impact.

In order to offset decline in existing oil production for just one year, around 10-40% of the world coal production is required (Table 4). Clearly, this cannot be regarded as feasible in any realistic case. Even if technical efficiencies were achieved, significant shares of world coal would disappear into CTL-plants for a relatively modest contribution to world oil supply. If a 10% share of world coal production could be diverted, it would limit the CTL-production to only a few Mb/d at most. Consequently, it is unrealistic to claim that CTL provides a feasible solution to liquid fuels shortages created by peak oil. For the most part, it can only be a minor contributor and must be combined with other strategies.

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Nomenclature

BTL	= biomass-to-liquids
CTL	= coal-to-liquids
DCL	= direct coal liquefaction
FT	= Fischer-Tropsch
GTL	= gas-to-liquids
ICL	= indirect coal liquefaction
b/d	= barrels per day

References

- [1] International Energy Agency, World Energy Outlook 2008, see also: <http://www.worldenergyoutlook.org/> (accessed 2009-05-20)
- [2] Campbell, C., Laherrere, J., The End of Cheap Oil, *Scientific American* 1998, March issue
- [3] Aleklett, K., Campbell, C., The Peak and Decline of World Oil and Gas Production, *Minerals and Energy - Raw Materials Report* 2003, 18(1): 5-20, DOI: 10.1080/14041040310008374
- [4] Meng, Q.Y., Bentley, R., Global oil peaking: Responding to the case for 'abundant supplies of oil', *Energy* 2008, 33(8): 1179-1184, DOI: 10.1016/j.energy.2008.04.001
- [5] Feng, L., Junchen, L., Pang, X., China's oil reserve forecast and analysis based on peak oil models, *Energy Policy* 2008, 36(11): 4149-4153, DOI:10.1016/j.enpol.2008.07.037
- [6] Bridgwater, A.V., Anders, M., Production costs of liquid fuels by indirect coal liquefaction, *International Journal of Energy Research* 1994, 18(2): 97-108, DOI: 10.1002/er.4440180207
- [7] Hirsch, H.L., Bezdek, R., Wendling, R., Peaking of World Oil Production: Impacts, Mitigation, & Risk Management. February 2005. Report to US Department of Energy. See also: http://www.netl.doe.gov/publications/others/pdf/Oil_Peaking_NETL.pdf (accessed 2009-05-20)
- [8] National Petroleum Council, Facing the Hard Truths about Energy and supplementary material: Topic Paper #18 – Coal to Liquids and Gas, July 2007. See also: <http://www.npchar truthsreport.org/> (accessed 2009-05-20)
- [9] US Department of Energy, Early days in coal research, see also: http://fossil.energy.gov/aboutus/history/syntheticfuels_history.html (accessed 2009-05-20)
- [10] Sasol, Unlocking the potential wealth of coal, information brochure, see also: http://www.sasol.com/sasol_internet/downloads/CTL_Brochure_1125921891488.pdf (accessed 2009-05-20)
- [11] Davis, B.H., Occelli, M.L., Fischer-Tropsch Synthesis, Catalysts and Catalysis, Elsevier, 2006, 420 p.
- [12] Fanning, L.M., Our Oil Resources, McGraw-Hill: New York, 1950, 344 p
- [13] Collings, J., Mind over Matter - The Sasol Story: A half-century of technological innovation, 2002, see also: http://sasol.investoreports.com/sasol_mm_2006/index.php (accessed 2009-01-12)
- [14] Höök, M., Hirsch, R., Aleklett, K., Giant oil field decline rates and their influence on world oil production, *Energy Policy* 2009, 37(6): 2262-2272, DOI: 10.1016/j.enpol.2009.02.020
- [15] Yang, J., Sun, Y., Tang, Y., Liu, Y., Wang, H., Tian, L., Wang, H., Zhang, Z., Xiang, H., Li, H., Effect of magnesium promoter on iron-based catalyst for Fischer-Tropsch synthesis, *Journal of Molecular Catalysis A: Chemical* 2006; 245(1-2): 26-36, DOI:10.1016/j.molcata.2005.08.051
- [16] Duvenhage, D., Coville, N.J., Deactivation of a precipitated iron Fischer-Tropsch catalyst — a pilot plant study, *Applied Catalysis A: General* 2006; 298: 211-216, DOI: 10.1016/j.apcata.2005.10.009
- [17] Longwell, J.P., Rubin, E.S., Wilson, J., Coal: Energy for the future, *Progress in Energy and Combustion Science* 1995; 21(4): 269-360, DOI: 10.1016/0360-1285(95)00007-0
- [18] Bacaud, R., Jamond, M., Diack, M., Gruber, R., Development and evaluation of iron based catalysts for the hydroliquefaction of coal, *International Journal of Energy Research* 1994, 18(2): 167-176, DOI: 10.1002/er.4440180214
- [19] Collot, A.G., Matching Gasification technologies to coal properties, *International Journal of Coal Geology* 2006; 65(3-4): 191-212, DOI: 10.1016/j.coal.2005.05.003
- [20] Fuelcor, patent description, 2006, see also: <http://www.fuelcor.com> (accessed 2009-05-20)
- [21] World Coal Institute, Coal: Liquid Fuels, report from 2006, see also: http://www.worldcoal.org/assets_cm/files/PDF/wci_coal_liquid_fuels.pdf (accessed 2009-05-20)
- [22] Couch, G.R., Coal to Liquids, IEA Clean Coal Centre, publication CCC/132, 2008, see also: <http://www.coalonline.info/site/coalonline/content/browser/81994/Coal-to-liquids>

- [23] Benito, A., Cebolla, V., Fernandez, I., Martinez, M.T., Miranda, J.L., Oelert, H., Prado, I.G., Transport fuels from two-stage coal liquefaction, *International Journal of Energy Research* 1994, 18(2): 257-265, DOI: 10.1002/er.4440180225
- [24] Fletcher, J.J., Sun, Q., Bajura, R.A., Zhang, Y., Ren, X., Coal to Clean Fuel – the Shenhua investment in Direct Coal Liquefaction, presentation at the third U.S.-China Clean Energy Conference, 18-19 October 2004, Morgantown, USA see also: <http://www.nrcce.wvu.edu/conferences/2004/China/> (accessed 2009-05-20)
- [25] Wise, J., Silvestri, J., Mobil process for the conversion of methanol to gasoline, paper presented at the Third International Conference on Coal Gasification and Liquefaction, University of Pittsburgh, Pittsburgh, Pennsylvania, 1976, 15 pages
- [26] Dry, M., The Fischer–Tropsch process: 1950–2000, *Catalysis Today* 2002; 71(3-4): 227-241
- [27] Durbin, T.D., Collins, J.R., Norbeck, J.M., Smith, M.R., Effects of Biodiesel, Biodiesel Blends, and a Synthetic Diesel on Emissions from Light Heavy-Duty Diesel Vehicles, *Environmental Science and Technology* 2000, 34(3): 349-355, DOI: 10.1021/es990543c
- [28] Szybist, J.P., Kirby, S.R., Boehman, A.L., NOx Emissions of Alternative Diesel Fuels: A Comparative Analysis of Biodiesel and FT Diesel, *Energy & Fuels* 2005, 19(4): 1484-1492, DOI: 10.1021/ef049702q
- [29] Yu Z, Wu L, Li K., Development of alternative energy and coal-to-liquids in China, paper presented at the Twenty-Fourth Annual International Pittsburgh Coal Conference, 10-14 September 2007, Johannesburg, South Africa
- [30] Williams, R., Larson, E., A comparison of direct and indirect liquefaction technologies for making fluid fuels from coal, *Energy for Sustainable Development* 2003; 7: 79-102
- [31] Comolli, A.G., Lee, L.K., Pradhan, V.R., Stalzer, R.H., Karolkiewicz, W.F., and Pablacio, R.M., Direct Liquefaction Proof-of-Concept Program, final report prepared by Hydrocarbon Technologies Inc. (Lawrenceville, New Jersey, USA) and Kerr-McGee Corporation (Oklahoma City, Oklahoma, USA) for the Pittsburgh Energy Technology Center, US Department of Energy, DE-92148-TOP-02, 1999, see also: <http://www.osti.gov/bridge/servlets/purl/772402-US5qhE/webviewable/772402.pdf>
- [32] Van den Burgt M, Van Klinken J, Sie S.T., The Shell Middle Distillate Synthesis Process, paper presented at the Fifth Synfuels Worldwide Symposium, Washington, DC, USA, November 11–13, 1985
- [33] Eilers, J., Posthuma, S.A., Sie, S.T., The shell middle distillate synthesis process (SMDS), *Catalysis Letters* 1990; 7: 253-269 DOI: 10.1007/BF00764507
- [34] Tijmensen, M., Faaij, A., Hamelinck, C., van Hardeveld, M., Exploration of the possibilities for production of Fischer-Tropsch liquids and power via biomass gasification, *Biomass and Bioenergy* 2002; 23: 129-152 DOI: 10.1016/S0961-9534(02)00037-5
- [35] van Vliet, O.P.R., Faaij, A.P.C., Turkenberg, W.C., Fischer-Tropsch diesel production in a well-to-wheel perspective: A carbon, energy flow and cost analysis, *Energy Conversion and Management* 2009, 50(4): 855-876, DOI: 10.1016/j.enconman.2009.01.008
- [36] National Energy Technology Laboratory, Emerging Issues for Fossil Energy and Water, 2006, 49 p. See also: <http://www.netl.doe.gov/technologies/oil-gas/publications/AP/IssuesforFEandWater.pdf>
- [37] Lumpkin, R.E., Recent progress in direct Liquefaction of coal, *Science* 1988; 239: 873-877, DOI: 10.1126/science.239.4842.873
- [38] Fletcher, J.J., Sun, Q., Comparative Analysis of Costs of Alternative Coal Liquefaction Processes, *Energy and Fuels* 2005; 19: 1160–1164 DOI: 10.1021/ef049859i
- [39] Vallentin, D. Policy drivers and barriers for coal-to-liquids (CTL) technologies in the United States, *Energy Policy* 2008; 36: 3198-3211, DOI:10.1016/j.enpol.2008.04.032
- [40] Northern Plains Resource Council, Montana’s Energy Future, 2005, see also: <http://www.northernplains.org/ourwork/coaltdiesel/>
- [41] Tingting, S., Shenhua plans to triple capacity of its direct coal-to-liquids plant, China Daily 2009, 8 January, page 14, see also: http://www.chinadaily.com.cn/cndy/2009-01/08/content_7376581.htm
- [42] Sasol, Investor Insight Newsletter, July 2006, see also: http://www.sasol.com/sasol_internet/downloads/Investor_Insight_July06_1152611604316.pdf
- [43] Huang, Y., Wang, S., Zhou, L., Effects of Fischer-Tropsch diesel fuel on combustion and emissions of direct injection diesel engine, *Frontiers of Energy and Power Engineering in China* 2008; 2: 261-267 DOI: 10.1007/s11708-008-0062-x
- [44] Hori, S., Sato, T., Narusawa, K., Effects of diesel fuel composition on SOF and PAH exhaust emissions, *JSAE Review* 1997; 18: 255-261 DOI: 10.1016/S0389-4304(97)00022-2
- [45] Mzinyati, A.B. Fuel-Blending Stocks from the Hydrotreatment of a Distillate Formed by Direct Coal Liquefaction, *Energy and Fuels* 2007, 21(5): 2751-2761, DOI: 10.1021/ef060622r
- [46] Farcasiu, M. Fractionation and structural characterization of coal liquids, *Fuel* 1977, 56(1): 9-14, DOI: 10.1016/0016-2361(77)90034-5
- [47] Jones, D.G., Rottendorf, H., Wilson, M.A., Collin, P.J. Hydrogenation of Liddell coal. Yields and mean chemical structures of the products, *Fuel* 1980, 59(1): 19-26.
- [48] Leckel, D. Diesel Production from Fischer–Tropsch: The Past, the Present, and New Concepts, *Energy and Fuels* 2009, 23(5): 2342-2358, DOI: 10.1021/ef900064c
- [49] Lipinski, J.A., Overview of Coal Liquefaction, U.S.-India Coal Working Group Meeting presentation in Washington D.C., 18 November 2005, see also: http://www.fe.doe.gov/international/Publications/cwg_nov05_ctl_lepinski.pdf
- [50] US Department of Energy, Current Industry Perspective Gasification, Office of Fossil Fuels information brochure from 2004, 28 p. See also: http://gasification.org/Docs/News/2005/Gasification_Brochure.pdf
- [51] Sung, N.W., Patterson, D.J., Theoretical limits of engine economy with alternative automotive fuels, *International Journal of Energy Research* 1981, Volume 7 Issue 2, Pages 121 – 127, DOI: 10.1002/er.4440070204
- [52] Henderson, C. Future developments in IGCC, IEA Clean Coal Centre report CCC/143, December 2008
- [53] Richardson, M., Chinas plan to turn coal into oil, 28 Aug 2005, accessed 2008-10-13 <http://www.opinionasia.org/node/39>
- [54] Alliance for Synthetic Fuels in Europe. Synthetic fuels: driving towards sustainable mobility, brochure from 2007, see also: http://www.synthetic-fuels.org/documents/20070221012942_ASFE%20Brochure_web.pdf

- [55] Arch Coal, Arch Coal Acquires Interest in DKRW Advanced Fuels, news release from 24 August 2006, see also: <http://news.archcoal.com/releasedetail.cfm?ReleaseID=208306>
- [56] Rentech Inc. and Peabody Energy, Rentech, Inc. and Peabody Energy enter into a joint development agreement for two Coal-to-Liquids projects, press release from 18 July 2006, see also: <http://www.rentechinc.com/pdfs/7-18-06-rtk-peabody-jda.pdf>
- [57] Lamprecht, D. Fischer–Tropsch Fuel for Use by the U.S. Military as Battlefield-Use Fuel of the Future, *Energy and Fuels* 2007, 21(3): 1448-1453, DOI:10.1021/ef060607m
- [58] Drazzen, Y.J. U.S. Military Launches Alternative-Fuel Push, Wall Street Journal 2008, 21 May, see also: <http://online.wsj.com/article/SB121134017363909773.html>
- [59] Malhotra, R., Direct coal liquefaction – lessons learned, paper presented at GCEP advanced coal workshop, Provo, UT, USA, Brigham Young University, 16 Mar 2005, see also: http://gcep.stanford.edu/pdfs/RxsY3908kaqwVPacX9DLcQ/malhotra_coal_mar05.pdf
- [60] Anglo Coal, Monash Energy Report 2006, information brochure, 2006 see also: http://www.angloamerican.co.uk/aa/development/sdreports/br/2008br/br_2008-03-17c/br_2008-03-17c.pdf
- [61] Milici, R. Coal-to-Liquids: Potential Impact on U.S. Coal Reserves, *Natural Resources Research* 2009, 18(2): 85-94, DOI: 10.1007/s11053-009-9093-1
- [62] ESI-Africa, Issue 2/2004. See also: <http://www.esi-africa.com/>
- [63] BP, BP Statistical Review of World Energy 2008, see also: <http://www.bp.com/>
- [64] National Coal Council, Coal: Americas Energy Future, 2006, see also: <http://nationalcoalcouncil.org/>
- [65] Southern States Energy Board, American Energy Security: Building a Bridge to Energy Independence and to a Sustainable Energy Future. July 2006. See also: www.americanenergysecurity.org/studyrelease.html
- [66] Höök, M., Aleklett, K. Historical trends in American coal production and a possible future outlook, *International Journal of Coal Geology* 2009, 78(3): 201-216, DOI:10.1016/j.coal.2009.03.002
- [67] Croft, G.D., Patzek, T.W. Potential for Coal-to-Liquids Conversion in the U.S.-Resource Base, *Natural Resources Research* 2009, article in press, DOI: 10.1007/s11053-009-9097-x
- [68] US Energy Information Agency. Annual Energy Outlook 2007, see also: [http://tonto.eia.doe.gov/ftproot/forecasting/0383\(2007\).pdf](http://tonto.eia.doe.gov/ftproot/forecasting/0383(2007).pdf)
- [69] US Energy Information Agency. Annual Energy Outlook 2009, figure 72 see also: <http://www.eia.doe.gov/oiaf/aeo/index.html>
- [70] Intergovernmental Panel on Climate Change (IPCC). Special Report on Emissions Scenarios, released in 2000, See also: http://www.grida.no/publications/other/ipcc_sr/?src=/climate/ipcc/emission/
- [71] Perry, H. Liquid fuel supplies, *International Journal of Energy Research* 1980, 4(2):103-107, DOI: 10.1002/er.4440040202