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Coal-to-Liquids: viability as a peak oil mitigation strategy

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Abstract

Converting coal to a liquid, commonly known as coal-to-liquids (CTL), can supply liquid fuels and has been successfully used in several countries, particularly in South Africa. However, it has not become a major contributor to the global oil supply. Increasing awareness of the scarcity of oil and rising oil prices has increased the interest in coal liquefaction. This paper surveys CTL technology, economics and environmental performance. Understanding the fundamental aspects of coal liquefaction technologies is vital for planning and policy-making since future CTL production will be integrated in a much larger global energy and liquid fuel production system.

The economic analysis shows that many CTL studies assume conditions that are optimistic at best. In addition, the strong risk for a CTL plant to become a financial black hole is highlighted. This helps to explain why China has recently slowed down the development of its CTL program.

The technical analysis investigates the coal consumption of CTL. Generally, a yield of between 1–2 barrels/ton coal can be achieved while the technical limit seems to be 3 barrels/ton coal. This puts a strict limit on future CTL capacity imposed by future coal production, regardless of other factors such as economic viability, emissions or environmental concern. For example, assuming that 10% of world coal production can be diverted to CTL, the contribution to the liquid fuel supply will be limited to only a few million barrels per day (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 a significant share of their fuel supply from CTL but those nations must also have access to equally significant coal production capacity. It is unrealistic to claim that CTL provides a feasible solution to liquid fuels shortages created by peak oil. At best, it can be only a minor contributor and must be combined with other strategies to ensure future liquid fuel supply.

Key words: Coal liquefaction, CTL, coal-to-liquids

1. Introduction

Oil is the largest contributor to mankind's energy needs and supplies well over 90% of all the energy required for transportation. Each year, new production must be brought on-stream to offset the decline from currently producing fields. More than two thirds of current crude oil production may need replacement by 2030 simply to prevent production from falling. This is likely to prove extremely challenging (UKERC, 2009).

The peaking of global oil production also implies a peak in liquid fuels. This also too has the potential to severely impact the world economy (Fantazzini et al., 2011), especially if alternative sources of energy and liquid fuels are unable to "*fill the gap*" on the timescale required. Coal liquefaction, coal-to-liquids (CTL), is often proposed as a possible mitigation strategy. CTL has been an important component in several peak oil mitigation outlooks (SRES, 2000; Hirsch et al., 2005; Hirsch, 2008; IEA, 2011).

A frequently cited example of producing synthetic fuel from coal is the case of the German military during the Second World War. It produced 90% of its jet fuel and 50% of its diesel through coal liquefaction (US DOE, 2009; Sasol, 2005). South Africa also developed CTL in 1960s and this technology has remained an important part of their liquid fuel supply ever since. Demonstration and pilot plants have also shown the technical feasibility of CTL as a provider of liquid fuels in smaller scales. Proponents of CTL claim that it will be capable of full or partial mitigation of the expected shortfall of conventional oil due to global oil peaking.

At present, world production of conventional oil stands at around 85 Mb/d and has been roughly constant since mid-2004. Current world CTL capacity is around 200 kb/d, providing only a marginal share of the global liquid fuel supply. Existing estimates place the decline in existing oil production between 3–8% annually, in other words, a capacity of 3–7 Mb/d is lost every year and requires replacement (Höök et al., 2009). Various observers have projected CTL to provide everything from a minor role to production levels of several Mb/d. Which of these expectations are reasonable? To assess this question, this paper reviews the technology, economics, environmental impact and supply chain of CTL.

2. CTL technology review

The idea of producing liquid fuel from coal was first developed around 100 years ago. This section begins with a brief overview of the underlying chemistry before proceeding to the main technology options.

2.1 Chemical overview

The idea behind CTL is to transform the long and solid hydrocarbon structures found in coal to shorter ones. This may be accomplished by partial breakdown directly to liquid hydrocarbons (direct coal liquefaction or DCL) or by full breakdown into hydrogen and carbon that can be reassembled into H-C-chains of a desired length (indirect coal liquefaction or ICL).

The Bergius process makes up the foundation for DCL. It splits coal into shorter hydrocarbons, resembling ordinary crude oil, by adding hydrogen under high pressure and temperature, thus eliminating the need for a gaseous middle stage (Formula 1).

$$nC + (n+1)H_2 \rightarrow C_nH_{2n+2} \qquad (1)$$

In contrast, the ICL approach is based on the Fischer-Tropsch (FT) process described by Formula 2. The idea is here to combine hydrogen and carbon monoxide into longer hydrocarbon chains of a desired length.

$$(2n+1)H_2 + nCO \rightarrow nH_2O + C_nH_{2n+2} \tag{2}$$

Carbon monoxide can be produced by gasification of coal or any other carbon-rich compound. The necessary reaction energy is applied by adding oxygen or steam under high temperatures in a controlled manner to avoid full oxidation into carbon dioxide (Formula 3).

$$C + \frac{1}{2}O_2 \rightarrow CO \tag{3}$$

This mixture of CO and H_2 is usually called a synthesis gas (or syngas) and is used to construct hydrocarbon chains of different lengths using condensation and a suitable catalyst. More specifically, the FT-process yields two products, described by two different reactions (Formula 4).

$$\begin{array}{ll} nCO + 2nH_2 \rightarrow nH_2O + C_nH_{2n} & (olefins) \\ nCO + (2n+1)H_2 \rightarrow nH_2O + C_nH_{2n+2} & (paraffins) \end{array} \tag{4}$$

Which product is created 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 chemical environment and reactions involved in CTL are significantly more complex and the basic processes presented here are only the fundamental reactions. The use of catalysts is essential to assist the reactions and the choice of catalysts has a large influence on process efficiency and process yield. Commonly used catalysts are iron, ruthenium or cobalt, but also transition metal sulphides, amorphous zeolites and many other compounds are used. Many catalysts are sensitive to sulfur–poisoning thus requiring that the sulfur be removed. A great deal of research has been done on different catalysts (Bacaud et al., 1994; Longwell et al., 1995; Duvenhage and Coville, 2006; Yang et al., 2006; Khodarov et al., 2007). In summary, some of the greatest chemical challenges can be found in optimizing catalyst performance in CTL.

The properties of the coal feedstock (ash content, grindability, sulfur content, plasticity, caking properties, etc.) can have a major influence on the CTL process. Certain coals are hard to grind or may easily clog outlets and pipes, thus preventing certain CTL designs from being feasible. Practical CTL-design can be found for all forms of coal (Collot, 2006), but it is essential to match the CTL-reactor design with the coal feedstock being used (Höök and Aleklett, 2010). However, this unfortunately reduces feedstock flexibility and may even tie a CTL process to a specific coal with specific properties.

2.2 CTL technology options

CTL-technology has improved significantly since the Second World War. However, only a small number of commercial enterprises have been undertaken. Indirect liquefaction using FT-synthesis has dominated the market but the first commercial DCL facility started operations a few years ago.

2.2.1 Pyrolysis

In a pyrolysis process, added heat decomposes coal and expulses volatile matter, leading to increased carbon content. Pyrolysis is used worldwide for manufacturing roofing, waterproofing and insulation products and as a raw material for various dyes, drugs and paints. There are three types of pyrolysis differentiated by their temperature regimes. High temperature pyrolysis operates around 950° C, medium temperature pyrolysis operates with temperatures of 450–650° C, while low temperature approaches can use even lower operating temperatures. Liquid yield typically increases with lower operating temperature.

The main products are solid fuels such as char, semi-coke and coke. Pyrolysis has primarily been used to upgrade low-ranking coals by increasing calorific value and reducing sulfur content and other pollutants. A demonstration plant for coal upgrading was built in the USA and was operational between 1992 and 1997 (WCI, 2006). The resulting tar-like liquids were mostly a by-product and reached a maximum yield of 20% (Ekinci, 2002; WCI, 2006). However, integrating reforming of methane by CO2 and coal pyrolysis have improved tar yield up to 32% (Wang et al., 2011). The coal tar still requires further treatment and refining before it can be used in most motors and engines. The efficiency and liquid yields of pyrolysis processes are low and it appears implausible that this technique will be able to generate significant amounts of liquid fuels.

2.2.2 Direct coal liquefaction (DCL)

The Bergius process (Formula 1) forms the chemical basis of DCL. Thermal energy is used to induce homolytic bond scissions in coal molecules to produce free radicals that later can isomerise, decompose or be used in other chemical reactions (Huang and Schobert, 2005; de Klerk, 2009). This is normally done at high temperature and pressures. More simply, adding hydrogen and a suitable catalyst initiate “*hydro-cracking*” where long, solid carbon chains will rupture into shorter ones that may be liquid or gaseous. Many closely-related DCL–technologies have been developed.

The advantage of DCL is its very high liquid yield, which can be in the excess of 70% of the dry weight coal, with thermal efficiencies of 60–70% (Benito et al., 1994; Couch, 2008). Because hydrogen is added, DCL liquids are typically of higher quality than the tar-like liquids obtained from pyrolysis. The DCL liquids are actually a synthetic crude oil (syncrude) and are directly usable in power generation or as an oil substitute in chemical processes. However, they require further treatment and refining before they can be used as a transport fuel. Refining can be done directly at the CTL facility or by sending the synthetic crude oil to a conventional refinery, where it can be made into gasoline- and diesel-like fuels as well as propane, butane and many other products.

DCL processes are classified into two major types, single-stage and two-stage liquefaction. The single-stage concept uses a combined dissolution and hydrogenation reactor. Only a few single-stage designs have been brought to demonstration stage, while the rest have been abandoned (de Klerk, 2009). The two-stage concept uses two reactors in series. The first stage handles coal dissolution without a catalyst or using a disposable low-activity catalyst. The heavy coal liquids from the first stage are hydrotreated in the second reactor in the presence of a highly active hydrocracking catalyst to produce additional distillate.

Some smaller pilot plants and testing facilities have yielded positive results (de Klerk, 2009). 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 the Inner Mongolia Autonomous Region (Fletcher et al., 2004). This plant recently became operational.

2.2.3 Indirect coal liquefaction (ICL)

In contrast to the sledgehammer approach of DCL, indirect liquefaction breaks down coal into other compounds via gasification. The resulting syngas is modified to obtain the required balance of hydrogen and carbon monoxide. Later, the syngas is cleaned, removing sulfur and other impurities capable of interfering with subsequent reactions. Finally, the syngas is reacted over a catalyst to provide the desired product using FT-reactions (Formula 2–4). Optimization is required to find the best design for a FT-system. Coal gasifier type can impact syngas quality while the desired products will impact system design (de Klerk, 2009).

In general, there are two types of FT-synthesis, a high temperature version that primarily yields a gasoline-like fuel and a low temperature version that provides a diesel-like fuel (Dry, 2002). Two classes of reactors are used in FT-synthesis: fixed or fluidized beds (Tavakoli et al., 2008). Only four group VIII-metals (Fe, Co, Ni, and Ru) have sufficiently high activities for hydrogenation of CO to merit their use as effective FT catalysts (Tavakoli et al., 2008). Cost and global availability is prohibitive for Ru, while Ni easily forms volatile carbonyls leading to continuous catalyst losses in the reactor. Thus, only Fe and Co-based catalysts are feasible (Day, 2003). More details on FT-synthesis via ICL-technology have been discussed by Bridgwater et al. (1994), Dry (2002) and de Klerk (2009).

Although ICL has been used in a number of plants since the 1940s, many of them have been small capacity demonstration or pilot plants (5000 b/d or less). The South African company Sasol was established in the early 1950s and their first synthetic fuels from coal were produced in 1955 (Sasol, 2002). Sasol constructed two new plants at Secunda in the 1980s, improving their CTL capacity by 120 000 b/d. In 2000, the plants were modernized and the old fluidized bed reactors were replaced with new Sasol Advanced Synthol reactors capable of giving 150 000 b/d of products in the range of C1–C20 (automotive fuels and light olefins) as well as 14 000 TJ of methane rich gas piped to the national gas distribution network (Chang, 2000). In total, Sasol has over 50 years of experience with ICL and has produced over 1.5 billion barrels of synthetic oil in that time (WCI, 2006).

2.3 Process efficiencies

Low thermal efficiencies, often in the range of 45–55%, have been a major argument against CTL. Both DCL and ICL are exothermic reactions and the reaction heat released corresponds to about 20% of the heat of combustion of the product. Thus, reaction temperature control and optimal use of released heat are major challenges (Liu et al., 2010). DCL is commonly seen as more energy efficient for making liquid fuels than ICL because only partial breakdown of the coal is required. However, such claims can be misleading because published DCL efficiencies usually refer to the making of an unrefined syncrude that still requires additional refining to produce a useable transportation fuel, In contrast, ICL efficiencies often refer to the making of a final product. Caution should always be exercised when dealing with CTL efficiencies.

The estimated overall efficiency of the DCL-process is 73% (Comolli, 1999). Other groups have estimated the thermal efficiency between 50-70% (WCI, 2006; Williams and Larson, 2003; Bellman et al. 2007). However, Sovacool et al. (2011) criticized these estimates for being misleading since industry tends to do their calculations by comparing heating value of the resulting liquids with the energy value of the inputs. Hydrogen production, product refining and other steps necessary to complete the entire product supply chain are not always included in the efficiency calculations; one needs to pay attention to how those assessments have been made.

Representative efficiencies for ICL are around 50%, while the theoretical maximum thermal efficiency has been estimated at 60% (van den Brugt et al., 1985; Eilers et al., 1990). Tijmensen et al. (2002) give overall energy efficiencies ranging from 33–50% for ICL using various biomass blends. Detailed studies on methanol and di-methyl-ether (DME) production found efficiencies of 58.3% and 55.1% (Williams and Larson, 2003), so finely tailored and optimized ICL-systems can reach high efficiencies. If the refining of DCL products is taken into account, some ICL-fuels can be produced with higher final end-use efficiency than their DCL-counterparts (Williams and Larson, 2003).

In essence, there is no significant advantage in terms of efficiency for either DCL or ICL. As a rule-of-thumb, a 50% thermal efficiency can be used for CTL in general assessments. This implies that only half of the coal energy invested in CTL will come out as energy available as transportation fuel. This naturally raises the issue of coal consumption and how much feedstock are needed to give a barrel of synthetic fuel from coal liquefaction.

2.4 Coal and water requirements

Many groups have assessed the coal consumption of CTL. Couch (2008) and Malhutra (2005) gave yields of ~3 barrels unrefined syncrude per ton bituminous coal for DCL, with a lower yield for low-ranking coals. Milici (2009) gives conversion ratios of 1.3–1.8 barrels per ton bituminous coal. The National Petroleum Council (2007) compiled other studies and gave conversion rates of 1–2 barrels/ton of coal. Empirical estimates from published Sasol coal use gave yields of 1–1.4 barrels/ton coal (Höök and Aleklett, 2010). However, liquid yield comparisons are tricky, due to dependence on the technical system, the coal type used, system borders and many other factors. Despite differences in methodologies, all coal consumption estimates end up at approximately similar figures.

As expected from the low thermal efficiencies, a significant amount of coal is required to generate liquid fuels in any substantial amount. Significant CTL production is viable only in areas with abundant coal reserves. It was earlier estimated that large scale CTL production will be limited to a few (about 6) countries with large coal reserves and the ability to divert significant fractions of that to liquefaction (Höök and Aleklett, 2010).

Water is a vital part of the conversion processes and CTL can be regarded as highly water intensive (Mielke et al., 2010). Disclosed industrial data claims that each ton of synthetic oil output requires 8–9 tons of fresh water for DCL and 12–14 tons of fresh water in ICL (Zhang et al., 2009). Synfuels China presented water consumption figures of 10–15 tons/ton of oil for CTL projects (Li, 2007). In contrast, the US Department of Energy found that water consumption is approximately equivalent for DCL and ICL at around 5–6 tons water/ton of oil (National Energy Technology Laboratory, 2006). Other American studies have arrived at water consumption figures of 6–12 ton/ton of oil (RAND, 2008).

3. Environmental performance

Coal liquefaction can impact the environment in a number of ways. Environmental impacts can be broadly classified into two categories: those that accompany the extraction of the coal feedstock, and apply to all uses of coal, and those that are specific to the manufacture of liquid fuel from coal.

First we will examine landscape modification, particulate emissions and acid mine drainage, which are just a few examples of how coal mining impacts the environment. (These impacts apply equally to power generation, coke making and other industrial applications of coal.) Then we will examine greenhouse gas emissions and water consumption of and contamination by CTL.

3.1 Landscape modification

When coal is located relatively near the surface, three types of surface mining are generally used to extract the coal: open-pit, strip mining and mountaintop removal. In all cases the overburden is removed to expose the coal. Open-pit mining creates a large crater-like depression. In strip-mining, as the overburden of the strip is excavated, it is placed in the excavation of the previous strip.

Mountaintop removal is a particularly controversial form of mining that changes the landscape extensively. Explosives are used to destroy the overburden (including forests) off the top of mountains, primarily in the Appalachian Mountains in the United States. The overburden is placed in the valleys, burying streams and creating more opportunities for leaching. According to the US Environmental Protection Agency, between 1992 and 2002 surface coal mining in Appalachia damaged or destroyed more than 1900 km of streams and deforested 150 000 hectares of land, while 34 000 hectares of valleys were filled (Environmental Protection Agency, 2005). All forms of surface mining tend to decrease biodiversity. In the United States, the Surface Mining Control and Reclamation Act of 1977 requires that reclamation plans must be filed before mining begins and bonds posted to ensure the reclamation occurs. It also established a mechanism and tax to reclaim abandoned mines.

3.2 Particulate emissions

Particulate emission is not a serious concern for the liquefaction of coal but particulates are emitted when coal is mined and via wind erosion until new vegetation covers reclaimed land. Hendryx et al. (2008) found that, after accounting for smoking, poverty, age, education, race and other variables, lung cancer mortality was higher in Appalachian counties with extensive coal mining. Coal contains carcinogenic compounds including zinc, cadmium, nickel, arsenic and several others. The mining and cleaning of coal at local processing sites creates large quantities of ambient particulate matter (and contaminated water).

3.3 Water contamination

Water is used extensively throughout the coal mining and liquefaction process. Surface mines use water for dust abatement and all coal, whether surface mined or mined underground, must be washed in coal-preparation plants. The coal is washed of soil and other contaminants to prepare it for sale. Local aquifers are often depleted near coal mines or are contaminated by acid mine drainage (AMD). As rainwater moves through the mine it meets pyrite, which forms sulfuric acid and that leaches into local aquifers. AMD often continues after the mine is no longer operational. Other contaminants that leach into the water supply from the entire mining process include cadmium, selenium, arsenic, copper, lead, mercury, ammonia, sulfur, sulfate, nitrates, nitric acid, tars, oils, fluorides, chlorides, and other acids and metals, including sodium, iron and cyanide (Spath et al., 1999; Palmer et al., 2010).

3.4 Greenhouse gas emissions

The CTL process itself produces significant amounts of carbon dioxide, the greenhouse gas primarily driving anthropogenic global warming. From a chemical perspective, this makes sense because coal has a very high carbon-to-hydrogen ratio (Dry, 2002). From a life cycle perspective, it is also important to remember the emission contributions from mining.

Coalification, the natural process by which coal is made, traps significant amounts of methane as the coal rock is formed. This methane, a potent greenhouse gas (GHG), is known as coal bed methane (CBM) and is released during the mining of coal, creating a safety hazard (leading to explosions) and constituting a significant source of GHGs when vented to the atmosphere. Methane represents approximately 14% of global GHG emissions and coal bed methane accounts for approximately 8% of total methane emissions (World Coal Association, 2012). Methane content in coal increases with mine depth, coal age and coal rank, reaching approximately 7 cubic meters of methane per ton of coal at a depth of 2000 meters (World Coal Association, 2012).

The 13 major coal-producing countries produce 85% of worldwide CBM, which in 2000 was estimated to be 0.24 $GtCO_2$ equivalents. China was the largest emitter (0.1 $GtCO_2$ equivalents) followed by the USA (0.04 $GtCO_2$ equivalents). Total CBM emissions are expected to exceed 0.3 $GtCO_2$ equivalents in 2020 with current trends (Environmental protection Agency, 1999). However, coal bed methane is increasingly being captured and pumped into natural gas networks or is used onsite for electricity generation. Approximately 53 billion cubic meters, or 8%, of U.S. natural gas is sourced from coal bed methane (EIA, 2012). Coal mines also emit nitrogen oxide and volatile organic compounds, which are recognized as toxic air pollutants under the U.S. Clean Air Act (but are not currently regulated if they are emitted from mines in the U.S.).

Brandt and Farrell (2007) find that a transition to coal-to-liquids synfuels could raise upstream GHG emissions by several Gt of carbon per year by mid-century unless mitigation steps are taken. Likewise, Vallentin (2008) found that the well-to-tank emissions were eight times higher than for conventional petroleum fuels. However, there are CTL configurations with CO_2 recycling/capture/storage that may be capable of reducing emissions significantly (Williams and Larson, 2003). Mantripragada and Rubin (2009) explore some of those configurations, but also stress that handling CO_2 responsibly dramatically raises CTL costs.

Rong and Victor (2011) also point out that the Chinese desire to reduce carbon intensity in current and future five-year plans is something that conflicts with a scaling up of coal liquefaction unless CCS were implemented. However, the uncertain economics of CCS is an issue that is more discussed in section 4. Co-firing with biomass is another possibility to reduce GHG emissions, but this brings about questions of biomass availability, transportation issues and need for additional technical customization.

3.5 Water consumption

The total amount of water required for liquefaction depends on factors like plant design, location, humidity, and coal properties. CTL is classified as a water intensive process (Mielke et al., 2010), and consumption estimates range from 6–15 tons as presented in Section 2.4. In certain regions it is entirely possible that CTL will generate or amplify water shortages. Sovacool et al. (2011) foresee possible and severe water shortages in 22 counties and 20 large metropolitan areas in the USA by 2025.

Water quality is also an issue for CTL, both for feed water as well as discharged water. Cooling, boiler and process water needs to be of reasonable quality to prevent corrosion and/or deposit formation and treatment is typically needed. The cost of this treatment increases as the quality of the raw water decreases. However, to determine the feasibility of locating a plant in a specific location, cost analysis of the treatment necessary to meet the specific requirements of particular water body would need to be performed (National Energy Technology Laboratory, 2006). Discharged water is comparable to that of the petroleum industry and must be treated before it can be released to the environment without causing harm (Lei and Zhang, 2009). Rong and Victor (2011) points to both water availability and quality issues as important factors behind the recent reversal of the pro-CTL policy in China to a more cautious one.

3.6 Accounting for environmental externalities

Currently, the cost of coal does not fully account for all of its environmental impacts i.e. these costs are externalized from production. In a comprehensive review, Epstein at al. (2011) conservatively estimate that the true cost of coal, were one to include the damage to the environment discussed so far and mitigation strategies to avoid this damage, is at least $345 billion more than its current cost in the United States. Accounting for these costs would add approximately 17.8 cents to a kWh of electricity.

4. Economic issues

The high cost of building a CTL plant is probably the major obstacle to the development of this energy technology. However, the high price of oil in the last decade, and particularly in the last five years, has completely changed the energy landscape (see Fantazzini et al. (2011) for a discussion) and has had a huge impact in the financial analysis related to CTL plants.

While this increase in oil price has improved the economic viability of CTL, it has also caused a large increase in the overnight costs and Total Plant Costs (TPC) for a CTL plant, as well as raising the break even crude oil equivalent (BEOP) price of FT liquids. For example, Figure 1 reports the time evolution of the Chemical Engineering Plant Cost Index (CEPCI). This index is widely accepted and consists of subcomponents dealing with equipment, labor costs, buildings, engineering, supervision and other parameters affecting costs. See Kreutz et al. (2008) for a comparison of the CEPCI with the Marshall and Swift index, the US GDP deflator and the Handy-Whitman Total Plant-All Steam Generation Index.

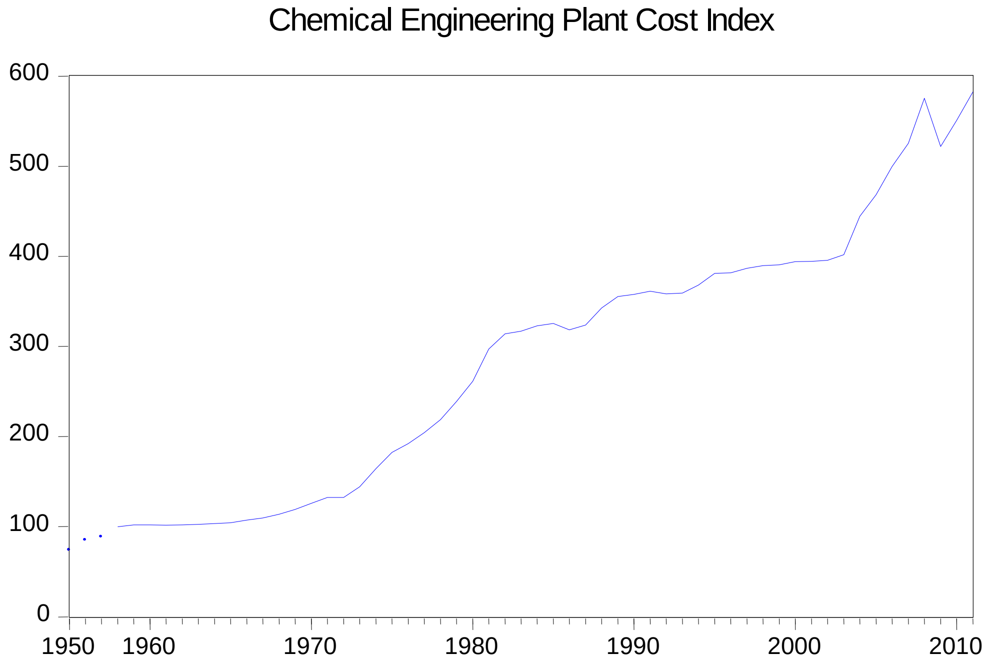


Figure 1. *Chemical Engineering Plant Cost Index (CEPCI)*

Due to costs escalation, the financial analyses of CTL performed before 2005/2006 have become largely unrealistic, as first shown by Höök and Aleklett (2010). Consequently, we examined here only the works from 2007 onwards. Table 1–3 report the main results in terms of economic and financial feasibility for CTL plants, (the table cells are filled either using data reported in the original papers, or performing some computations with the data in the original papers (whenever possible).

First, the following tables highlight a considerable reduction in the planned CTL plant capacity, as discussed in the studies published in the last five years, compared to the initial studies surveyed in Höök and Aleklett (2010). All studies examined here (except one) assumed a capacity equal or lower than 50 kb/d and some of them even analyzed coal- and biomass-to-liquids (CBTL) or biomass-to-liquids (BTL) plants with a capacity as low as 5 kb/d. Thus is mainly due to construction cost escalation: if we consider a 50 kb/d plant, the estimated total plant costs now range between \$3.5 billion (without CCS) and \$6.3 billion. Considering TPC per b/d capacity, the estimated costs now range from \$90 000 to over \$300 000 per b/d, with a mean value of \$145 000 per b/d.

However, it is the required break-even (crude) oil equivalent price (BEOP) of FT liquids that is probably the best indicator of the changed energy environment: it now ranges from 50 to 200 US\$/b, with a mean close to 85 \$/b.

Table 1. *Economic and financial feasibility of the CTL processes (papers 1-6. Base case, if not differently specified).*

	Höök and Aleklett (2010)	**Wu et al. (2011)**	**Williams et al. (2009) + Kreutz et al. (2008)**
Plant capacity (b/d)	20 000-80 000	40000	Large CTL RC - V CCS: 50 000 50 000 Small CTL OT - V CCS: 10 232 10 232 CBTL2 OT CCS - Large Small: 36 655 10 232 CBTL OT CCS: 8100
Base year for Valuation	2003\$-2008\$	2007\$	2009\$
Total Plant Cost -TPC (US\$ billion)	20 000 b/d: \$1.5 -\$4 ; 80 000 b/d: \$6-\$24	3.07	Large CTL RC - V CCS: 4.878 4.945 Small CTL OT - V CCS: 1.486 1.539 CBTL2 OT CCS - Large Small: 4.617 1.555 CBTL OT CCS: 1.379
Specific TPC per b/d	-	76 750	Large CTL RC - V CCS: 97 568 98 908 Small CTL OT - V CCS: 145 175 150 448 CBTL2 OT CCS - Large Small: 125 946 151 976 CBTL OT CCS: 170 189
Break even crude oil equivalent price of FT liquids	Range: \$48-\$75/b (\$2008)	\$66/b	(ALL Base Case: Mature Industry): \$/b: Large CTL RC - V CCS: 56 63 Small CTL OT - V CCS: 55 71 CBTL2 OT CCS - Large Small: 59 76 CBTL OT CCS: 101
	Talberth (2009)	**Hatch (2008)**	**Larson et al. (2009) + Kreutz et al. (2008)**
Plant capacity (b/d)	Case 1: 20 000 Case 2: 40 000	Case 1: 20 000 Case 2: 40 000 Case 3: 40 000 (with coal & gas)	Coal Only RC-V RC-CCS OT -V OT-CCS: 50 000 50 000 36 653 36 652 Coal+Stover OT- V OT-CCS: 7691 7692 Coal+MPG OT CCS: 13 039
Base year for Valuation	2008\$	2008\$	2007\$
Total Plant Cost -TPC (US\$ billion)	Case 1: 6.9 Case 2: 12.3	Case 1: 4.146 Case 2: 7.449 Case 3: 4.655	Coal Only RC-V RC-CCS OT -V OT-CCS: 4878 4945 4407 4597 Coal+Stover OT- V OT-CCS: 1245 1281 Coal+MPG OT CCS: 1944
Specific TPC per b/d	Case 1: 345 000 Case 2: 307 500	Case 1: 207 300 Case 2: 186 200 Case 3: 116 400	Coal Only RC-V RC-CCS OT -V OT-CCS: 97 568 98 908 120 239 125 434 Coal+Stover OT- V OT-CCS: 161 870 166 577 Coal+MPG OT CCS: 149 092
Break even crude oil equivalent price of FT liquids	*Not stated* Case 1: \$106/b Case 2: \$95/b (Computed dividing by 1.3 the FT liquid price)	*Not stated* Case 1: \$106/b Case 2: \$95 Case 3: \$83 (Computed dividing by 1.3 the FT liquid price)	(ALL Base Case: Mature Industry): \$/b: Coal Only RC-V RC-CCS OT -V OT-CCS: 53 59 35 50 Coal+Stover OT- V OT-CCS: 72 89 Coal+MPG OT CCS: 88

To consider inflation, we then raised the previous TPCs and BEOPs to \$2011 using the Chemical Engineering Plant Cost Index (CEPCI). For the sake of brevity, we report below in figures 2-3 only the plots of the updated TPCs and BEOPs for CTL plants (left figures) and CBTL/BTL plants (right figures), without separating them based on additional technical details (like with and without CCS, with and without power generation, etc.).

If we consider the updated costs for a 50 kb/day CTL plant, for instance, the TPCs now range from 4.1 billion \$ (without CCS) to 7 billion \$, while the updated BEOPs range from 50\$/b till 110\$/b. We remark that all plants in Figure 3 with BEOPs lower than 60\$/b are without CCS. Venting CO_2 to the atmosphere can be the cheapest option, although the environmental costs of such an option are hardly bearable. For a detailed analysis of natural resource damage costs, we refer to Talberth (2009) and references therein.

Table 2. *Economic and financial feasibility of the CTL processes (papers 7-11. Base case, if not differently specified)*

	DOE/NETL (2007)	**Robinson & Tatterson (2008)**	**Berg et al. (2007)**
Plant capacity (b/d)	50 000 b/d	Range: (4428 - 9019) (Diesel only)	32 502 (bituminous coal) 32 401 (lignite)
Base year for Valuation	$2006	$2008	$2006
Total Plant Cost -TPC (US$ billion)	4.528	Illinois no. 6: $1.603 (best case) Illinois no. 6: $2.404 (worst case) Montana subbituminous : 1) CTL (9019 b/d): 1.850 2) IGCC (-): 1.048 3) CTL + Power (4428 b/d): 1.603 4) IGCC (4439 b/d) ultragreen: 1.720	Bituminous coal with CCS: 3.339 Bituminous coal with CCS and 2X Power: 3.602 Lignite coal with CCS: $ 3.684
Specific TPC per b/d	$90 574	Illinois no. 6: $362 014 (best case) Illinois no. 6: $542 908(worst case) Montana subbituminous : 1)CTL: $205 123 2) IGCC: - 3) CTL +power : $362 014 4) IGCC ultragreen: $382 817	Bituminous with CCS: $102 732 Bituminous with CCS and 2X Power: $110 823 Lignite coal with CCS: $113 700
Break even crude oil equivalent price of FT liquids [$/b]	$61 (Base) ROI >10% if WTI > 37$ ROI >15% if WTI > 47$	Range: $75 - $135	Base (bituminous): $56.02 (19% IRR) $51.68 (17% IRR) Base (lignite) : $58.46 (19% IRR) $53.58 (17% IRR)
	DOE/NETL (2009)		**Chen et al. (2011) + DOE/NETL (2007)**
Plant capacity (b/d)	50 000 (CTL), 30 000 - 50 000 (CBTL), 5000 (BTL)		50 000 b/d
Base year for Valuation	$2008		$2009
Total Plant Cost -TPC (US$ billion)	100% coal, no CCS 50k 5.50 100% coal, CCS 50k 5.70 100% coal, CCS+ATR 50k 6.05 8% bio-, CCS 50k 6.10 15% bio-, CCS 50k 6.15 30% bio-, CCS 30k 4.17 100% bio-, No CCS 5k 1.17 100% bio-, CCS 5k 1.23 100% bio-, CCS+ATR 5k 1.27		CTL without CCS: 3.672 CTL with CCS: 4.513
Specific TPC per b/d	100% coal, no CCS 50k 110000 100% coal, CCS 50k 114000 100% coal, CCS+ATR 50k 121000 8% SG, CCS 50k 122000 15% SG, CCS 50k 123000 30% SG, CCS 30k 139000 100% SG, No CCS 5k 233000 100% SG, CCS 5k 246000 100% SG, CCS+ATR 5k 254000		CTL without CCS: $73 440 CTL with CCS: $90 260
Break even crude oil equivalent price of FT liquids [$/b]	$/b 100% coal, no CCS 50k $84 100% coal, CCS 50k $86 100% coal, CCS+ATR 50k $92 8% SG, CCS 50k $92 15% SG, CCS 50k $95 30% SG, CCS 30k $109 100% SG, No CCS 5k $216 100% SG, CCS 5k $225 100% SG, CCS+ATR 5k $234		CTL may become economic in regions such as China, India, Africa, and the USA in 2015, with the price of crude oil over $91 ($2010). In FSU and other Annex I countries during 2020-2025 with a C.O.P between $105-$118 ($2010)

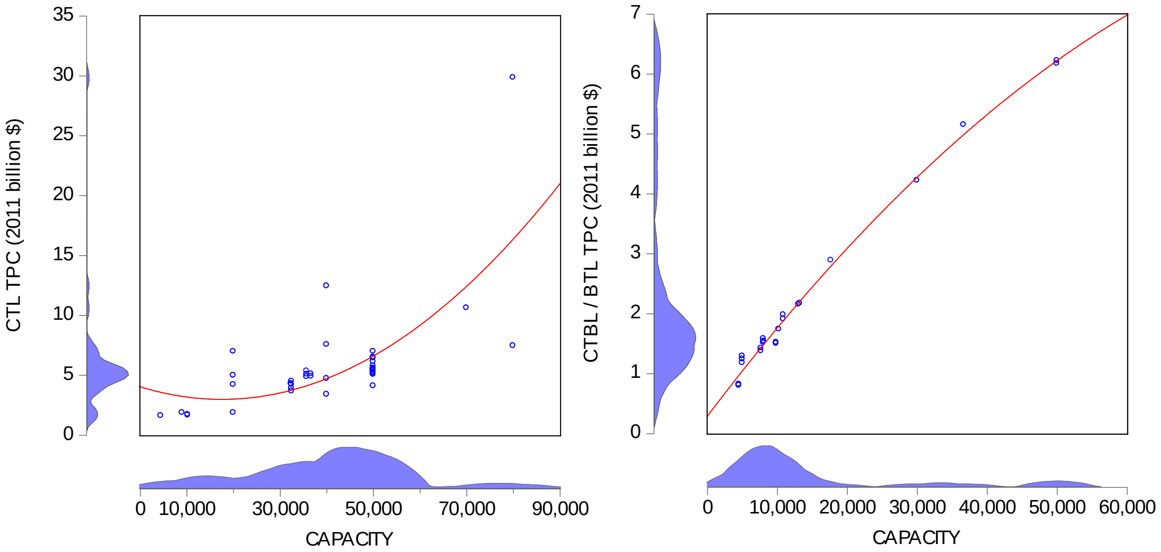


Figure 2. *TPCs for CTL plants (left) and CBTL/BTL plants (right) expressed in 2011 billion $, with kernel densities on the axis borders and a polynomial fit of second order.*

Table 3. *Economic and financial feasibility of the CTL processes (papers 12-16. Base case, if not differently specified)*

	Erturk (2011)	**Bartis et al. (2008) + Camm et al. (2008)**	**NPC (2007) + EIA (2006) + SSEB (2006)**
Plant capacity (b/d)		32502	10 000 - 70 000
Base year for Valuation	$2007-$2008	$2007	$2006
Total Plant Cost -TPC (US$ billion)	-	3.300–4.050	-
Specific TPC per b/d	100 000 - 125 000 (USA) 60 000 - 62 000 (China)	10 0000 - 125 000	60 000 - 130 000
Break even crude oil equivalent price of FT liquids [$/b]	-	$55 to $65 (with 10% real RoR) $62 to $75 (with 12% real RoR) Subbituminous coal is less expensive: - $5 Lignite: required increases in capital and operational costs who will offset the cost advantage	$34 - $60
	Liu et al. (2009) + Kreutz et al. (2008)	**Mantripragada and Rubin (2011)**	
Plant capacity (b/d)	CTL-RC-V 50 000 CTL-RC-CCS 50 000 CTL-OT-V 35 706 CTL-OT-CCS 35 705 CTL-OTA-CCS 35 705 BTL-RC-V 4521 BTL-RC-CCS 4521 CBTL-RC-V 9845 CBTL-RC-CCS 9845 CBTL-OT-V 8036 CBTL-OT-CCS 8036 CBTL1-OT-CCS 8036 CBTL-OTS-CCS 13 213 CBTL-OTA-V 10 881 CBTL-OTA-CCS 10 882 CBTL-OTAS-CCS 17 669	50 000 (Illinois#6 bituminous coal) (sensitivity: 10 000 to 125 000 b/d)	
Base year for Valuation	$2007	$2007	
Total Plant Cost -TPC (US$ billion)	CTL-RC-V 4852 CTL-RC-CCS 4919 CTL-OT-V 4390 CTL-OT-CCS 4574 CTL-OTA-CCS 4826 BTL-RC-V 724 BTL-RC-CCS 737 CBTL-RC-V 1349 CBTL-RC-CCS 1369 CBTL-OT-V 1372 CBTL-OT-CCS 1427 CBTL1-OT-CCS 1369 CBTL-OTS-CCS 1955 CBTL-OTA-V 1720 CBTL-OTA-CCS 1786 CBTL-OTAS-CCS 2611	Liquids-only: No CCS 4.595; With CCS 4.655 Co-production: No CCS 5.790; With CCS 5.855; With CCS 6.295	
Specific TPC per b/d	CTL-RC-V 97 040 CTL-RC-CCS 98 380 CTL-OT-V 122 949 CTL-OT-CCS 128 105 CTL-OTA-CCS 135 163 BTL-RC-V 160 142 BTL-RC-CCS 163 017 CBTL-RC-V 137 024 CBTL-RC-CCS 139 055 CBTL-OT-V 170 732 CBTL-OT-CCS 177 576 CBTL1-OT-CCS 170 358 CBTL-OTS-CCS 147 960 CBTL-OTA-V 158 074 CBTL-OTA-CCS 164 124 CBTL-OTAS-CCS 147 773	Liquids-only: No CCS 91 900; With CCS 93 100 Co-production: No CCS 115 800; With CCS 117 100; With CCS 125 900	
Break even crude oil equivalent price of FT liquids [$/b]	CTL-RC-V 58 CTL-RC-CCS 65 CTL-OT-V 44 CTL-OT-CCS 59 CTL-OTA-CCS 73 BTL-RC-V 133 BTL-RC-CCS 145 CBTL-RC-V 100 CBTL-RC-CCS 110 CBTL-OT-V 91 CBTL-OT-CCS 110 CBTL1-OT-CCS 93 CBTL-OTS-CCS 84 CBTL-OTA-V 78 CBTL-OTA-CCS 104 CBTL-OTAS-CCS 88	*Not stated* (*) Liquids-only: No CCS / With CCS; Co-production: No CCS / With CCS(a) / With CCS (b) $0 ton/CO2: 58.5 / 62.9 / 45 / 53.4 / 60.2 $25 ton/CO2: 68 / 62.9 / 58.6 / 56.5 / 60.5 (*) Computed dividing by 1.3 the FT liquid price	

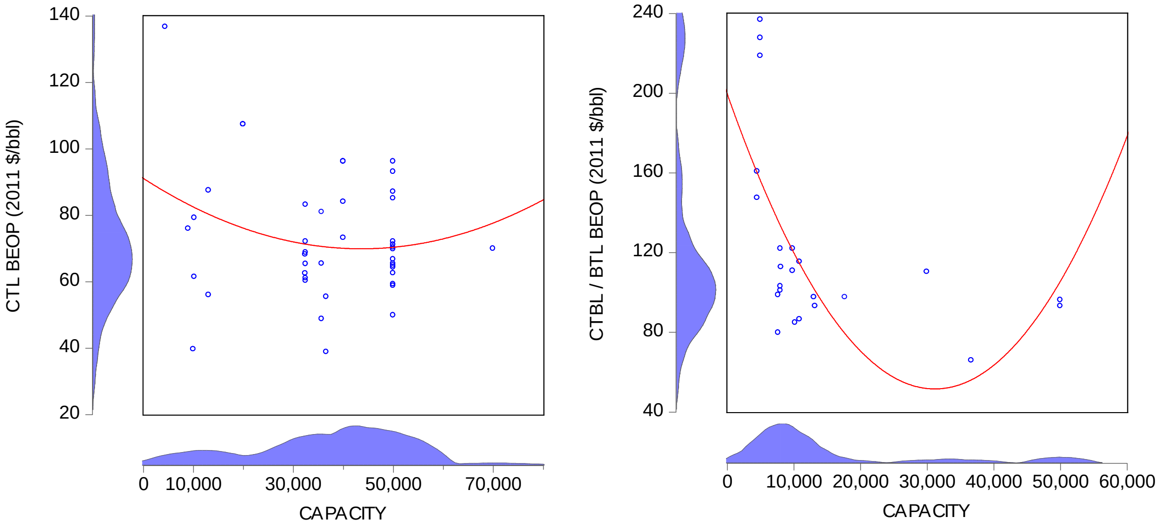


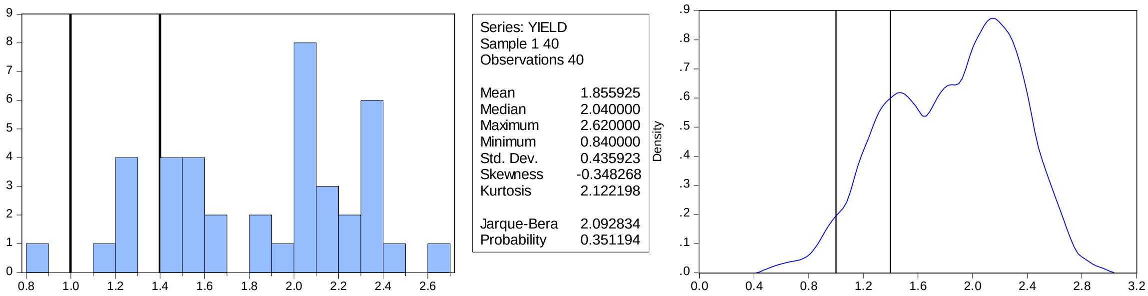
Figure 3. *BEOPs for CTL plants (left) and CBTL/BTL plants (right) expressed in 2011 $/b, with kernel densities on the axis borders and a polynomial fit of second order.*

4.1 Sensitivity analyses

Many papers considered in this work performed some sort of sensitivity analysis in which the authors changed some inputs and verified how much the estimated TPCs and FT Required Selling Prices (RSPs) changed as a result. While a more detailed examination of these analyses is left to a future specific article on CTL, we discuss below the most important results.

- Most studies used the assumption a mature industry as a base case even though this is true only for South Africa. Clearly, any new CTL plant that could be built outside of South Africa (even with assistance from Sasol) would behave much more like an early mover. This problem was analyzed by Williams et al. (2009), who showed that a 50 kb/d plant with CO_2 vented to the atmosphere (i.e. the cheapest technical configuration), in the base case for a mature industry has a TPC of $98 000 per b/d and a BEOP of $56/b. Instead, the case of an early mover resulted in a TPC of $110 000 per b/d and a BEOP of $86/b – more than a 50% increase. More complex configurations involving CCS, ATR, etc. would be even more financially prohibitive under early mover conditions. Similar results also hold for CBTL plants.
- The price of FT diesel is particularly sensitive to "*engineer, procure, construct*" (EPC) costs, changes in the Internal Rate of Return (IRR), capital structure, plant size, construction time, coal prices, debt amortization period, electricity price, and final availability (i.e. capacity factor).
- The cost of carbon sequestration implies an increase in the price of FT liquids from $5/b to $20/b (10–30% increase) depending on the chosen technical configuration.
- FT liquid fuels tend to be less costly when electricity is a major co-product of a CTL plant than when the plants are designed to produce mainly liquid fuels. Moreover, it can reduce credit concerns and improve financing. However, a decent electricity selling price is required: Mantripragada and Rubin (2011) suggest $40–$80/MWh.
- Wu et al. (2011) show that the RSP of FT fuels increases linearly with the mine-mouth price of coal, *when holding the other system assumptions constant*.
- Wu et al. (2011) also show that a 5% increase in the liquid fuel yield results approximately in a 5% decrease of the RSPs for all the mix levels of coal and biomass, and *vice versa*. The relationship between yield and RSP is approximately linear in the ±10% range.

This last point brings us to an interesting issue: the vast majority of the papers we surveyed considered a liquid fuel yield higher than 1.4 b/ton and the majority of them assumed a yield higher than 2 (see Figure 4).



Series: YIELD
Sample 1 40
Observations 40

Mean	1.855925
Median	2.040000
Maximum	2.620000
Minimum	0.840000
Std. Dev.	0.435923
Skewness	-0.348268
Kurtosis	2.122198
Jarque-Bera	2.092834
Probability	0.351194

Figure 4. *Histogram, descriptive statistics, and kernel density of the distribution of the yields across the surveyed papers. The 1–1.4 yield range by Sasol is highlighted using two black vertical lines.*

While obtaining such high yields at the laboratory level is not an issue, at the commercial level the actual situation is rather different: using data from Sasol in South Africa, which owns the only commercial-scale ICL plants, Höök and Aleklett (2010) found a conversion ratio of ***1–1.4 barrels/ton for bituminous coal***. These lower yields should not come as a surprise since suboptimal conditions, losses, leaks and similar factors are unavoidable realities. Coal quality issues, refining and further treatment can additionally diminish yields.

Therefore, bituminous coal feedstock costs should be 50% higher *on average* than those reported, and 100% higher when *the theoretical yields are higher than 2*. Moreover, if the approximate linear relationship between RSPs and yield ratios found by Wu et al. (2011) holds true also for large yield variations, this implies an *approximate increase of 30–40% on average in the final RSPs (and relative BEOPs)*, and an *approximate increase of 50% of the reported RSPs (and relative BEOPs) when the theoretical yields are higher than 2.*

To make matters worse, the price of coal has also risen in the last decade, as Figure 5 clearly shows. Unfortunately, most of the surveyed papers considered much lower prices than those observed in this decade (Figure 6). The mean price for bituminous coal across papers was close to 42$/ton, while almost two-thirds of the prices considered were lower than 40$ (Figure 7). Given that in 2011 the average spot price for US Central Appalachian coal was close to 80$, the purchase cost for bituminous coal feedstock reported in theoretical works should be 100% higher *on average* than what is reported. Furthermore, if we consider the difference between theoretical and empirical yield, the cost for the bituminous coal feedstock reported in theoretical works should be 200% higher on average and 300% higher when the reported theoretical yields are higher than 2.

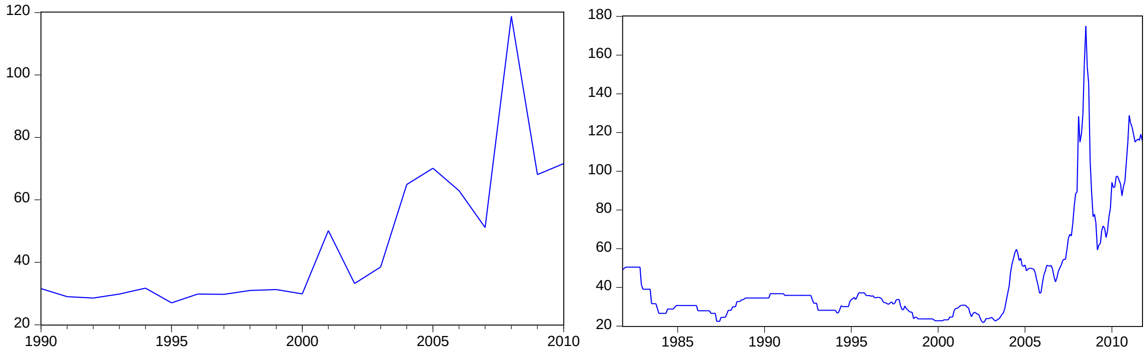
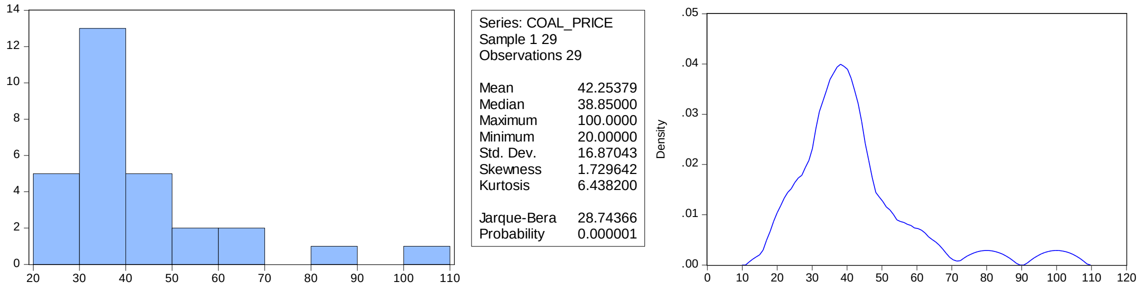


Figure 5. ***Left:*** *Average yearly US Central Appalachian coal spot price, ($/short ton), 1990-2010. Source: Platts and BP Statistical Review of World Energy. Prices are for 12500 BTU, 1.2%* SO_2*, FOB.* ***Right:*** *Monthly price for Australian thermal coal ($/short ton), November 1981 to October 2011. Source: GlobalCOAL and Indexmundi. Prices are for 12000 BTU, less than 1% sulfur, FOB.*



```
Series: COAL_PRICE
Sample 1 29
Observations 29

Mean          42.25379
Median        38.85000
Maximum       100.0000
Minimum       20.00000
Std. Dev.     16.87043
Skewness      1.729642
Kurtosis      6.438200

Jarque-Bera   28.74366
Probability   0.000001
```

Figure 6. *Histogram, descriptive statistics, and kernel density of the distribution of the coal prices across the surveyed papers.*

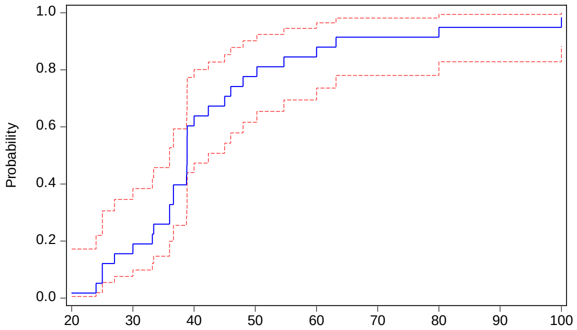


Figure 7. *Empirical Cumulative Distribution Function (CDF) of the coal prices across the surveyed papers.*

Unfortunately, many of these theoretical analyses assume conditions that are optimistic at best. For example, the DOE/NETL (2009) paper, and other papers as well, assumed a construction period of 3 years, a plant availability/capacity factor of 90%, and a plant life of 30 years:

- A construction period of 4/5 years is a much more realistic estimate. For example, the Sasol's Oryx gas to liquid (GTL) project in Qatar came online in 2007 but, due to initial problems, did not become fully operational until early 2009.
- Considering water constraints in many coal rich regions, or in general the specific local settings where potential CTL plants could be set (like Alaska), plus the fact that this is new technology not tested at the industry-commercial level (except for South Africa), then a more conservative estimate of 80–85% availability should be considered. Sasol's Oryx GTL demonstration plant in Qatar was initially riddled with problems that caused performance to be substantially less than the planned output. We note that Berg et al. (2007) showed that a decrease of 5% in the plant availability results in an increase of 8% in the RSP for FT fuels, while Talberth (2009) found that a smaller 85% availability might reduce annual revenues for the planned Fairbanks CTL plant in Alaska up to $180 million.
- A long plant life is crucial to guarantee an adequate return to investors given the high up front capital investment. Therefore, it is important to verify whether the local coal reserves will be sufficient to sustain the projected demand for 30 years. For example, Talberth (2009) found that coal deposits for the planned Fairbanks CTL plant would be depleted in 8 or 16 years (depending on the specific technical configuration), assuming no competing purchasers for the coal.

Finally, there is an input that has been downplayed by most studies so far, but can have a critical impact on economic (and environmental) viability of CTL; namely ***water use***:

1) *CTL requires large amounts of water, as previously discussed in section 2.*
2) *Waste-water treatment and discharge systems are required.*

The first aspect can exacerbate the problems of water availability and quality in regions which are poor in water resources, like China's coal regions or Wyoming and Montana in the US. Moreover, water rights in water stressed regions can be expensive (Loomis et al., 2003), while the presence of water constraints can severely impact the plant availability. Berg et al. (2007) showed that a decrease of 5% in plant availability can increase the final RSP by almost 8 %.

The second aspect implies the need to treat waste-water to remove oil and other dangerous pollutants prior to their discharge. A complete financial analysis should include an estimate of the required capital and operating costs for pollution control measures and potential damages associated with *unexpected spills, groundwater leaching, or planned discharges*, as suggested by Talberth (2009). Therefore, our analysis highlights a strong risk for CTL plants to become financial black holes, and helps explain why a country such China has strongly slowed down the development of its CTL program, as discussed in detail by Rong and Victor (2011).

4.2 Financing

The vast majority of studies examined assumed that CTL/CBTL plants are financed by using both equity and debt: more specifically, the assumed equity proportion ranges from 30% to 50%, even though some papers consider also the case of a 100% equity financed project.

The assumed return on equity range from 12% to 20%, but some analyses that considered early mover conditions or more realistic scenarios deliver a return as low as 5%. Interestingly, these latter works (i.e. see Talberth (2009) and Hatch (2008)) are also among the few that performed rigorous Net Present Value (NPV) analyses, which were negative in both cases. Instead, DOE/NETL (2009) showed that for most of its assumed CTL and CBTL plants the NPV is positive, even though the conditions assumed in that work are optimistic at best (they showed a negative NPV for BTL plants.) The cost of debt is usually assumed to be 8–9%, while lower interest rates are possible only in the case of government loan guarantees. Almost all papers admit that financing CTL projects can be difficult unless public incentives and subsidies are provided.

Berg et al. (2007) examined a large set of public incentives, including loan guarantees, investment tax credits, and excise tax credits, tax exemptions for debt, purchase agreements and grants. Except for purchase agreements, they showed that the total cost for the taxpayer would range from $87 million to $1.5 billion in the case of a 30 kb/day plant. As for purchase agreements, while they are favored by many industry experts because they ensure a minimum cash flow (thus managing oil price volatility), they can be extremely expensive and cost more than the total cost of a CTL plant. Furthermore, according to Berg et al. (2007), loan guarantees can provide greater benefits than tax incentives, which leads to a lower liquid fuel price with a very low public budget impact.

Unfortunately, Bartis et al. (2008) and Camm et al. (2008) highlighted that loan guarantees require a lot of caution: while a loan guarantee is of no use without default risk, the higher the default risk the more a loan guarantee will reduce the interest rate paid on debts because it imposes a larger cost on the government offering the default protection. In the case of a loan guarantee, the investor wants to increase the project debt share because of the government’s willingness to bear a portion of the default risk: however, this means that the government increases the probability of default. In this regard, Bartis et al. (2008) and Camm et al. (2008) found that:

- *Except at very low expected petroleum prices, if the investor holds its debt share constant, a loan guarantee has only small effects on real after-tax internal rate of return flows.*
- *How much a loan guarantee costs the government depends fundamentally on how much responsibility the government takes to oversee the project to limit the potential for moral hazard.*
- *The power of any loan guarantee to promote early CTL investment ultimately lies in how much default risk the government is willing to accept.*

Finally, we remark that all the studies we surveyed emphasize the need to combine public incentives to deal with specific project risks and improve the project's long-term competitiveness, particularly in the case of multiple risk factors. Berg et al. (2007) found that the combination of a *small state grant* early in the life of a project to facilitate its development and completion, a *loan guarantee* to improve the cash flow of the project, and an *excise tax credit* to have additional income during the ramp-up period of the plant, may be the most cost-effective intervention by government agencies. However, the cost for the taxpayers would still range from $383–$781 million, depending on the specific incentive package. Bartis et al. (2008) and Camm et al. (2008) preferred instead packages composed of a *floor on the oil price* to help the investor in case of low oil prices, *investment tax credits* to improve the private rate of return in case of high oil prices, and an *income-sharing agreement* to share net revenues between investors and the government in a situation of high oil prices.

5. Supply chain issues

Supply chain risks, vulnerabilities and uncertainties are another important topic for energy strategies involving major CTL undertakings. High oil prices or oil shortages that make CTL more attractive may also bring about problems for parts of the CTL supply chain. Mining, transportation, manufacturing and even demand are just some parts that may be negatively influenced. Business risks have been broadly reviewed by Oke and Gopalakrishnan (2009). For a CTL supply chain, we have identified three major risk categories.

In a joint report, Lloyd's of London and Chatham House have advised all businesses to begin scenario-planning exercises for the oil price spike they assert is coming in the medium term (Lloyd's, 2010). It will prove imperative that business addresses this Schumpetarian shock (a structural change to industry that can alter what is strategically relevant) in a timely fashion (Barney, 1991). Risk preparation requires a holistic view of the entire supply chain and the aim should be improving resilience and agility (Bunce and Gould, 1996; Krishnamurthy and Yauch, 2007; Schmitt and Singh, 2012), implying the loosening of tight and often brittle couplings between suppliers and manufacturers (Christopher and Towill, 2000; Towill and Christopher, 2001).

5.1 Material flow risks

Material flows involve physical movements within and between supply chain elements, such as coal transportation, movement of spare parts for CTL facilities and delivering CTL products to consumers.

Today, petroleum products supply 95% of all energy used in global transports (IPCC, 2007). Oil price volatility or supply disruptions may have a major impact on transportation and this may completely change the competitiveness of CTL facilities located at a distance from coal mines. For the USA, coal accounts for 44% of the railroad tonnage (McCollum and Ogden, 2009), while the corresponding figure for China is more than 50% (Rong and Victor, 2011). Rail capacity issues and bottlenecks have been a persistent problem in several cases and future rail policies can have significant impact on CTL supply chains. The only exception is CTL facilities at mine-mouth locations.

Outsourcing is commonly found in supply chains. While outsourcing may reduce operating costs and improve responsiveness, it also leads to increased complexity of the supply chain and often to additional transport requirements. When considering outsourcing, it is vital to analyze supplier reliability, country risk, transport reliability and supplier's supplier reliability (Levary, 2007).

Furthermore, just-in-time manufacturing systems with minimization of warehousing due to frequent replenishment of parts by parts suppliers — sometimes with multiple deliveries a day — have little tolerance for delivery delays. With little or no slack in the system (fewer warehoused parts, etc.), just one supplier failing to deliver a part or supplier hoarding can shut down an entire production chain (Schmitt and Singh, 2012). Manufacturers in particular will have to contend with increased difficulties making and delivering products as oil production declines (Hirsch et al., 2005).

5.2 Financial flow risks

Inability to settle payments, improper investments, exchange rate uncertainties and financial strength of supply chain partners and their financial handling/practices can also give rise to risks. In a globalized economy, the exchange rate has a significant influence on a company's profit after tax, supplier selection, market development and other operation decisions. A financially weak supply chain partner can bring down the entire chain unless alternatives can be found. Kerr (2006) also stresses that money-handling practices can complicate the financial flow within the supply chain. For example, lack of control and visibility of procure-to-pay process may cause legal complications and high velocity/frequency payments necessitate urgent attention. Additional financial issues were discussed in section 4.2

5.3 Information flow risks

Supply chains are also influenced by information flows such as demand, inventory status, order fulfillments, design changes and capacity updates. Some observers even perceive information as a bonding agent between material and financial flows. Firstly, accuracy is a key factor for risk analysis since incorrect or inaccurate information can affect decisions with major repercussions for the entire supply chain.

Information system security and disruptions could arise from internally ill-managed systems or potentially by outside sources such as industrial espionage, hackers or similar (Faisal et al., 2007). Intellectual property rights and patents are also associated with increasing information flows within the supply chain, but there is also a risk for exposing trade secrets or inefficient information exchange flow hampering improvements. Information outsourcing allows a company to focus on core-competence, but this comes at the expense of increased risk exposure to vendor opportunism, information security apprehension, hidden costs, loss of control, service debasement, disagreements, disputes, litigation and poaching (Faisel et al., 2007).

6. Concluding discussions

The technology behind CTL is both proven and flexible, especially for ICL. DCL and ICL systems have comparable system efficiencies, essentially resulting in a stalemate. However, it is vital to look at the entire system and also integrate factors outside the CTL plant into the analysis. Höök and Aleklett (2010) earlier concluded that ICL seems to be the more likely option for a CTL development based on higher flexibility, better environmental capabilities and stronger supporting experience and infrastructure.

We also note that coal production is a major factor in CTL feasibility. Significant CTL production requires equally significant coal production and resources that only a few countries or regions realistically can develop. CTL capacities in the Mb/d-range will effectively be limited to the largest coal countries in the world: China, USA, India, Russia, Australia and South Africa. Even if several Mb/d could be derived from CTL, this would account for only a minor share of global oil production and barely offset the decline in existing oil production (Höök and Aleklett, 2010).

Furthermore, environmental impacts of large scale development of CTL must be considered. Political complications of developing such a CO_2-intensive technology could become an obstacle in countries where anthropogenic climate change is seen as an important question. Although CCS and low emission configurations are available, required coal mining increases can be seen as significant environmental impact. Obtaining public acceptance, and later political acceptance, for CTL might be problematic. Furthermore, water use is commonly overlooked although CTL is a water-intensive undertaking. In fact, water issues were identified as one of the most important factors behind the Chinese policy reversal (Rong and Victor, 2011).

A review of recently published studies shows that coal costs were often underestimated. Liquid yield was assumed to be significantly higher than seen in the only available commercial example (i.e. Sasol). We also note that almost all papers admit that financing CTL projects can be difficult unless public incentives and subsidies are provided. To conclude, our analysis highlights a strong risk for CTL plants to become financial black holes, and helps explain why China has strongly slowed the development of its CTL program, as discussed in detail by Rong and Victor (2011).

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