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Hydrocarbon liquefaction: viability as a peak oil mitigation strategy

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Abstract
Current world capacity of hydrocarbon liquefaction is around 400,000 barrels per day (kb/d), providing a marginal share of the global liquid fuel supply. This study performs a broad review of technical, economic, environmental, and supply chains issues related to coal-to-liquids (CTL) and gas-to-liquids (GTL). We find three issues predominate. First, significant amounts of coal and gas would be required to obtain anything more than a marginal production of liquids. Second, the economics of CTL plants are clearly prohibitive, but are better for GTL. Nevertheless, large scale GTL plants still require very high upfront costs, and for three real world GTL plants out of four, the final cost has been so far approximately three times that initially budgeted. Small scale GTL holds potential for associated gas. Third, CTL and GTL both incur significant environmental impacts, ranging from increased greenhouse gas emissions (in the case of CTL) to water contamination. Environmental concerns may significantly affect growth of these projects until adequate solutions are found.

Key words: hydrocarbon liquefaction, gas-to-liquids, CTL, GTL, coal-to-liquids, peak oil

Nomenclature.

ATR	Auto-Thermal Reformer
b, b/d, $/b	barrel ≈ 159 litre, barrel per day, dollar per barrel
BTL	Biomass-to-Liquids
CAPEX	Capital expenditures
CBTL	Coal / Biomass to Liquids
CBTL1	coal + biomass to FTL fuels (diesel/jet, gasoline) + electricity (~12% of input feedstock is biomass - HHV basis), [from Liu *et al* 2011].
CBTL2-OT-CCS	It is a plant designed with the same FTL output capacity as CTL-OT-CCS (36,655 barrels per day) but with some of the coal input replaced by 1 million dry tonnes of switch grass per year [from Kreutz *et al*. 2008].
CCS	CO_2 capture and storage
CCS-A	Capturing only the pre-combustion (Selexol-based) CO_2 from the gasification and FT units (99% capture), but not the CO_2 from the gas turbine exhaust gases [from Mantripragada and Rubin 2011]
CCS-B	Capturing both pre-combustion (Selexol) and post-combustion (MEA, 90% capture) CO_2. In this case, exhaust CO_2 from the gas turbine is captured - using an amine-based (MEA) chemical absorption process [from Mantripragada and Rubin 2011]
CTL	Coal-to-Liquids
FT	Fischer-Tropsch
GTL	Gas to Liquids
IGCC	Integrated gasification combined cycle
IRR	Internal rate of return
LNG	Liquefied Natural Gas
MPGs	Mixed Prairie Grasses
MCF	1,000 cubic feet
NPV	Net Present Value
-OT	FTL synthesis systems that pass syngas only once through (OT) synthesis reactor and use unconverted syngas to make coproduct power in a combined cycle power plant [from Kreutz *et al*. 2008 and Liu *et al* 2011].
-OTA	OT system to which an autothermal reformer and extra CO_2 capture equipment are added downstream of synthesis to increase the fraction of feedstock C not in FTL products that is captured/stored as CO_2 [from Kreutz *et al*. 2008 and Liu *et al* 2011]
-OTS	OT plant design that uses biomass grown on carbon-depleted soils, leading to substantial buildup/storage of carbon in soil and roots, complementing underground storage of CO_2 captured at the conversion facility CO_2 [from Kreutz *et al.* 2008 and Liu *et al*. 2011].
-OTAS	OTA plant design that uses biomass grown on carbon-depleted soils, leading to substantial buildup/storage of carbon in soil and roots, complementing underground storage of CO_2 captured at the conversion facility [from Kreutz *et al.* 2008 and Liu *et al.* 2011].
ROI	Return On Investment
ROR	Rate of Return
-RC	FTL synthesis systems that recycle (RC) unconverted syngas to maximize FTL production
-S	Biomass is mixed prairie grasses grown on C-depleted soils providing substantial soil/root C build-up over the life of the FTL production facility as a biomass carbon storage mechanism complementing underground storage of supercritical photosynthetic CO_2 [from Kreutz *et al.* 2008].
-V	CO_2 is vented

1. Introduction

Oil is the largest contributor to mankind's energy needs and provides over 90% of all transportation energy (IPCC, 2007). Each year, new production must be brought on-stream to offset declining output from current production. More than two thirds of current crude oil production may need replacement by 2030 simply to meet current demand. This is likely to prove extremely challenging, and there is a significant risk of a peak of conventional oil production before 2020 (UKERC, 2009).

Peaking global oil production would imply a peak in oil-sourced liquid fuels. This could potentially severely impact the world economy (Fantazzini *et al.*, 2011), especially if alternative sources of energy and liquid fuels are unable to "*fill the gap*" between climbing demand and falling production on the timescale required. Coal-to-liquids (CTL) is often proposed as a possible mitigation strategy and 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 with coal-based synthetic fuels is the German military during the Second World War. It produced 90% of its jet fuel and 50% of its diesel through CTL (US DOE, 2009; Sasol, 2005). South Africa developed CTL in 1960s and this has remained an important part of their liquid fuel supply ever since. Demonstration and pilot plants have shown the technical feasibility of CTL as a provider of liquid fuels at smaller scales worldwide. Proponents of CTL claim that it will be capable of full or partial mitigation of the expected shortfall of conventional oil due to a global oil peak.

Similarly, liquefaction of natural methane gas (gas-to-liquids, or GTL) has emerged as a promising option to monetize stranded gas assets (Fleisch *et al.*, 2002; Wood *et al.*, 2012). Several established processes have been commercially proven in various projects and could be used as substitutes for petroleum-derived fuels, for example, shale gas could potentially mitigate part of the expected liquid fuel shortage which would arise from peak oil.

At present, world production of conventional oil stands at around 85 million barrels/day (Mb/d) and has been roughly constant since mid-2004 (Fantazzini *et al.*, 2011). Current world CTL and GTL capacity is around 400 kb/d. Existing estimates place the global decline in existing oil production rates at between 3 and 8% annually, or in other words, new capacity of 3–7 Mb/d is required every year (Höök *et al.*, 2009). Various observers advocate hydrocarbon liquefaction to provide everything from a minor role to production levels of several Mb/d. What expectations are reasonable? To assess this question, this paper reviews the technology, economics, environmental impact and supply chain of CTL and GTL.

2. Hydrocarbon liquefaction

This section performs a brief overview of the underlying chemistry and the main technology options from the pioneering efforts of German chemists in the early 20th century.

2.1 Underlying chemistry

Coal is a complex compound consisting of carbon, hydrogen, oxygen, sulphur, and minor proportions of other elements. It is an aggregate of microscopically distinguishable, physically distinct and chemically different subparts baked together. CTL works by breaking up the solid hydrocarbon structures found in coal. 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 chemical reactions involved in reality are significantly more complex than the simple overview presented here.

The Bergius process is the foundation for DCL. It splits coal into shorter hydrocarbons, resembling ordinary crude oil, through reaction with hydrogen under high pressure and temperature (Reaction 1).

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

Alternatively, it is also possible to assemble short and gaseous hydrocarbon chains into liquids for both natural gas (i.e. GTL) and via indirect coal liquefaction (i.e. ICL) featuring the Fischer-Tropsch (FT) process displayed in Reaction 2.

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

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 (Reaction 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 reactions with a suitable catalyst. More specifically, the FT-process yields two products, described by two different reactions (Reaction 4).

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

The CTL processes are influenced significantly by the properties of the coal feedstock (ash content, grindability, sulphur content, plasticity, caking properties, etc.). GTL displays fewer issues in this respect since natural gas is a more homogenous feedstock. Process efficiency and yield are further influenced by the choice of catalyst (Bacaud *et al*., 1994; Longwell *et al*., 1995; Duvenhage and Coville, 2006; Yang *et al*., 2006; Khodarov *et al*., 2007). 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). A more detailed discussion of FT-synthesis via ICL-technology can be found in Bridgwater *et al*. (1994), Dry (2002) and de Klerk (2009).

2.2 CTL technology options

CTL technology, using coal or coal plus biomass feedstock, 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 commenced operations a few years ago.

2.2.1 Pyrolysis

In a pyrolysis process, heat decomposes the coal expelling volatile compounds, leading to increased carbon content in the remaining solid, leaving products such as char, semi-coke and coke. Pyrolysis' primary use is to upgrade low-ranking coals by increasing their calorific value and reducing sulphur content and other pollutants. A demonstration plant for upgrading coal was built in the USA operating 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, integration of reforming of methane by CO_2 and coal pyrolysis has improved tar yields up to 32% (Wang *et al.*, 2011). Coal tar requires further refinement before it is usable in engines. The efficiency and liquid yields of pyrolysis processes are inherently 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 (Reaction 1) forms the chemical basis of DCL. Thermal energy is used to induce homolytic bond scissions in coal molecules to produce free radicals that can subsequently isomerise, decompose or be used in other chemical reactions normally performed at high temperature and pressures (Huang and Schobert, 2005; de Klerk, 2009). Adding hydrogen and a suitable catalyst initiates "*hydro-cracking*" where long, solid hydrocarbon chains rupture into shorter ones that may be liquid or gaseous. Many closely-related DCL–technologies have been developed.

DCL processes are classified into two major types, single-stage and two-stage liquefaction. The single-stage concept uses a solvent to facilitate both coal extraction and hydrogen addition in a combined reactor. Only a few single-stage designs have been demonstrated, the rest being abandoned (de Klerk, 2009). The two-stage concept uses two reactors in series, where the first converts coal to a soluble form with little change in chemical composition while the second reactor adds hydrogen converting the dissolved coal into liquid products.

Some smaller DCL 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 commercial DCL plant in the Inner Mongolia Autonomous Region (Fletcher *et al.*, 2004), which has recently become operational.

The advantage of DCL is its very high liquid yield – potentially >70% of the dry weight coal (Benito *et al.*, 1994; Couch, 2008). DCL liquids are typically of higher quality (i.e. less nitrogen, sulphur, phenols, aromatics, etc.), due to hydrogen addition, than liquids obtained from pyrolysis. The DCL liquids are effectively a synthetic crude oil (syncrude) and are directly usable in power generation or in petrochemical processes. However, they require further 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.

2.2.3 Indirect coal liquefaction (ICL)

In contrast to the approach of DCL, indirect liquefaction breaks down coal into other compounds via gasification (see Reaction 3). The resulting syngas is modified to obtain the required balance of hydrogen and carbon monoxide, then cleaned, removing sulphur 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 (Reactions 2–4).

Although ICL has been used in a number of plants since the 1940s, many of them have been small capacity demonstration or pilot plants of 5,000 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, which is 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 GTL technology options

There are many ways to liquefy natural gas, and several pilot plants, trial projects and research initiatives exist. However, only two companies – Sasol and Shell – have built large-scale commercial plants (>5,000 b/d capacity). The GTL industry is essentially immature and many important patents are held by relatively few companies (Wood *et al.*, 2012). Established GTL approaches have much in common with ICL technologies, as they both work with FT-synthesis and gaseous chemistry. Both high temperature and low temperature FT synthesis can be used to provide liquid fuels.

There are commonly three main stages in a GTL facility: synthesis gas generation, FT reaction and product upgrading (Panahi *et al.*, 2012). Auto-thermal reforming is the preferred technology to generate syngas since it offers better H_2/CO ratio compared to all alternatives (Iandoli and Kjelstrup, 2007). The syngas generation stage is often the most capital intensive part of a GTL plant. A schematic process chain of a GTL complex can be seen in Figure 1.

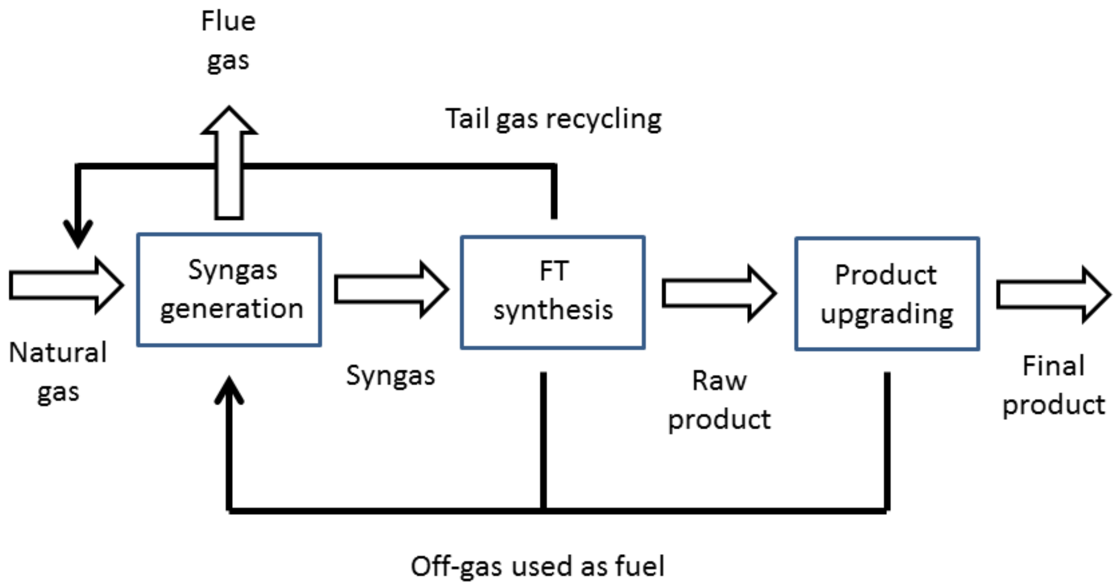

Figure 1. *Simplified process chain for a GTL complex.*

It is also possible to use GTL to provide oxygenates such as methanol or dimethyl ether (DME) (Haid and Koss, 2001). Methanol can also be converted into a high-quality gasoline through the Mobil methanol-to-gasoline (MTG) process (Yurchak, 1988). A GTL plant with 14,500 b/d capacity using the MTG process was operational from 1985 to 1997 in New Zealand before the gasoline production was permanently idled to provide only chemical grade methanol (Fleisch *et al.*, 2002).

2.3.1 Commercial GTL developments

Sasol developed the Sasol slurry phase distillate GTL process in the 1980s from their CTL technologies. Hot syngas is bubbled through a slurry of catalyst particles and liquid reaction products (Fleisch *et al*., 2002). Initially iron was used as a catalyst, but recent developments have used cobalt-based catalysts providing greater conversion rates.

Developments by Sasol resulted in the construction of a stand-alone GTL plant with a capacity of 22,000 b/d in Mossel Bay in 1992. The project became known as Mossgas and is considered the first commercial GTL plant (Wood *et al*., 2012). A subsequent collaboration between Sasol and Qatar Petroleum used auto-thermal syngas production, slurry phase FT-reactors and an isocracking product upgrading technology to develop a 32,400 b/d facility known as the Oryx plant in Qatar. The project agreement was signed in 2001 and completed in 2008 after delays and budget overruns.

Sasol later engaged in a GTL feasibility study for a Nigerian plant together with Texaco in 1998. The Escravos project was agreed in 2002 and involved Sasol, Chevron Corporation and Nigerian National Petroleum Company, using the same design as the Oryx project. Delays and cost overruns caused Sasol to withdraw in 2009, although their technologies are still used under license. The capacity of the Escravos GTL plant will be 32,400 b/d when completed in 2013 – similar to Oryx in design and size.

In 1993, a joint-venture consisting of Shell, Mitsubishi, Petronas and Sarawak State completed a GTL plant in Bintulu, with a final capacity of 14,700 b/d. Experience from Bintulu was used by Shell in the design of the world's largest GTL project, the Pearl GTL plant in Ras Laffan Industrial City, Qatar. Construction started in 2007 as a joint venture between Shell and Qatar Petroleum, and production began in 2011, reaching full capacity of 140,000 b/d in 2012.

2.4 System efficiencies

Thermal or energy efficiency is the percentage of the energy in the feed-stock that is converted into energy output as products. Low thermal efficiencies, often in the range of 45–55%, have been a major argument against hydrocarbon liquefaction (Liu *et al*., 2010). DCL is commonly seen as more efficient for producing 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 formation of an unrefined syncrude requiring additional processing into useable liquid fuels. In contrast, ICL efficiencies often refer to the final products. Caution should always be exercised when dealing with efficiencies.

The estimated overall efficiency of the DCL-process is 73% (Comolli, 1999). Other groups have estimated a thermal efficiency of 50-70% (WCI, 2006; Williams and Larson, 2003; Bellman *et al*., 2007). However, Sovacool *et al.* (2011) criticized these estimates as misleading, because industry tends to compare the heating value of the resulting liquids with that 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 efficiency for FT-synthesis used in ICL and GTL is around 50%, while the theoretical maximum has been estimated at 60–65% (van den Burgt *et al*., 1988; Eilers *et al*., 1990; Fleisch *et al*., 2002; Steynberg and Nel, 2004). Tijmensen *et al*., (2002) give overall energy efficiencies ranging from 33–50% for ICL co-using various biomass blends. Detailed studies on methanol and DME production found efficiencies of 58.3% and 55.1% (Williams and Larson, 2003), so fine-tuned ICL systems can reach high efficiencies.

In essence, there is no significant efficiency advantage for either DCL or ICL, while GTL is somewhat more efficient. As a rule-of-thumb, a 50-60% thermal efficiency can be used for hydrocarbon liquefaction in general assessments. This implies that only half of the coal energy invested in liquefaction will come out as energy available as transportation fuel.

2.5 Process requirements

CTL coal consumption has been assessed by many groups. 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 US 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 relatively 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 has been estimated that large scale CTL production will be limited to about 6 countries with large coal reserves and the ability to divert significant fractions of that coal to liquefaction (Höök and Aleklett, 2010).

Obtaining reliable GTL gas consumption figures is harder. For example, the Pearl project is designed to consume 45.3 Mm^3 per day to yield 120,000 b/d of condensate, propane, butane, and ethane and 140,000 b/d of GTL products (Wood *et al.*, 2012). The National Petroleum Council (2007) gives an average conversion factor of 283 m^3 natural gas per barrel GTL product. Others have estimated the carbon efficiency, i.e. the amount of carbon in the feed gas converted to saleable products, at 53-77% (Fleisch *et al.*, 2002).

Water is a vital part of the conversion processes and CTL is highly water intensive (Mielke *et al.*, 2010). Zhang *et al.* (2009) state that each ton of synthetic oil output requires 8–9 tons of freshwater for DCL and 12–14 tons of fresh water in ICL. In contrast, the US Department of Energy found that water consumption is approximately equivalent for DCL and ICL at around 5–6 ton water/ton of oil (National Energy Technology Laboratory, 2006) and RAND calculated 6–12 ton water/ton of oil (RAND, 2008).

3. Environmental issues

Environmental impacts from hydrocarbon liquefaction can be broadly classified into two categories: those that accompany the extraction of the coal and gas feedstock, and apply to all uses of the feedstock, and those that are specific to the manufacture of liquid fuel.

3.1 Environmental impacts from CTL

When considering CTL, first we will examine impacts that apply equally to all industrial applications of coal, including landscape modification, particulate emissions and acid mine drainage. We will then examine water consumption, water contamination and greenhouse gas emissions specific to CTL.

Landscape modification

Three types of surface mining are generally used to extract shallow 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 a strip is excavated, it is placed in the excavation of the previous strip.

Mountaintop removal is applicable to horizontal coal seams in mountainous country, notably the Appalachian Mountains in the United States. At current coal prices, mountaintop removal is often the only cost-effective way to mine coal in this area. Explosives are used to remove the entire mountain top overburden and vegetation, including forests, which is placed directly in stream valleys. 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).

Particulate emissions and coal processing

Particulates are emitted both when coal is mined and via wind erosion until new vegetation covers reclaimed land. Hendryx *et al*. (2008) found that, after accounting for other variables, lung cancer mortality was higher in Appalachian counties with extensive coal mining. Coal dust contains carcinogenic compounds and metals including zinc, cadmium, nickel and arsenic. The mining and cleaning of coal at local processing sites creates large quantities of ambient particulate matter as well as contaminated water.

Water contamination and water consumption

Water is used extensively throughout the coal mining and liquefaction process. Surface mines use water for dust abatement and all coal must be washed to remove soil and other contaminants before further processing. Water requirements often cause local aquifers to be depleted near coal mines. As rainwater drains through the mine it reacts with and oxidises pyrite (FeS_2) in the coal, producing sulphuric acid that may leach into local aquifers in a process called acid mine drainage (AMD). AMD often continues after the mine is no longer operational. Other contaminants that may leach into the water supply from the entire mining process include cadmium, selenium, arsenic, copper, lead, mercury, ammonia, sulphur, sulphate, nitrates, nitric acid, tars, oils, fluorides, chlorides, sodium, iron and cyanide (Spath *et al*., 1999; Palmer *et al*., 2010).

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 of water per ton of fuel, as noted earlier. CTL may generate or amplify water shortages in certain regions.

Cooling, boiler and process water in CTL plants needs to be of reasonable quality to prevent corrosion and/or deposit formation, and treatment is typically needed. Discharged water must be treated before it can be released to the environment without causing harm (Lei and Zhang, 2009). Rong and Victor (2011) point to water availability and water quality issues as important factors behind the recent caution toward CTL in China.

Greenhouse gas emissions

The CTL process produces significant amounts of carbon dioxide, the greenhouse gas primarily driving anthropogenic global warming. From a life-cycle perspective, it is also important to include 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, called coal bed methane (CBM) that is released during the mining of coal. Methane represents approximately 14% of global GHG emissions (in CO_2-equivalent) and CBM accounts for approximately 8% of total methane emissions (World Coal Association, 2012).

Annual worldwide CBM release in 2000 was estimated to be 0.24 Gt CO_2-equivalent. This compares with approximately 35 Gt of anthropogenic CO_2 released annually (IPCC 2007). Brandt and Farrell (2007) find that even a partial transition to coal-to-liquids synfuels could raise upstream GHG emissions by several Gt of carbon per year by mid-century, approximately 7% of the current total carbon emissions, unless mitigation steps are taken. However, there are CTL plant configurations using 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.

3.2 Environmental impacts from GTL

For GTL, the natural gas can come from conventional or unconventional sources. Unconventional sources include biogas, shale or tight gas and coal-bed methane. There are current concerns over the impact of obtaining tight gas using hydraulic fracturing, also known as "*hydro-fracturing*" or "*fracking*." Some environmental impacts are common to conventional and unconventional gas extraction, such as GHG emissions, particulate emissions and water requirements. Others are unique to conventional extraction, like gas flaring, or to unconventional extraction, including possible contamination of aquifers, wastewater disposal and seismic activity.

Unconventional gas production

Worldwide there are 400 tcm (trillion cubic meters) of conventional gas and almost as much unconventional gas resource (IEA, 2011), with developed reserves standing at 208 tcm (BP, 2012). Unconventional gas production in the U.S. passed conventional gas production in 2009, and shale gas alone is expected to comprise 49% of all U.S. gas production by 2035 (EIA, 2012a).

The hydro-fracturing process involves drilling a well horizontally through shale formations that usually lie more than 1,000 meters below the ground surface. The well casing is perforated using explosives, then a mixture of water, sand and chemicals is pumped down at very high pressures, causing the shale to fracture and release the trapped gas (see also Chew, this volume). When the well pressure is released, much of the hydro fracturing fluid and gas flow to the surface.

The reported and potential negative environmental impacts include:

- Occasional contaminated surface water from illegal dumping of used hydro fracturing fluid and accidental spills
- Occasional contaminated aquifer water (PNAS, 2011)

- Wastewater containing radioactive and other materials that sewage treatment plants are incapable of treating
- Minor induced seismicity
- Methane leakage

The International Energy Agency points out that if the environmental concerns about hydro-fracturing are not addressed by industry, the expansion of the method worldwide could be slowed or halted (IEA, 2012c). Several countries have completely banned or declared moratoria on hydro-fracturing, including France, Bulgaria, Romania, South Africa, Germany and Ireland.

Greenhouse gas emissions

Gross GHG emissions from GTL are not likely to be significant in comparison to conventional oil. The IEA estimates that only 750,000 b/d will be produced by 2035, mostly by Qatar (IEA, 2010). It is possible to prevent approximately 90% of the upstream release of CO_2 from the GTL process through carbon capture and sequestration (Williams and Larson, 2003).

Water contamination

Water contamination is primarily caused by surface water pollution from improperly disposed wastewater and spills, well leaks and (as yet unproven) underground, upward fluid migration. The industry has used over 2,500 different chemicals in the fracturing process, to control bacterial growth, inhibit corrosion, decrease pumping friction and improve proppant placement (proppant is sand-size material helping to keep fractures open) (US House, 2011). Many companies do not disclose the chemicals used, but they include benzene, lead and at least 29 other known or possible carcinogens that are regulated under the U.S. Safe Drinking Water Act or are listed as hazardous air pollutants under the U.S. Clean Air Act.

Of the 17 million litres of hydro-fracturing fluid that can be pumped into a well, up to one third is recovered (Myers 2012). Myers used computer modelling to suggest that the typically slow upward migration of the remaining water through very thick shale layers, generally thought to take tens of thousands of years, may be greatly accelerated by hydro-fracturing, and in certain scenarios this time could be reduced to less than 100 years. Where there are pre-existing geologic fractures in the rock, the upward fluid migration could occur in as little as a few decades. A U.S. Government panel called the possibility of such accelerated fluid migration “remote” (US Department of Energy, 2011). Since there are as yet no monitoring systems in place that can demonstrate this effect conclusively (Myers, 2012), computer modelling is just an initial attempt to understand and predict aquifer contamination.

Seismic activity

The US National Research Council (NRC, 2012) conducted an extensive review of the literature that discusses seismic activity due to gas and oil drilling. Seismic activity has been noted since the 1920s but events are rare when compared to the total number of wells drilled. There is only one confirmed instance of seismic activity directly due to hydro fracturing wells, in the U.K., with a magnitude of 2.3 (de Pater and Baisch, 2011), and one suspected, but not confirmed, case in the U.S. (Holland, 2012) with magnitude ~2.8. Other reports of seismic activity can be attributed to the injection of wastewater into deep wells, rather than to hydro-fracturing. The estimated overall risk of seismic activity due to hydro-fracturing is currently very low.

4. Economic issues

The high cost of building a CTL plant is a key obstacle to the development of this energy technology. 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 impacted in the financial analysis of 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[1] and Total Plant Costs (TPC) for a CTL plant, as well as raising the break even crude oil equivalent price (BEOP) of CTL products. For example, Figure 2 reports the time evolution of the Chemical Engineering Plant Cost Index (CEPCI), which is a dimensionless number used to update the capital cost required to build a chemical plant from a past date to a later time. This index is widely accepted and consists of subcomponents dealing with equipment, labour costs, buildings, engineering, supervision and other parameters affecting costs. Kreutz *et al.* (2008) provide 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.

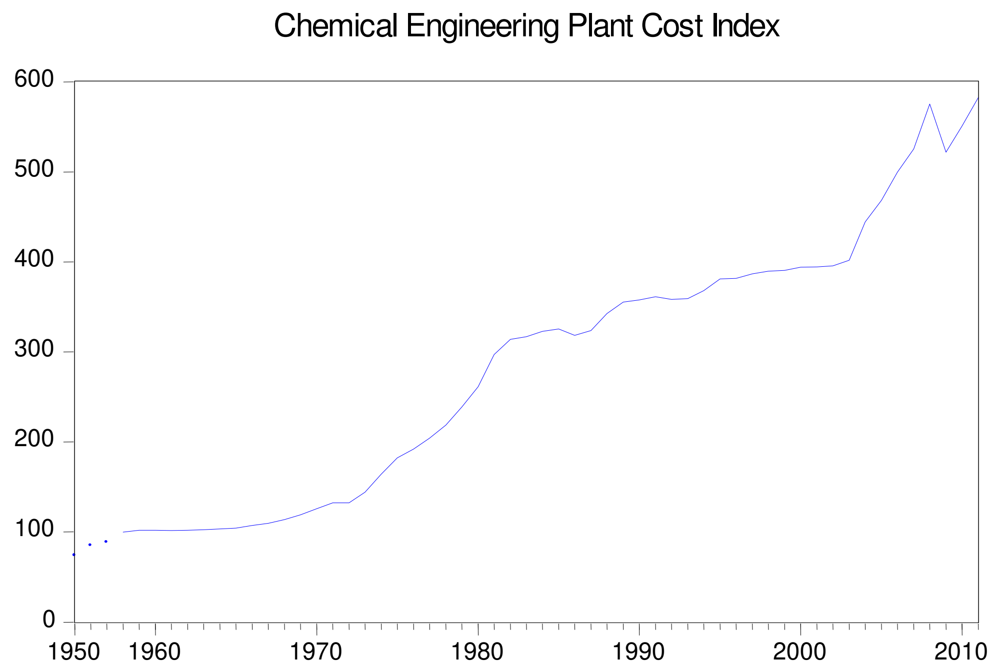

Figure 2. *Chemical Engineering Plant Cost Index (CEPCI)*

4.1 CTL economics

Due to cost escalation, financial analyses of CTL performed before 2005/2006 have become largely unrealistic, as shown by Höök and Aleklett (2010). Consequently, we examine here only studies from 2007 onwards.

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1 An overnight cost is the cost incurred for building a plant immediately, i.e. “overnight”. It does not include any assumptions on interest expenses that occur during the construction period.

Tables 1–3 in the Appendix 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 are calculated with the data in the original papers, whenever possible): differently from the studies before 2006 (see Höök and Aleklett (2010) for a review), the works published in the last five years highlight a considerable reduction in planned CTL plant capacity. All studies examined here (except one) assumed a capacity equal to or lower than 50 kb/d, and some even analyse coal- and biomass-to-liquids (CBTL) or biomass-to-liquids (BTL) plants with a capacity as low as 5 kb/d. This is mainly due to construction cost escalation: if we consider a 50 kb/d plant, the estimated total plant cost now lies 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 synfuels that is probably the best indicator of the changed energy environment: it now ranges from $50/b to $200/b, with a mean close to $85/b.

To account for inflation, the TPCs and BEOPs reported in Tables 1-3 have been raised to 2011$ using the Chemical Engineering Plant Cost Index (CEPCI). For the sake of brevity, figures 3 and 4 show the updated TPCs and BEOPs for CTL plants (left figures) and CBTL/BTL plants (right figures), without separating them based on additional technical details (e.g. with and without CCS).

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 to $110/b. All plants in Figure 4 with BEOPs lower than $60/b are without CCS. Venting CO_2 to the atmosphere is the cheapest option, although the environmental costs of such an option are considerable. For a detailed analysis of natural resource damage costs, see Talberth (2009) and references therein.

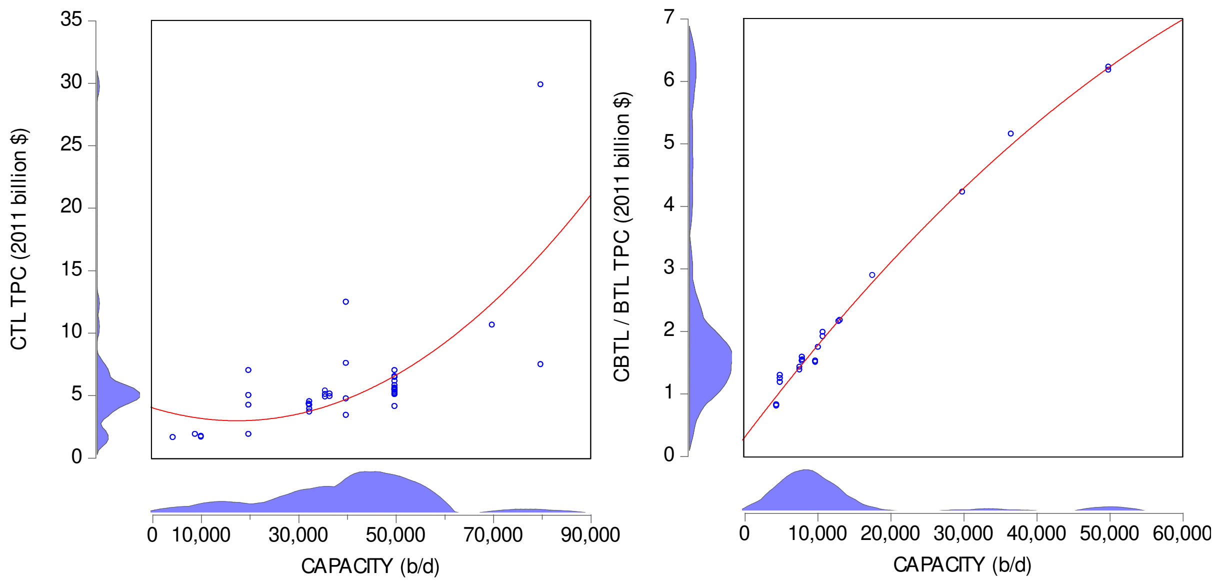

Figure 3. *TPCs for CTL plants (left) and CBTL/BTL plants (right) expressed in 2011 billion $, with kernel densities on the axis borders and a polynomial fit of second order.*

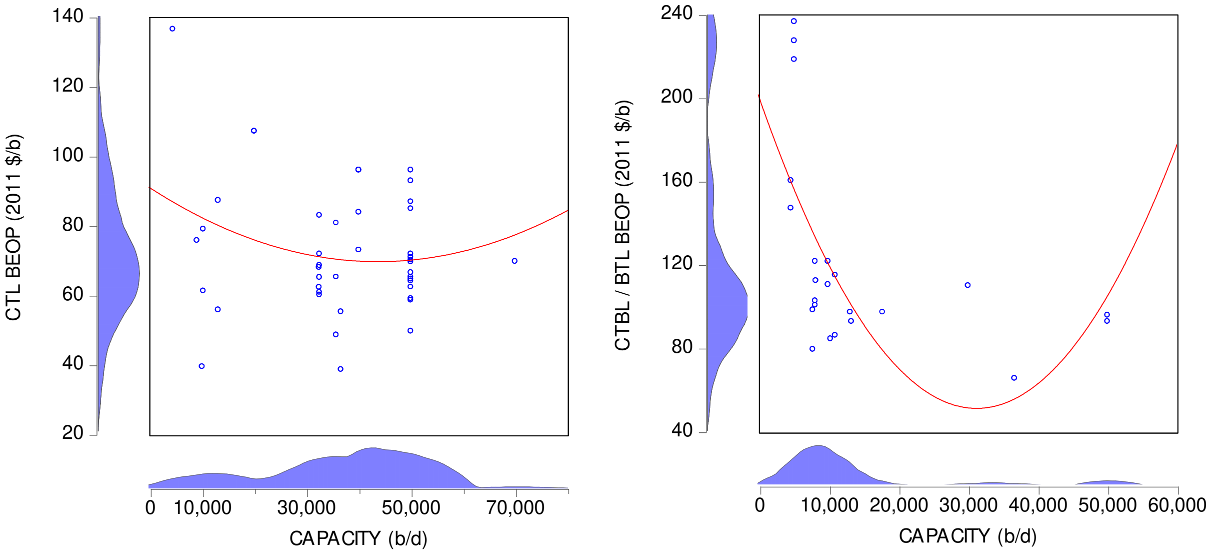

Figure 4. *BEOPs for CTL plants (left) and CBTL/BTL plants (right) expressed in 2011 $/b, with kernel densities on the axis borders and a polynomial fit of second order.*

4.1.1 Sensitivity analyses

Many papers surveyed for this work performed sensitivity analysis in which the authors changed some inputs and verified how much the estimated TPCs and synfuel Required Selling Prices (RSPs) changed as a result. We discuss below the most important results.

- Most studies used the assumption of 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) may behave more like an early mover[2]. This problem was analysed 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. 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 constrained 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. the capacity factor [3]).

2 Early mover conditions are intended to better reflect the costs and risks of being first movers: a conservative training algorithm for equipment components in estimating capital costs and much higher financing cost. See Williams et al. (2009) for details.

3 The capacity factor is the ratio of the actual output of a plant over a period of time and its potential output if it had operated at full nameplate capacity the entire time.

- The cost of carbon sequestration implies an increase in the price of FT liquids of between \$5/b and \$20/b (a 10–30% increase) depending on the chosen technical configuration.
- Synfuels 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 generous electricity selling price is required: Mantripragada and Rubin (2011) suggest \$40–\$80/MWh.
- Wu *et al*. (2011) show that the RSP of synfuel 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 raises an interesting issue: the vast majority of the papers we surveyed considered a liquid fuel yield higher than 1.4 b/ton and most assumed a yield higher than 2 b/ton (see Figure 5).

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 world's only commercial-scale ICL plants, Höök and Aleklett (2010) found a conversion ratio of only 1–1.4 b/ton for bituminous coal. These lower yields should not come as a surprise since sub-optimal conditions, losses, leaks and similar factors are unavoidable realities. Coal quality issues, refining and further treatment can additionally diminish yields.

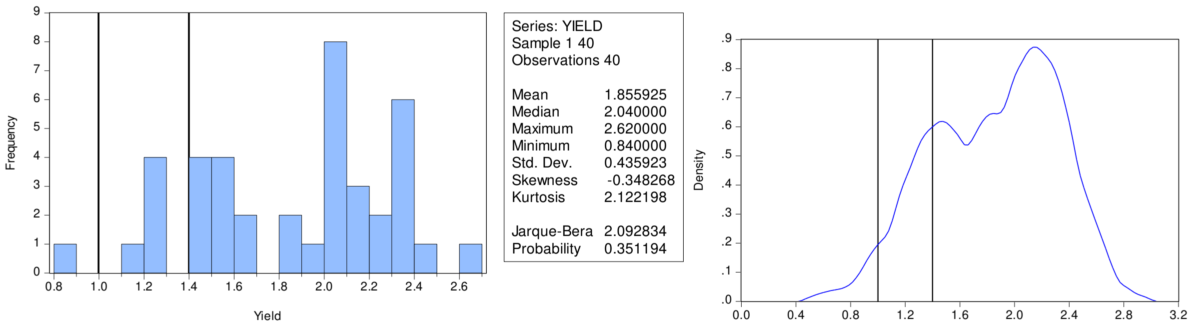

Figure 5. *Histogram, descriptive statistics, and kernel density of the distribution of the yields across the surveyed papers. The 1–1.4 b/ton yield range by Sasol is highlighted using two black vertical lines.*

Therefore, in Tables 1-3, the bituminous coal feedstock costs should be 50% higher *on average* than those reported, and 100% higher when *the theoretical yields are higher than 2 barrels/ton*. 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 b/ton.*

To make matters worse, the price of coal has also risen in the last decade, as Figure 6 clearly shows. Unfortunately, most of the surveyed papers considered much lower prices than those observed in this decade (Figure 7). The mean price for bituminous coal throughout the literature was close to \$42/ton, while almost two-thirds of the prices considered were lower than \$40. . Given that in 2011 the average spot price for US Central Appalachian coal was close to \$80/ton, 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 we have noted between theoretical and empirical yields, 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 b/ton.

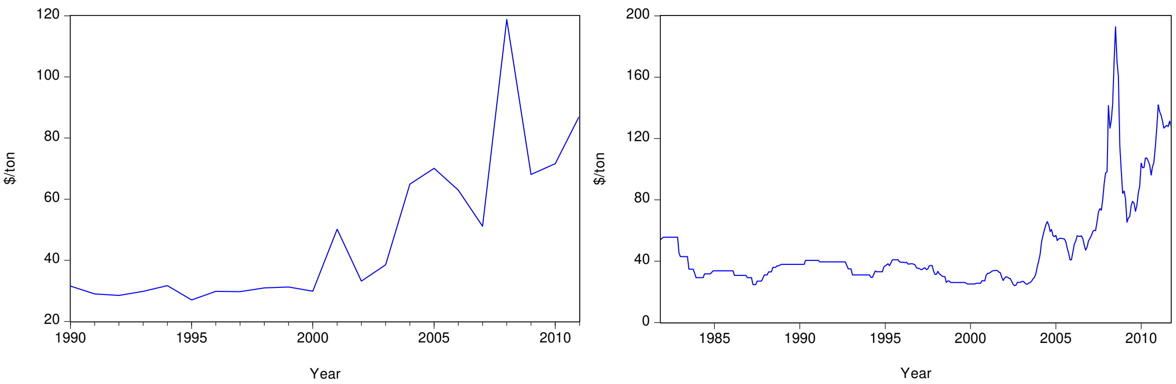

Figure 6. ***Left:*** *Average yearly US Central Appalachian coal spot price, (\$/short ton), 1990-2011. Source: Platts and BP Statistical Review of World Energy. Prices are for 12,500 BTU, 1.2%* SO_2*, FOB.* ***Right:*** *Monthly price for Australian thermal coal (\$/short ton), November 1981 to October 2011. Source: GlobalCOAL and Indexmundi. Prices are for 12,000 BTU, less than 1% sulphur, FOB. Both prices are in nominal terms.*

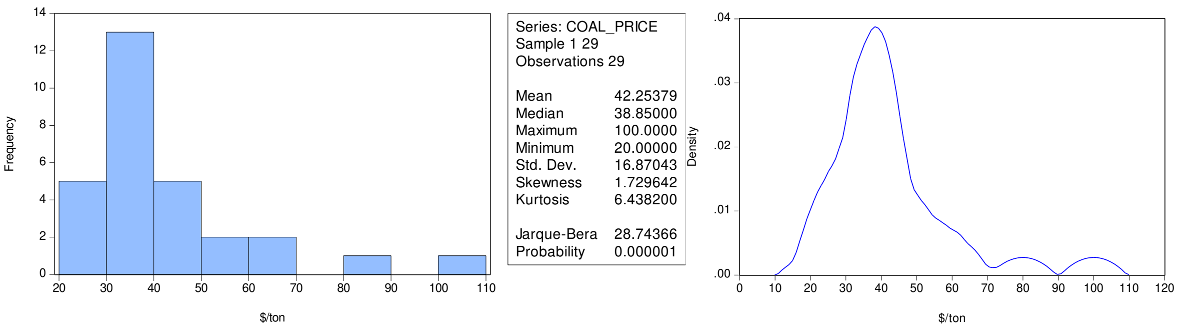

Figure 7. *Histogram, descriptive statistics, and kernel density of the distribution of the coal prices across the surveyed papers.*

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.
- 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 a 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. 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 synfuels.
- A long plant life is crucial to guarantee an adequate return to investors given the high initial capital investment. Therefore, it is important to verify whether the local coal reserves will be sufficient to sustain the projected demand for 30 years, a condition not always likely to be met.

Finally, CTL requires large amounts of water, as previously discussed in section 2, and waste water treatment and discharge systems are required, which increase plant costs. In summary, our analysis highlights a strong risk for CTL plants to become financial black holes, and helps explain why China has strongly slowed down the development of its CTL program (Rong and Victor, 2011).

4.2 GTL economics

Unlike CTL plants, the construction and operation of large scale GTL plants is now a reality, with increasing momentum. After the experiences of Sasol's Mossgas GTL plant in South Africa and Shell's Bintulu plant in Malaysia the first decade of the 21st century has witnessed the construction and start of the Oryx 34,000 b/d GTL plant and the Pearl 140,000 b/d plant, both in Qatar. Moreover, a 34,000 b/d GTL plant is being built in the Escravos region in Nigeria and is expected to become fully operational in 2013.

This difference in outcome between CTL and GTL plants is mainly explained by the price differential between oil (close to \$100/b or higher values from 2008 onwards) and natural gas (currently in the range \$2-\$3/MM Btu [≃ 0.18 barrel oil] in the US, thanks to the influx of shale gas), moreover, for large gas producers like Qatar, the effective cost of the gas feedstock is zero (Pearl GTL plant) or close to zero (Oryx GTL plant). Despite the high upfront costs of building a GTL plant, the price differences between the gas feedstock costs and the premium liquid product justifies the building of a GTL plant.

Tables 4–7 in the Appendix report the main results of recent studies in terms of economic and financial feasibility of GTL plants (the table cells are filled either using data reported in the original papers, or are calculated with the data in the original papers, whenever possible). However, we warn the reader to take care with the GTL results more than the previous CTL ones. Most of the work on GTL is not peer-reviewed and in some cases costs were not adjusted for inflation. We can now consider the real costs of three GTL plants, shown in Table 8. In the same table, we also report the indicative economics of small scale GTL plants. To have a clearer and more correct picture of all estimates, we increased the previous TPCs and BEOPs reported in Tables 4-7 to 2011\$ using the Chemical Engineering Plant Cost Index and show them in Figure 8:

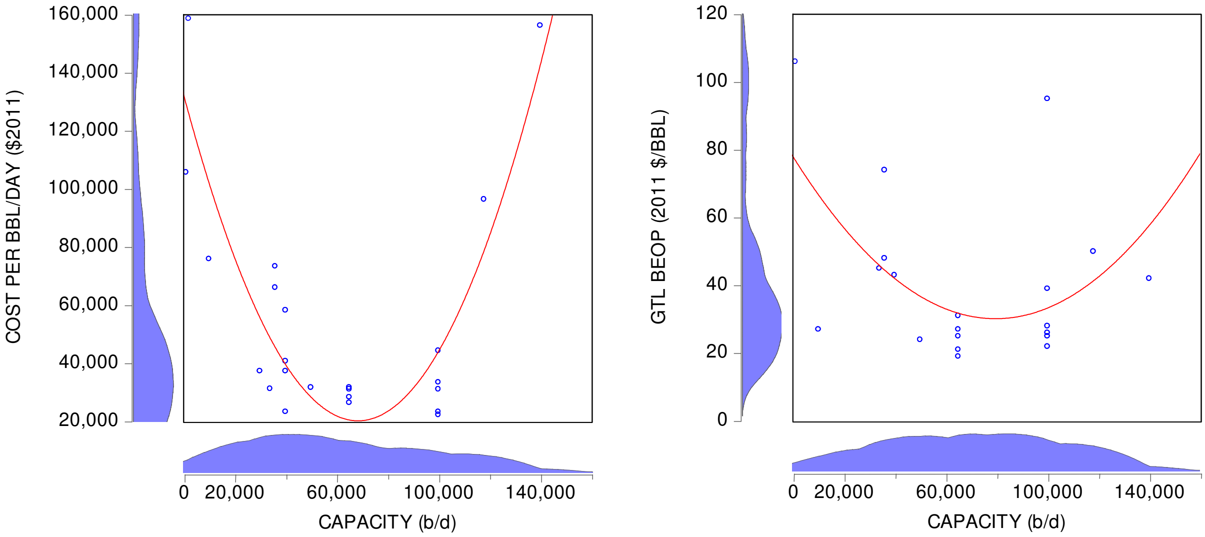

Figure 8. *Costs per b/d for GTL plants (left) and BEOPs for GTL plants (right), expressed in 2011 \$, with kernel densities on the axis borders and a polynomial fit of second order.*

The updated figures reveal that most of the studies expect (in $2011) a unit cost for GTL plants ranging mostly between $20,000 and $40,000 b/d, while almost all studies expect a BEOP below $60. But how do these cost estimates compare with the real costs observed with the three GTL plants built (or being built) in recent years? We show in Figure 9 the unit costs for the Pearl, Oryx and Escravos GTL plants and compare them with the theoretical unit costs retrieved from the studies dealing with GTL, as well as with the theoretical unit costs retrieved from studies dealing with CTL: the latter are shown for sake of interest, given that the engineering and the cost structure for CTL and GTL plants are similar.

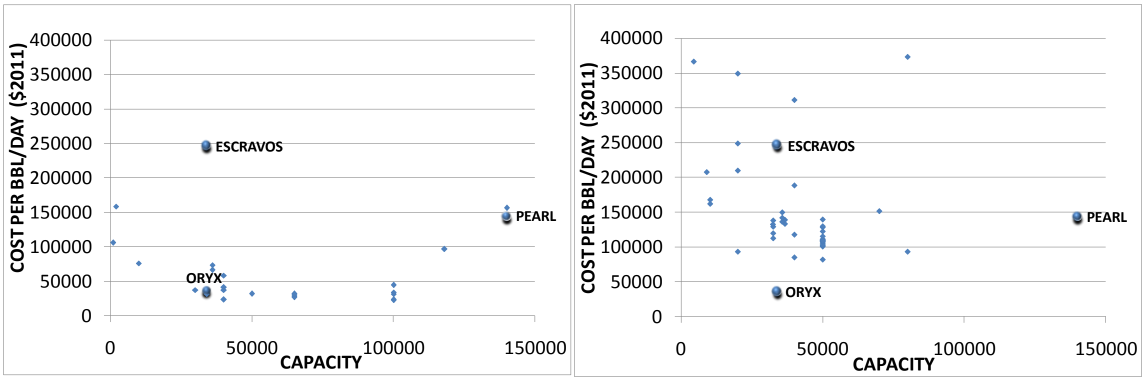

Figure 9. *Theoretical unit costs per b/d for GTL plants (left) and theoretical unit costs per b/d for CTL plants (right). The real unit costs for Escravos (latest), Oryx and Pearl are highlighted in both plots.*

Escravos: the real cost is a complete outlier in case of the theoretical studies dealing with GTL plants, whereas it is in the middle of the cloud of estimates for CTL plants;

Oryx: the real cost is in line with what was expected in GTL theoretical studies, while it was too cheap for theoretical CTL studies. Interestingly, on August 4, 2011, during an official presentation in Canada, Sasol "*...indicated that were Oryx to be built today, the cost would be closer to $2 billion to $2.5 billion, or about $65,000 per barrel*" (New Technology Magazine, 2011);

Pearl: this plant represents an outlier for both types of studies but for different reasons. In CTL studies, the unit cost for this plant is very close to the mean estimate but a plant of this size was not considered due its large capacity (140,000 b/d) and extremely high cost. In GTL studies, the real cost is much higher than what was expected except for the work of Velasco *et al*. (2010), who used the data reported in Rahmim (2008) exactly referring to the Pearl plant.

Unfortunately, cost escalation often occurs: apart from the Oryx plant, *the final total cost has so far been approximately three times that initially budgeted.* In the case of the World GTL plant in Trinidad and Tobago, the original CAPEX was expected to be 0.125 billion$, while the last estimate is roughly 0.400 billion $ (Ramdass, 2010). The unit cost is approximately $178,000 b/d, in between the Pearl and the Escravos plants — and more than 3 times the original estimate.

Finally, we make a couple of comments on the small scale GTL technologies, recently proposed by CompactGTL and Velocys (a subsidiary of Oxford Catalyst Group). Their size allows them to be installed on ship decks and in small offshore plants. Although the unit cost seems to be in the same order of magnitude of the large scale plants, their small size requires much smaller upfront costs and allows cost escalation to be more easily controlled. This new technology can be of particular interest for associated/flare/stranded gas, usually associated with oil deposits and flared into the atmosphere, particularly in Russia (see Oil and Gas Eurasia 2009), where traditional large scale GTL plants are not economically viable.

4.3 Financing

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

The assumed return on equity ranges 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, 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 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. While purchase agreements are favoured 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 presence 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. Berg *et al*. (2007) found that grants, loan guarantees, excise tax credits may be the most cost effective incentives.

4.4 Supply chain issues

Supply chain risks, vulnerabilities and uncertainties (Simangunsong *et al.*, 2012) are another important topic for energy strategies involving major hydrocarbon liquefaction undertakings. High oil prices or oil shortages that make CTL more attractive may also bring about problems for parts of the liquefaction supply chain. Business risks have been broadly reviewed by Oke and Gopalakrishnan (2009). For a CTL/GTL 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 in a timely fashion (Barney, 1991).

Material flow risks

Material flows involve physical movements within and between supply chain elements, such as coal transportation, movement of spare parts for CTL/GTL facilities and delivering CTL/GTL products to consumers. These concerns, and issues such as capacity change over time relate to typical supply chain design problems (Carle *et al.*, 2012; Singh *et al.*, 2012) complicated by many of the risks discussed above that are specific to the chemical industry (Floudas *et al.*, 2012; Liu *et al.*, 2011).

Today, petroleum products supply 95% of all energy used in global transportation (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. It should also be noted here that CTL/GTL may also impact existing hydrocarbon supply chains negatively and these concerns have led to the abandonment of certain projects (Rong and Victor, 2011).

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. Additional financial issues were discussed in section 4.2

Information flow risks

Supply chains are also influenced by information flows such as demand, inventory status, order fulfilments, design changes and capacity updates. Some observers even perceive information as a bonding agent between material and financial flows. 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).

5. Concluding discussions

The technology behind CTL is both proven and flexible, especially for ICL, with DCL and ICL systems have comparable system efficiencies. 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. If this is coupled with the development of FT-based GTL projects, additional synergy for hydrocarbon liquefaction may arise.

We also note that coal production requirement 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 producing 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 a significant environmental impact. Obtaining public acceptance, and later political acceptance, for CTL might be problematic. Furthermore, water use is commonly overlooked even though 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 slowed the development of its CTL program, as discussed in detail by Rong and Victor (2011).

GTL faces similar problems and risks. Those include high capital costs, technical efficiency and reliability issues, oil price volatility, uncertainty of petroleum product markets, project financing: in this regard, for three real GTL plants out of four, the final cost has been so far approximately three times initial budget. One additional factor is access to technology, as only a small number of companies hold many important patents (Wood *et al.*, 2012). However, GTL faces a better situation compared to CTL, due to cheaper inputs and lower water requirements. Moreover, small scale GTL units recently commercialized require much smaller upfront costs and have the potential to be a solution to the problem of stranded gas, usually associated with oil deposits.

Finally, both CTL and GTL incur significant environmental impacts, ranging from increased greenhouse gas emissions (in the case of CTL) to water contamination (in the case of obtaining unconventional gas for GTL). These environmental concerns may significantly slow or even stop growth of these projects until adequate solutions are found.

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APPENDIX 1. COAL-TO-LIQUIDS: main results of the economic and financial analysis reported in the reviewed studies.

Table 1. *Published economic and financial feasibility for CTL plants (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)** **[*7 process configurations for FTL fuels production were analyzed*]**
Plant capacity (b/d)	20,000-80,000	40,000	Large CTL RC: V 50,000; CCS 50,000 Small CTL OT: V 10,232; CCS 10,232 CBTL2 OT CCS: Large 36,655; Small 10,232 CBTL OT CCS: 8,100
Base year for valuation	2003-2008	2007$	2009$
Total Plant Cost -TPC ($ billion)	20,000 b/d: $1.5 -$4 ; 80,000 b/d: $6-$24	$3.07	Large CTL RC: V $4.878; CCS $4.945 Small CTL OT: V $1.486; CCS $1.539 CBTL2 OT CCS: Large $4.617; Small $1.555 CBTL OT CCS: $1.379
Specific TPC per b/d	-	$76,750	Large CTL RC: V $97,568; CCS $98,908 Small CTL OT: V $145,175; CCS $150,448 CBTL2 OT CCS: Large $125,946; Small $151,976 CBTL OT CCS: $170,189
Break even crude oil equivalent price of FT liquids [$/b]	Range: $48-$75/b ($2008)	$66/b	(ALL Base Case: Mature Industry): $/b: Large CTL RC: V 56; CCS 63 Small CTL OT: V 55; CCS 71 CBTL2 OT CCS: Large 59; Small 76 CBTL OT CCS: 101
	Talberth (2009)	**Hatch (2008)**	**Larson et al. (2009) + Kreutz et al. (2008)** **[*7 process configurations for FTL fuels production were analyzed*]**
Plant capacity (b/d)	Case 1: 20,000 Case 2: 40,000	Case 1: 20,000 Case 2: 40,000 Case 3: 40,000 (with coal & gas)	Coal Only: RC-V 50,000; RC-CCS 50,000; OT -V 36,653; OT-CCS 36,652 Coal+Stover Corn+MPG: OT- V 7,691; OT-CCS 7,692; OT CCS 13,039
Base year for valuation	2008$	2008$	2007$
Total Plant Cost -TPC ($ 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 $4.878; RC-CCS $4.945; OT -V $4.407; OT-CCS $4.597 Coal+Stover Corn+MPG: OT- V $1.245; OT-CCS $1.281; OT CCS $1.944
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 $97,568; RC-CCS $98,908; OT -V $120,239; OT-CCS $125,434 Coal+Stover Corn+MPG: OT- V $161,870; OT-CCS $166,577; OT CCS $149,092
Break even crude oil equivalent price of FT liquids [$/b]	*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): Coal Only: RC-V $53; RC-CCS $59; OT -V $35; OT-CCS $50 Coal+Stover Corn+MPG: OT- V $72; OT-CCS $89; OT CCS $88

Table 2. *Published economic and financial feasibility for CTL plants (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: 4,428 - 9,019 (Diesel only)	32,502 (bituminous coal) / 32,401 (lignite)
Base year for valuation	2006$	2008$	2006$
Total Plant Cost -TPC ($ billion)	$ 4.528	Illinois no. 6: $1.603 (best case) / $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) ultra-green: $ 1.720	Bituminous coal with CCS: $ 3.339 Bituminous coal with CCS and 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 ultra green: $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) $53.58 (17% IRR)
	DOE/NETL (2009) [*9 process configurations for FTL fuels production were analyzed*]		**Chen et al. (2011) + DOE/NETL (2007)**
Plant capacity (b/d)	50,000 (CTL), 30,000 – 50,000 (CBTL), 5,000 (BTL)		50,000 b/d
Base year for valuation	2008$		2009$
Total Plant Cost -TPC ($ 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 $110,000 100% coal CCS 50k $114,000 100% coal CCS+ATR 50k $121,000 8% bio CCS 50k $122,000 15% bio CCS 50k $123,000 30% bio CCS 30k $139,000 100% bio No CCS 5k $233,000 100% bio CCS 5k $246,000 100% bio CCS+ATR 5k $254,000		CTL without CCS: $73,440 CTL with CCS: $90,260
Break even crude oil equivalent price of FT liquids [$/b]	100% coal no CCS 50k $84 100% coal CCS 50k $86 100% coal CCS+ATR 50k $92 8% bio CCS 50k $92 15% bio CCS 50k $95 30% bio CCS 30k $109 100% bio No CCS 5k $216 100% bio CCS 5k $225 100% bio 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)

Table 3. *Published economic and financial feasibility for CTL plants (papers 12-16. Base case, if not differently specified)*

	Bartis et al. (2008) + Camm et al. (2008)	**Erturk (2011)**	**NPC(07)+EIA(06) + SSEB (2006)**
Plant capacity (b/d)	32,502		10,000 - 70,000
Base year for valuation	2007$	2007-2008	2006$
Total Plant Cost -TPC ($ billion)	$3.300–$4.050	-	-
Specific TPC per b/d	$100,000 - $125,000	$100,000 -$125,000 (USA) $60,000 - $62,000 (China)	$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*: requires increases in capital and operational costs who will offset the cost advantage]	-	$34 - $60

	Liu et al. (2009) + Kreutz et al. (2008) [*16 process configurations for FTL fuels production were analyzed*]	**Mantripragada and Rubin (2011) [*5 process configurations for FTL fuels*]**
Plant capacity (b/d)	CTL-RC-V 50,000 CBTL-RC-V 9,845 CBTL-OTA-CCS 10,882 BTL-RC-CCS 4,521 CTL-RC-CCS 50,000 CBTL-RC-CCS 9,845 CBTL-OTAS-CCS 17,669 CTL-OT-V 35,706 CBTL-OT-V 8,036 CBTL-OTS-CCS 13,213 CTL-OT-CCS 35,705 CBTL-OT-CCS 8,036 CBTL1-OT-CCS 8,036 CTL-OTA-CCS 35,705 CBTL-OTA-V 10,881 BTL-RC-V 4,521	50,000 (Illinois#6 bituminous coal) (sensitivity: 10,000 to 125,000 b/d)
Base year for valuation	2007$	2007$
Total Plant Cost -TPC ($ billion)	CTL-RC-V $4.852 CBTL-RC-V $1.349 CBTL-OTA-CCS $1.786 BTL-RC-CCS $0.737 CTL-RC-CCS $4.919 CBTL-RC-CCS $1.369 CBTL-OTAS-CCS $2.611 CTL-OT-V $4.390 CBTL-OT-V $1.372 CBTL-OTS-CCS $1.955 CTL-OT-CCS $4.574 CBTL-OT-CCS $1.427 CBTL1-OT-CCS $1.369 CTL-OTA-CCS $4.826 CBTL-OTA-V $1.720 BTL-RC-V $0.724	Liquids-only Co-production No CCS With-CCS No-CCS With-CCS-A With-CCS-B $4.595 $4.655 $5.790 $5.855 $6.295
Specific TPC per b/d	CTL-RC-V $97,040 CBTL-RC-V $137,024 CBTL-OTA-CCS $164,124 BTL-RC-CCS $163,017 CTL-RC-CCS $98,380 CBTL-RC-CCS $139,055 CBTL-OTAS-CCS $147,773 CTL-OT-V $122,949 CBTL-OT-V $170,732 CBTL-OTS-CCS $147,960 CTL-OT-CCS $128,105 CBTL-OT-CCS $177,576 CBTL1-OT-CCS $170,358 CTL-OTA-CCS $135,163 CBTL-OTA-V $158,074 BTL-RC-V $160,142	Liquids-only Co-production No CCS With-CCS No-CCS With-CCS-A With-CCS-B $91,900 $93,100 $115,800 $117,100 $125,900
Break even crude oil equivalent price of FT liquids [$/b]	CTL-RC-V $58 CBTL-RC-V $100 CBTL-OTA-CCS $104 BTL-RC-CCS $145 CTL-RC-CCS $65 CBTL-RC-CCS $110 CBTL-OTAS-CCS $88 CTL-OT-V $44 CBTL-OT-V $ 91 CBTL-OTS-CCS $84 CTL-OT-CCS $59 CBTL-OT-CCS $110 CBTL1-OT-CCS $93 CTL-OTA-CCS $73 CBTL-OTA-V $78 BTL-RC-V $133	Liquids-only(*) Co-production(*) No CCS With-CCS No-CCS With-CCS-A With-CCS-B $58.5 $62.9 $45 $53.4 $60.2 (**)$68 $62.9 $58.6 $56.5 $60.5 (*)*Not stated* : Computed dividing by 1.3 the FT liquid price (**) 25$/ton for CO_2

APPENDIX 2. GAS-TO-LIQUIDS: main results of the economic and financial analysis reported in the reviewed studies.

Table 4. *Published economic and financial feasibility for GTL plants (papers 1-5)*

	Patel (2005)	Black (2010)	Balogun and Onyekonwu (2009)	Adedeji (2008)	Rahman (2008)
Plant capacity (b/d)	100,000	50,000	100,000	68,000	65,000
Base year for valuation	2005$	2010$	2009$	2008$	2008$
Total Plant Cost -TPC ($ billion)	$2.5	$1.5	$2 - $3		$1.82
Specific TPC per b/d	$25,000	Sensitivity analysis: $20,000-$45,000 Base: $30,000	Range: $20,000-$30,000		$28,000
Break even crude oil equivalent price of FT liquids [$/b]	$22-23	$22.29	Oil > US$35/bbl Gas: US$0.25-1.5/mmBtu	$ 21.86	$15-$23
COMMENTS		Sensitivity analysis Oil Price: $15 -$90 Base:$40	Simulation results show a 92.5% probability of the IRR being over 10%.The profitability of LNG and GTL is very close, with GTL having a potential superior return at high oil prices and preferable under conditions of limited capital.		

Table 5. *Published economic and financial feasibility for GTL processes (papers 6-10)*

	Chijemezu (2009)	NONOX BV (2007)	Castelo Branco et al. (2010)	Hossain and Gulen (2007)	Purwanto et al. (2005)
Plant capacity (b/d)			100,000 (offshore)	40,000	Range: 10,000 - 50,000 (optimal: 30,000-40,000)
Base year for valuation	2009$	2007$	2009$	2006$	2004$
Total Plant Cost -TPC ($ billion)				$0.8 - $1.4 - $2	
Specific TPC per b/d				$20,000 - $35,000 - $50,000	$30,000 - $60,000
Break even crude oil equivalent price of FT liquids [$/b]	$65-$102 [Computed dividing by 1.3 the FT liquids price]	$21	the GTL plant is economically feasible without the need to consider the value of the carbon avoided, at $85 /bbl	$37 (but if NatGas costs $6 Mmbtu, Oil price>$70)	$22
COMMENTS					NPV generally negative with small scale plants. In general, the impact of gas price is the most sensitive compare to other parameters. However, product price and plant capacity have also significant impacts. Integrated GTL with co-production approach has higher IRR than GTL standalone.

Table 6. *Published economic and financial feasibility for GTL processes (papers 11-15)*

	Velasco et al. (2010)+ Rahmin(2008) +Gradassi (2001)	Al-Shalchi (2006) + Woods et al. (2002)	Ogugbue et al. (2007)+ Robertson (1999)	Ang et al. (2010)+ Rahman and Al-Maslamani, (2004)	Bao et al. (2010)
Plant capacity (b/d)	100,000	100,000	100,000	65,000	118,000
Base year for valuation	2009$	2006$	2007$	2010$	2009$
Total Plant Cost -TPC ($ billion)		$2	$4		$10.2
Specific TPC per b/d	Range: $28,000 - $140,000	$20,000	$40,000	$25,000 - $30,000	$86,440
Break even crude oil equivalent price of FT liquids [$/b]	$20 [from Dry (2004)]	$18-$20	$23	$20	$45 (*)
COMMENTS		With oil price at 60$ the max price for gas to make a GTL plant economic viable is between $5 / $6		-	The minimum plant capacity required to make profit is 57,000 bpd. (*) computed by dividing the FT liquid price by 1.3

Table 7. *Published economic and financial feasibility for GTL processes (papers 16-19)*

	Deutsche Bank (2010): Proposed Uzbekistan GTL	Deutsche Bank (2010): Proposed North America GTL	Economides (2005)	Chedid et al. (2007)
Plant capacity (b/d)	36,000	36,000	65,000	
Base year for valuation	2010$	2010$	2005$	2006$
Total Plant Cost -TPC ($ billion)	$2.5	$2.25	$1.625	
Specific TPC per b/d	$69,444	$62,500	$25,000	$28,000
Break even crude oil equivalent price of FT liquids [$/b]	$ 45	$70	NPV > 0 for oil price $22/bbl, and $1/MCF . NPV > 0 for oil price $25/bbl, and $1.5/MCF NPV > 0 for oil price $20/bbl, and $0.5/MCF	$21.9
COMMENTS	Sensitivity analysis: Oil price ($/bbl): a) 40 b) 60 c) 80 d)100 e)120. ***NPV million*** $: a) 345 b)1117 c)2556 d)3989 e)5418 Gas cost (US$/mmBtu) with US$80/bbl oil: e) 1.5 f)2.6 g)3.6 h) 4.85 ***NPV million*** $: e)2,556 f)1,721 g)959 h) 0	IRR and NPV have a much higher sensitivity to gas prices, differently from the Uzbekistan GTL project, where the key variable is basically the oil price.	At a price of oil equal to $30 per barrel, a natural gas price of $4 per MCF or higher would render LNG more attractive; a lower price of gas would make GTL more attractive. At $50 per barrel, this breakdown is $6 per MCF. Conversely, if the price of natural gas is maintained below $3 per MCF, then any price of oil above $20 would render GTL more attractive.	Sensitivity analyses changing the following parameters: a) Diesel incremental cost over CO. b) Feedstock NG price c) O&M cost. d) GTL plant capital cost. -> IRR found to vary in the range 14–17%.

APPENDIX 3. Economics of real GTL plants (first 7 rows) and indicative economics of small scale GTL plants manufacturers (lower 7 rows)

	REAL: Shell Pearl QATAR	REAL: SASOL Oryx, QATAR	REAL: CHEVRON (75%) /Nigerian National Petroleum Corporation (NNPC,15%)/SASOL(10%) Escravos, NIGERIA
Plant capacity (b/d)	140,000	34,000	34,000
Base year for valuation	2010$	2009$	2011$
Total Plant Cost -TPC ($ billion)	(original budget: $6) Final: $19 (*)	(original budget: $0.95) Final: $1.1 (*)	(original budget: 2.7) Latest: $8.4 (*)
Specific TPC per b/d	$136,000	$32,350	$247,000
Break even crude oil equivalent price of FT liquids [$/b]	$40 (**)	$40 (**)	
COMMENTS	(*) Reed and Tuttle (2010) (**) http://www.upstreamonline.com/live/article204485.ece	(*) Magill (2011) (**) http://www.gasstrategies.com/node/74017	(*) Reddall (2011)
	VELOCYS (2010-2011) [Official indicative economics (*)]	**COMPACTGTL (2011) [Official indicative economics (*)]**	**Nunez Mata (2010) +VELOCYS (2010)+CompactGTL(2010) for Brazilian Offshore oil plant**
Plant capacity (b/d)	500 - 5,000 bbl/d	500 - 2,000 bbl/d	1,000 (low cost case) - 2,000 (high cost case)
Base year for valuation	2010$ and 2011		2010$
Total Plant Cost -TPC		$ 50 million (incremental capex)	$ 100 million (low cost case) $ 300 million (high cost case)
Specific TPC per b/d	$12,000 to $16,000 (only the FT unit) $44,000 to $53,000 for the natural gas reforming, syngas conditioning prior to the FT unit and remaining CAPEX		100,000 (low cost) - 150,000 (high cost)
Break even crude oil equivalent price of FT liquids [$/b]		Pre-Tax Incremental Oilfield NPV $ 150 million with oil price at $75 /barrel	Oil prices > $100 (for 1,000 bpd plant) "The cost of the GTL module would need to decrease about 50% (to 40 - 60 $ mln range) to be able to breakeven at $70 /bbl, and an average of 25% to breakeven at $ 90 /bbl."
COMMENTS	This is a company which has started the commercialization of its products based on Microchannel GTL only recently and which is still conducting tests worldwide. Any costs and data reported in the official documentations is therefore it be considered only as indicative. We thank Velocys Inc. for the active collaboration.	This is a company which has started the commercialization of its products based on Microchannel GTL only recently and which is still conducting tests worldwide. Any costs and data reported in the official documentations is therefore it be considered only as indicative. We thank CompactGTL for the active collaboration.	NPV negative for all scenarios considered. "Contrary to the expectation, NPV for both GTL options decrease with higher volumes, which indicate that higher revenue stream is not enough to pay for the required additional infrastructure"