Gas-to-Liquids (GTL): a Review of an Industry Offering Several Routes for Monetizing Natural Gas

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Abstract

Gas-to-liquids (GTL) has emerged as a commercially-viable industry over the past thirty years offering market diversification to remote natural gas resource holders. Several technologies are now available through a series of patented processes to provide liquid products that can be more easily transported than natural gas, and directed into high value transportation fuel and other petroleum product and petrochemical markets. Recent low natural gas prices prevailing in North America are stimulating interest in GTL as a means to better monetise isolated shale gas resources. This article reviews the various GTL technologies, the commercial plants in operation, development and planning, and the range of market opportunities for GTL products.

The Fischer-Tropsch (F-T) technologies dominate both large-scale and small-scale projects targeting middle distillate liquid transportation fuel markets. The large technology providers have followed strategies to scale-up plants over the past decade to provide commercial economies of scale, which to date have proved to be more costly than originally forecast. On the other hand, some small-scale technology providers are now targeting GTL at efforts to eliminate associated gas flaring in remote producing oil fields. Also, potential exists on various scales for GTL to supply liquid fuels in land-locked gas-rich regions. Technology routes from natural gas to gasoline via olefins are more complex and have so far proved difficult and costly to scale-up commercially. Producing dimethyl ether (DME) from coal and gas are growing markets in Asia, particularly China, Korea and Japan as LPG substitutes, and plans to scale-up one-step process technologies avoiding methanol production could see an expansion of DME supply chains.

The GTL industry faces a number of challenges and risks, including: high capital costs; efficiency and reliability of complex process sequences; volatile natural gas, crude oil and petroleum product markets; integration of upstream and downstream projects; access to technology. This review article considers the GTL industry in the context of available opportunities and the challenges faced by project developers.

Keywords: GTL, Gas-to-liquids, Fischer-Tropsch, Dimethyl Ether, DME, Gas to Methanol, Gas to Olefins, Gas to Gasoline

1. **Introduction**

As the world's population continues to grow and economies develop, the demand for energy also continues to grow significantly. This increased demand is also being strengthened by the quest for cleaner sources of energy to minimize impact on the environment. Demand for natural gas is likely to overtake other fossil fuels due to its availability, accessibility, versatility and smaller environmental footprint. For example, the International Energy Agency (IEA) proposed in May 2012 (IEA, 2012) that global demand for natural gas could rise more than 50% by 2035, from 2010 levels, particularly if a significant portion of unconventional shale gas, tight gas and coal-bed methane (CBM) resources are exploited and flared associated gas is harnessed rather than wasted.

Several Gas-to-Liquids (GTL) technologies have emerged over the past three decades as a credible, but sometimes challenging, alternative for natural gas owners to monetise their gas (Figure 1). While pipeline and liquefied natural gas (LNG) options focus on the natural gas markets, GTL presents an attractive alternative for gas monetisation for gas-producing countries to expand and diversify (Wood, 2005) into the transportation fuel markets. GTL processes produce a variety of high-quality liquid fuels, particularly diesel (without sulphur and with a high cetane number) and jet fuel. This paper reviews the GTL gas conversion alternative technologies, how they have been deployed and the potential growth markets for their high-quality products. It also highlights the technical complexities, high costs and price risks that continue to inhibited the rapid uptake of GTL.

Figure 1. Methane can be converted into a range of liquid and gaseous chemicals via the synthesis gas process route. Methane itself can be derived from natural gas resources or generated by the gasification of coal and various biomass resources. Source updated from Wood et al., 2008.

2. **Global Gas Supply and Demand: A Role for GTL**

Global natural gas reserves are increasing as the rate of new discovery is greater than the rate of consumption. The rapid expansion in the exploitation of unconventional gas in North America and Australia has, in recent years, accelerated that trend. Indeed the future development of unconventional gas in China and other energy-starved nations suggests that trend may continue for several decades at least. However, a substantial amount of the global natural gas resource endowment frustratingly remains stranded or isolated in remote locations, as it has done for several decades (e.g. Rahmim, 2003, ENI, 2005). Monetization of these gas reserves is an important factor for gas-resource-rich nations and companies, but commonly requires large amounts of capital investment to build processing and export infrastructure and long-term sales contracts to underpin such investments (Wood & Mokhatab, 2008). Of additional concern is the considerable amounts of associated natural gas that is flared or vented in order to facilitate oil production (e.g. Russia, Nigeria and many oil-producing nations of the Middle East (see World Bank video, 2009). Gas conversion has the potential to play a big role in the reduction of flaring, if costs can be overcome and the technologies become more widely available.

Lecarpentier & Favreau (2011) contrast the evolution of natural gas reserves among the main gas-producing areas

- Middle East showed the highest increase (+ 3,510 bcm), essentially as a result of reserves additions/re-evaluations by Iran (which some question as they are not independently audited or verified);

- The Commonwealth of Independent States also showed a strong increase (+ 1,442 bcm), following the major reserves re-evaluation of the giant South-Iolotan field in Turkmenistan;

- North America (+ 471 bcm), with the sustained growth of shale gas reserves in the United States and Canada;

- Asia-Oceania arithmetically gained 258 bcm, mainly due to the growth of Australian conventional and unconventional reserves (+ 110 bcm), Timor-Leste/Australia JPDA reserves (+ 105 bcm) and Chinese reserves (+ 102 bcm).

Natural gas production globally was some 3.3 tcm in 2010 with the IEA forecasting (IEA,2012) that to potentially rise to some 4.0 tcm in 2012 and to 5.1 tcm in 2035 in its "Golden Rules" case, in which unconventional gas would account for some 32% of global natural gas production by 2035. That IEA forecast involves a compound annual growth rate (CAGR) of some 1.8% between 2010 and 2035, with gas production in Asia growing at 3.4% (CAGR) including China at 6.6% (CAGR). Other recent forecasts also see a rapid rise in gas production and consumption over the next two decades or so (e.g. BP, 2012 forecast gas consumption to grow by 2.1% CAGR by 2030; ExxonMobil, 2011 forecasts global gas demand to rise by 60% between 2010 and 2040) with much gas-fired, combined-cycle power generation required to back-up the substantial intermittent renewable energy infrastructure to be deployed by resource-poor consuming countries. Most of this gas is currently supplied to the ultimate consumers by pipeline distribution, with about 30% of gas exported from the country of production moved in the form of liquefied natural gas (LNG). However, a considerable portion of the world natural gas reserves fall into the category termed as 'stranded' where conventional means of transportation via pipeline is not practical or economical. 'Stranded' gas reserves are either located remotely from consumers or are in the region where the demand for gas is limited (e.g., Patel, 2005). Hence in order for the forecasted growth in gas consumption to occur massive investment in gas export infrastructure will be required over the coming decades.

Transporting energy commodities in bulk by ship, train, or truck is often a cost-effective way to move energy commodities in liquid form. However, methane's high volume in its gaseous state, even when under significant pressure prevents it from being transported long distances or stored easily in bulk at low cost. LNG is one way of accomplishing this by shrinking the gas more than 600 times by applying cryogenic temperatures to induce a physical transformation from the gaseous state to the liquid state. GTL technologies offer an alternative, i.e., chemically converting methane into longer-chain hydrocarbon molecules

that exist in liquid states at or close to atmospheric conditions. It has been recognised for some time that GTL technologies have the potential to enable gas producers to convert methane into liquid fuels and other valuable liquid hydrocarbons (e.g. lubricants and base oils), which can be transported much more compactly and easily (Samuel, 2003, Tillerson, 2005).

For many countries with large stranded natural gas reserves (conventional and/or unconventional), GTL technologies present potentially attractive alternatives for gas monetisation. In addition to serving liquid-transportation-fuel markets, resource owners can also add value via GTL by transforming some of their gas into high quality lubricant base stocks and fuel blend stocks – a move that in certain market conditions, and where the technologies can be deployed at realistic costs, can be worth the investment.

Some forecast the world's demand for diesel has the potential to increase from 25 million barrels per day in 2011 to 37 million barrels per day by the year 2035 (OPEC World Oil Outlook, 2011). OPEC notes in their forecast (OPEC, 2011) that of the 23 million barrels / day of additional demand for transportation fuel by 2035 compared to the 2010 level, around 57% is for middle distillates (highlighting the growth in diesel-fuelled vehicles across the world) and another 40% is for gasoline and naphtha (Figure 2). GTL technologies have the potential to contribute to this rapidly growing demand for transportation fuels. However, the continued dependence on refinery-produced petroleum products for fuelling the transportation sector is recognised as a threat to energy security, with detrimental environmental impacts, and a drain on economic resources. This has stimulated much research and development into alternative transport fuels (e.g. the production of diesel from algal sources, e.g. Aurora Algae, 2011), which could compete with GTL technologies in the medium term for a share of the diesel fuel and jet fuel markets, depending upon the respective costs of supply of the technologies.

Figure 2. OPEC's Global petroleum product demand forecast emphasizes the significant growth expected over the next two decades, especially for middle distillates. Source OPEC, 2011.

This case for GTL technology is further strengthened by the growing demand from consumers, environmentalists, governments and automotive producers for cleaner, higher performing fuels. Diesel is significantly more energy efficient than gasoline and contributes to the drive to reduce carbon dioxide emissions in the transportation sector. Diesel produced by the Fischer-Tropsch GTL processes in production today is demonstrated to possess a significantly higher quality than diesel derived through typical refining processes applied to crude oil. GTL diesel has a high cetane number (at least 70 compared with a 45 to 55 rating of most diesels), low sulphur (less than five parts per million), low aromatics (less than 1%), which leads to lower density, and good cold flow characteristics, which can be optimised to suit specific applications (Buchanan, 2006).

3. GTL technology development: Its Origins

GTL and coal-to-liquids (CTL) technologies were pioneered in Germany during the 1920s, using a process, which came to be known as Fischer-Tropsch (F-T) synthesis, when Germany found itself short of petroleum but with ample reserves of coal (Heng & Idrus, 2004). A concerted effort to secure the supply of liquid fuels resulted in the development of high-temperature F-T plants, which turned coal into gas and then into liquids. Although a technical success, the F-T process could not compete economically with the refining of crude oil and consequently, early applications were limited to fulfil supply shortage where economic competitiveness was less relevant (e.g. during World War II in Germany and during oil embargoes imposed upon South Africa during its apartheid era). For the past three decades there has been renewed interest in F-T synthesis in the form of GTL, using low-temperature F-T conversion of natural gas primarily into middle distillates. This was prompted not just as a result of the abundant supply of economically-priced stranded gas, but also by restricted access to crude oil supplies and the global desire for higher-quality transportation fuels and the need to improve local air quality in many cities around the World (Heng & Idrus, 2004).

4. Technology Overview for Fischer-Tropsch (F-T) GTL Plants

Natural gas to liquids conversions can be achieved via several chemical reaction processes resulting in a range of end products. The Fischer-Tropsch technologies are currently the most widely deployed.

5. Fischer Tropsch GTL Process and Chemistry

The basic F-T GTL process consists of three fundamental steps, which require significant supporting infrastructure and a secure feed gas supply to function effectively (Figure 3).

1. The production of synthesis gas (syngas). The carbon and hydrogen are initially divided from the methane molecule and reconfigured by steam reforming and/or partial oxidation. The syngas produced, consists primarily of carbon monoxide and hydrogen.
2. Catalytic (F-T) synthesis. The syngas is processed in Fischer-Tropsch (F-T) reactors of various designs depending on the technology creating a wide range of paraffinic hydrocarbons product (synthetic crude, or syncrude), particularly those with long-chain molecules (e.g. those with as many as 100 carbons in the molecule).
3. Cracking – product workup. The syncrude is refined using conventional refinery cracking processes to produce diesel, naphtha and lube oils for commercial markets (Agee, 2005). By starting with very long chain molecules the cracking processes can be adjusted to an extent in order to produce more of the products in demand by the market at any given time. In most applications it is the middle distillate diesel fuels and jet fuels that represent the highest-value bulk products with lubricants offering high-margin products for more limited volume markets. In modern plants, F-T GTL unit designs and operations tend to be modulated to achieve desired product distribution and a range of product slates (Rahmim, 2005).

The Fischer-Tropsch processes are not limited to using gas derived from large conventional, non-associated natural gas as a feedstock; coal seam gas, associated gas, coal or biomass can all be processed using F-T technologies by changing the catalyst and temperature pressure conditions. The technologies are therefore more generically referred to as "XTL" reflecting the range of hydrocarbon feedstock that can be processed (as referenced in Figure 1). A secure supply of feed gas, from whatever origin, is important for the commercial viability of large-scale F-T GTL plants. Integrated upstream and downstream projects therefore offer GTL project developers lower-risk returns

Figure 3.Large-scale F-T GTL projects become more economically robust for the developer if they involve integrated upstream and downstream components securing feed gas supplies and additional revenues from NGL and condensate extracted from the feed gas. Source updated from Wood & Mokhatab, 2008.

Synthesis gas ("syngas") is typically produced using either partial oxidation or steam reforming processes (Rahmim, 2003). Syngas is an intermediate gas feed for many different petrochemical processes including a range of GTL alternative technologies:

- Partial oxidation: $CH_4 + 1/2\ O_2 \longrightarrow CO + 2\ H_2$ (exothermic)
- Steam reforming: $CH_4 + H_2O \longrightarrow CO + 3\ H_2$ (endothermic)
- Other possible reactions are:

$$CO + H_2O \rightleftharpoons CO_2 + H_2$$
$$CH_4 + CO2 \rightleftharpoons 2\ CO + 2\ H_2$$
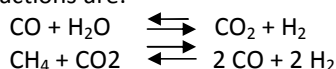
6. Partial Oxidation of Methane to Produce Synthesis Gas

The chemical reaction involved in this approach requires air separation units to remove the nitrogen from air to yield an oxygen-based atmosphere for the reaction:

$$CH_4 + 1/2\ O_2 \longrightarrow CO + 2H_2$$
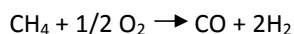
Rahmim (2003) noted the key components required for this approach include:

- A combustion chamber operated at high temperatures (1200-1500°C) without catalysts.
- Process designs to impede a competing reaction to syngas formation which involves the decomposition of methane to carbon black (due to high temperature, non-catalytic nature of the chemistry).

Three process sections are typically involved (Rahmim, 2003):

1. A burner section where combustion occurs (with oxygen only and excluding nitrogen). In some processes manufacturing ammonia, urea and some fertilisers it is not necessary to exclude nitrogen;
2. A heat recovery section;
3. A carbon black removal section: first by water scrubbing, then extraction by naphtha from the sludge.

7. Steam Reforming to produce Synthesis Gas

The steam reforming process is widely used to generate synthesis gas for feedstock to a range of petrochemical processes and for the production of hydrogen used in refinery hydro-crackers. It involves the reaction:

$$CH_4 + H_2O \longrightarrow CO + 3H_2$$

Steam reforming is usually carried out in the presence of catalyst—e.g. nickel dispersed in alumina in operating conditions involving temperatures of 850-940°C and pressure of about 3 MPa. The process is typically conducted in tubular, packed reactors with heat recovery from flue gases used to pre-heat the feed gas or to raise steam in waste heat boilers. Several well-established engineering companies offer their own variants of this process, e.g. Foster Wheeler, M.W. Kellogg, Lurgi and Haldor Topsoe.

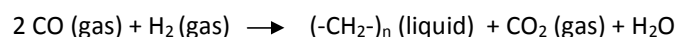### 8. Autothermic Synthesis Gas Production Processes

In Auto Thermal Reformers (ATRs) the synthesis gas production process combines steam reforming with partial oxidation. It uses the heat produced from partial oxidation to provide heat for steam reforming. Gases from partial oxidation burner are mixed with steam and sent to the steam reformer, rendering the process autothermic. In autothermic processes the temperature level at which the reaction proceeds is maintained by the heat of reaction alone. Engineering companies such as Lurgi and Haldor Topsøe offer the ATR process.

9. Fischer – Tropsch Synthesis

Fischer-Tropsch synthesis is one **o**f several technologies to polymerise the carbon and hydrogen components into long-chain molecules:

$$CO + 2H_2 \rightarrow —CH_2— + H_2O \text{ (very exothermic)}$$
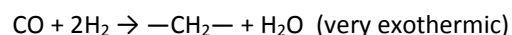
Which in practice operates more typically as:

$$2 CO \text{ (gas)} + H_2 \text{ (gas)} \longrightarrow (-CH_2-)_n \text{ (liquid)} + CO_2 \text{ (gas)} + H_2O$$

The process involves some carbon dioxide emission and water / steam production along with the hydrocarbon liquid production.

The typical F-T reactions compete with the methanation (reverse of steam reforming) reaction (and reactions that lead to the production of propane and butane (LPG), which are also highly exothermic:

$$CO + 3H_2 \leftrightarrow CH_4 + H_2O$$

In order to promote the F-T reaction in preference to methanation (or LPG reactions), the synthesis is run at low temperatures: 220-350°C; pressure: 2-3 MPa with carefully selected

catalysts (i.e. commonly cobalt) in reactors that encourage the growth of long-chain hydrocarbon molecules. Several companies hold patents associated with XTL catalysts, process vessels and process sequences (e.g. ConocoPhillips, CompactGTL, ExxonMobil, Rentech, Sasol, Shell, Syntroleum and others), however, it is only Sasol and Shell that have built large-scale commercial plants (i.e. >5000 barrels/day of GTL product) rather than pilot-scale or demonstration plants. The industry therefore remains in its infancy and the many patents held by relatively few companies act as a costly barrier to entry for resource-rich gas companies and countries wishing to use GTL as an alternative means of monetising their gas.

10. Gas-based F-T technologies

There are two major categories of natural gas-based FT process technology: the high-temperature and the low-temperature types.

HTFT (High-Temperature Fischer Tropsch): In HTFT, because of the process conditions and the catalysts involved, the syncrude produced includes a high percentage of short chain (i.e., <10 carbon atoms) with significant amounts of propane and butane mixed with olefins (e.g. propylene and butylene). These short-chain hydrocarbon gases are typically extracted from the tail gas stream, utilising cryogenic separation. The resultant lean tail gas is recycled and, mixed with additional lean feed gas for further syngas production (Minnie, et al., 2005). The high-temperature (HT), iron catalyst-based FT GTL process produces fuels such as gasoline and diesel that are closer to those produced from conventional oil refining. The resultant GTL fuels are sulphur-free, but contain some aromatics (Waddacor, 2005). Typical process operation conditions for HTFT are temperatures of approximately 320 °C and pressures of approximately 2.5 MPa. Conversion in HTFT can be > 85 % efficient (De Klerk, 2012), but not all the products are readily usable or capable of producing high-quality transport fuels. HTFT processes tend to be conducted in either circulating fluidized bed reactors or fluidised bed reactors (see Velasco et al., 2010)

LTFT (Low-Temperature Fischer Tropsch): LTFT involves the use of low-temperature (LT), cobalt-catalyst-based processes, either in slurry-phase bubble-column reactors (e.g. Sasol) or in multi-tubular fixed-bed reactors (e.g. Shell). LTFT produces a synthetic fraction of diesel (GTL diesel) that is virtually free of sulphur and aromatics. Typical process operation conditions for LTFT are temperatures of approximately 220°C to 240 °C and pressures of approximately 2.0 to 2.5 MPa. Conversion in LTFT is typically only about 60 % with recycle or the reactors operating in series to limit catalyst deactivation (De Klerk, 2012).

The primary focus of most large-scale F-T technologies in current market conditions is to produce, high-quality low-emissions GTL diesel, jet fuel and naphtha (for petrochemical feedstock or gasoline blending).

11. Small-scale F-T Strategies

Some companies have been looking for some time at smaller-scale simpler F-T processes that can be deployed in small modular units to process associated gas, e.g. a UK-based

company CompactGTL (Wood et al, 2008). This approach feeds associated gas through a steam methane reformer to produce syngas, which itself feeds into a Fischer-Tropsch (FT) reactor that converts the feedstock into synthetic crude oil, water and a "tail gas" comprising hydrogen, carbon monoxide and light hydrocarbon gases. The main synthetic crude oil is then exported to a conventional refinery for onward processing. Petrobras' CENPES Research and Development Centre successfully concluded a three-year qualification test program of the CompactGTL technology. This involved the construction of a demonstration plant commissioned in December 2010 at Petrobas' Aracaju site for which Sumitomo designed and manufactured the reactor blocks for that demonstration plant. Petrobras is considering the use of the CompactGTL technology in the development of its large deepwater pre-salt oil fields currently underway (Veazey, 2012). In June 2012 Sumitomo Corporation announced that it had signed a contract with CompactGTL to supply further reactor blocks for this technology, stating that it was seeking to expand sales of it by potentially enabling oilfield development in regions such as Russia, Africa, the Middle East, Asia and South America

This compact approach does not involve the direct on-site production of high-value distillate products, but it has the advantage of obtaining feed gas at no cost as by using it avoids flaring or the costs of re-injection. Conceptual, feasibility and pre-feed studies for potential deployment of the CompactGTL technology are reported to be underway in Russia, Latin America, Africa and Asia for onshore and offshore plants ranging from 2 to 50 MMscfd (200-5,000 barrels/day syncrude). This type of approach has the ability to broaden the focus of GTL to a wide range of smaller-scale stranded gas applications.

Another company pursuing smaller-scale F-T GTL processes include Velocys (part of the Oxford Catalyst group) which has a 1000 barrels/day modular system designed for offshore deployment at an estimated capital cost of US$100,000/ barrel/day capable of producing diesel and naphtha at a total cost of US$67.5/barrel (including US$14/barrel operating costs) (Fenwick, 2012). For a larger plant (i.e. up to about 15,000 barrels/day output) it is targeting US$80,000/barrel/day capital costs and US$64/barrel total production cost. Infra technology and Axens are other companies pursuing smaller-scale XTL processes producing petroleum products rather than just syncrude.

Syntroleum Corporation offers its synthetic fuels technologies for GTL, CTL and BTL alternatives with capabilities to design XTL systems in the range 3,000 to 30,000 barrels per day. They currently have a 100 barrel/day demonstration plant in operation and are also building a 5,000 barrels/day plant that processes animal fat and vegetable oils. Syntroleum's technologies are simpler but less efficient than the larger-scale GTL plants built by Shell and Sasol. Syntroleum's indicative capital costs for an XTL plant are less than US$ 100,000 /barrels/day with plant operating costs less than US$20/barrel for a gas usage of some 11 mcf/barrel of product.

12. F-T GTL Products Compared to Crude Oil Refinery Products

F-T GTL plants can be configured to produce a wide range of products, from lubricating base oils and waxes through to petrochemical naphtha and speciality chemicals. Most of the

already developed and planned plants target the production of diesel fuels (C_{14} – C_{20}) together with some kerosene / jet fuel (C_{10}-C_{13}), naphtha (C_5 –C_{10}), lubricants (>C_{50}) and a little LPG (C_3 –C_4). By adjusting operating conditions in the Fischer-Tropsch reactor, the mix of products can be altered. This enables F-T GTL products to be produced in quantities that enable them to target the high-value product markets of petroleum products produced by conventional oil refineries.

However, the yield pattern from a typical F-T GTL plant is significantly different to that from a catalytic cracking crude oil refinery (Figure 4). Typically, the diesel yield of F-T GTL plants is around 70%, much higher than for crude oil refineries, which is typically some 40% (Pytte, 2005). Most oil refineries yield some low-value fuel oil, the yield depending on the quality of the crude processed and the type and capacity of the refinery's fuel-oil conversion units. By contrast, the F-T GTL plants are configured to yield only higher-value (relative to crude oil) light and middle distillate products. From a plant with existing technology, the yield of middle distillates (gasoil/diesel and kerosene) is nearly a third more of the total product slate than that from a typical oil refinery (Corke, 2005).

Figure 4. The products derived from upgrading syncrude produced by F-T GTL differ significantly from those produced by refining a barrel of crude oil. Notably F-T GTL produces more high-value, zero-sulphur products, especially middle distillates. On the other hand refining crude oil, particularly heavy oil produces substantial quantities of low-value fuel oil, i.e. more than prevailing markets can consume. Source modified from Fleisch et al., 2003.

As predicted a decade ago (Cherillo et al., 2003) globally, diesel demand is growing rapidly at some 3% a year, more quickly than other refinery products. Against this backdrop, refiners face significant challenges to meet diesel demand and quality in the future as crude oil supply becomes heavier and sourer (Wood, 2007). Forecasts for the next two decades suggest that growth in diesel demand is set to continue (e.g. Figure 2).

13. Other Natural Gas GTL Conversion Technologies

13.1 Gas to Methanol (GTM)

Methane conversion to methanol (CH_4 to CH_3OH, where one hydrogen atom is replaced by a hydroxyl group) involves the following reaction:

$$CO + 2\ H_2 \longrightarrow CH_3OH + energy$$
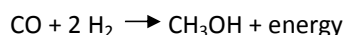
Methanol production typically involves a two-step process: steam reforming to produce syngas; a high-temperature reaction of the syngas then yields methanol. Syngas is typically converted to methanol over a copper or platinum catalyst at high temperature. This process is not very efficient due to accidental total oxidation to carbon dioxide and water. One of the most effective and widely licensed processes involves gas-phase, low-pressure conversion of syngas using a $CuO/ZnO/Al_2O_3$ catalyst at 200-300 °C and 3.5-5.5 MPa. In this process the per pass conversion is < 35 % to improve selectivity to methanol which is > 90 % (De Klerk, 2012).

Methanol is one of the seven highest volume commodity petrochemicals, with a consumption of more than 40 million ton per year. However, methanol markets are volatile and frequently existing capacity exceeds demand. As methanol cannot be easily handled as a transportation fuel, for safety reasons, its markets are substantially smaller than middle distillates markets. Methanol is widely used as a base chemical to make other oxygenates, e.g. formaldehyde, solvents, antifreeze and acetic acid, for use in the petrochemical sector.

13.2 Gas to Di-Methyl-Ether (DME)

DME (CH_3-O-CH_3) is a simple oxygenate having physical properties similar to LPG enabling it to be handled in a similar way. Its boiling point is -25°C at atmospheric pressure, rising to ambient temperatures under 5 to 6 bars of pressure. DME has potential as a clean, versatile and easily-handled, versatile fuel (i.e. it can be used as a LPG substitute and most is currently consumed as a blendstock for LPG). It can be manufactured by chemical conversion of natural gas, coal or biomass at a much lower cost than FT GTL diesel. China has over the past decade developed several plants to produce DME from coal, in some cases via the dehydration of methanol and in other cases via syngas. The majority of DME currently consumed worldwide is produced in China from coal-derived methanol via the catalytic dehydration process where two molecules of methanol react to form one molecule of DME and one molecule of water (Fleisch et al., 2012). A 5,000 metric tons/day (mt/d) DME plant requires about 210 million scf/day (mmscfd) of feed gas.

To be price competitive in the fuel market, more efficient larger-scale DME production processes are being developed. In recent years a number of new processes have been offered for license by Air Products, Topsoe, JFE (Japanese steel producer) and KGTC (Korea Gas Technology Corporation) involving the direct route to DME from synthesis gas, i.e., avoiding the intermediate step of generating methanol (Ogawa et al. 2003). KGTC announced in February 2011 the award of a basic engineering and design package for a plant that would manufacture 300,000 tons of DME per year, although it is yet to be decided where such a plant would be built. Korea has reported discussions and pre-FEED studies since 2009 for locating such a plant in the Middle East (e.g. Oman or Saudi Arabia) providing access to large-scale gas resources at low cost. However, no investment decision or cooperation agreement appears to be pending for a DME plant on such a scale. Nevertheless, the "DME Fuel Demonstration & Empirical Study Technology Development" project was started by Kogas (Korean Gas Corporation) in December 2007 and successfully concluded in April 2010. Starting in July 2010 DME-LPG mixed fuel was initially supplied to a total of 400 locations distributed through four refuelling stations across Korea for household and commercial use for a year. The successful demonstration of DME as a one-to-one substitute and additive for LPG in Korea is leading to the further development of the DME market there.

DME from coal has been marketed in China over the past decade as a clean energy fuel alternative to burning coal or LPG for domestic heating and cooking (up to 20% blend in LPG does not require modification to appliances), as well as for larger-scale power generation. Key challenges for DME are located at the downstream end of the supply chain. It has

potential to be used as a clean fuel in power plants, as a transportation fuel (i.e. substitute for diesel, but requires engine modifications) for both heavy goods vehicles and cars and as substitute for LPG as a fuel for domestic and industrial heating and cooking appliances. However, some of the cost savings relative to F-T GTL made upstream are offset by costs incurred in modifying engines and burner tips to handle it downstream. The main markets for DME are likely to remain in Asia as an LPG substitute, but could be greatly expanded if the one-step technologies from syngas to DME, avoiding methanol as an intermediate product, are deployed as larger-scale plants to supply transport fuel and power generation fuel markets. As with F-T technologies natural gas, coal and biomass can all provide feedstock for DME processes.

Other high population developing countries with large consumption of LPG for domestic cooking and/or heating are also potential markets for DME (e.g. Egypt, India, Indonesia Philippines, and Vietnam). Pure DME vapour has a relatively higher calorific value of about 14,200 Kcal/nm^3 compared to 21,800 Kcal/nm^3 for propane and about 8,600 Kcal/nm3 for pure methane, on a LHV basis (Fleisch et al., 2012). DME therefore has the potential for use as a substitute gas turbine fuel, or as a substitute for diesel fuel in a diesel generator, in remote isolated markets.

13.3 Gas to Olefins (GTO)

Olefins are the base chemicals typically manufactured in petrochemical industry by cracking ethane, LPG or naphtha. The conversion of methane-rich gases to olefins has proved challenging to achieve on a commercial scale for many decades. Processes incorporating an oxidative coupling methane conversion reactor and downstream process units have been demonstrated to produce olefin products, typically ethylene and propylene from methane (e.g. Gradassi & Green, 1995). However, currently most process routes from methane to olefin progress via methanol.

In July 2011 UOP (Honeywell) announced that it had been awarded a project to build a commercial scale methanol-to-olefins plant by China's Wison (Nanjing) Clean Energy Company Ltd to be located in Nanjing, China. The plant using UOP's proprietary technology is scheduled to produce some 290,000 metric tons per year (mtpa) of ethylene and propylene by 2013.

In the absence of a commercial-scale one-step route from methane to olefin, i.e. avoiding the production of methanol, it is unlikely that many stranded gas fields, remote from the main petrochemical markets will be developed with olefin production as a primary objective.

13.4 Gas to Gasoline (GTG)

A simple chemical process route from methane-rich natural gas to gasoline has long been sought, without much success. It is possible to produce gasoline from methanol, but it involves several not very efficient and expensive steps. Mobil developed the first methanol to gasoline (MTG) plant in New Zealand (i.e. 14,500 barrels/day plant at New Plymouth, 75%

owned by New Zealand government; 25%-owned by Mobil) , which operated from 1985 to 1997 producing a sulphur –free gasoline of approximately 92-RON quality. The process (patent held by Exxon Mobil) converts methanol to DME and then to light olefins, which are catalytically synthesized into C5+ olefins and on into paraffins, naphthenes and aromatics.

 The catalysts used in the MTG process limits molecules to less than about ten carbon atoms and results in a product with some 53% paraffins, 9% naphthenes and 26% aromatics (EMRE, 2010). Methanol is fed into a fixed bed reactor system where all of the methanol is converted to hydrocarbon and water. The MTG reactor effluent is then separated into gas, raw gasoline and water. The raw gasoline is separated into LPG, light gasoline & heavy gasoline. The heavy gasoline is hydro-treated to reduce durene content and the heavy gasoline and light gasoline are then re-combined into finished MTG gasoline. MTG gasoline yields are typically just 38% of the feed with a low-sulphur, low-benzene gasoline constituting 87% hydrocarbon content (EMRE, 2010). A second generation MTG technology with improved process efficiency has been deployed at the 2,500 barrels/day MTG:JAMG plant in Shanxi Province China.

Although the original development of the MTG technology processes methanol from natural gas feedstock, the same technology can be used for methanol produced from other sources such as coal, petroleum coke and biomass. In June 2012 EMRE announced that it had entered into a licensing agreement with Sundrop Fuels who intend to apply the technology at its planned biomass fuels plant near Alexandria, Louisiana (USA). The biomass complex envisaged in this project will gasify forest waste supplemented with hydrogen produced from natural gas to make synthesis gas. Hence, it will be a hybrid renewable and fossil fuel feedstock plant. The syngas then will be converted to methanol and fed into the MTG process, producing some 3,500 bpd of high-quality gasoline.

A small Texas-based company, Synfuels International, has developed a process that initially cracks methane to form acetylene (C_2H_2, also known as ethyne, the simplest alkyne) at high temperatures, and then, using its proprietary catalyst, converts some 98% of the acetylene into ethylene, which it then converts into a range of fuels particularly gasoline. Synfuels International claimed in 2008 to be able to produce a barrel of gasoline for <US$25/barrel compared to US$35/barrel for a larger scale F-T GTL plant (Hamilton, 2008). A small demonstration plant has been in operation at Texas A&M University since 2005, but as yet, there are no plans announced to scale up this complex process. Other companies are also pursuing gas to gasoline routes. The multiple steps involved in the MTG and other gas to gasoline processes make it unlikely that such routes will be widely deployed as a preferred GTL route due to capital cost requirements and the tightly held patents for some of the process steps.

14. Large-scale F-T GTL Plant Evolution

Although there are other GTL technologies available and in use, as described above, most of the capital investment in GTL remains focused on the Fischer Tropsch (F-T) technologies. Large scale F-T GTL processing facilities built to date are based on technologies held by just two companies

14.1 SASOL GTL Plants

Sasol developed its patented and integrated three-step slurry phase distillate (SPD) GTL process in the 1980s as an evolution from its Secunda coal to liquids (CTL) plants in Mpumalanga province, South Africa. That technology was used to develop a stand-alone 22,000 barrels/day GTL plant in Mossel Bay, South Africa. Originally called Mossgas that plant is considered by many to be the first commercial GTL plant commissioned in the world (1992). The Mossgas plant is now owned and operated by PetroSA and called the PetroSA GTL plant.

Sasol's technology has evolved to consist of an autothermal gas reformer to produce syngas, Sasol's slurry phase F-T reactor and its proprietary cobalt catalyst and is followed by Chevron's isocracking product upgrading technology. Sasol scaled up its technology with an agreement with Qatar Petroleum (51% QP; 49% Sasol) in 2001 to build the Oryx plant in Qatar. Construction of that project commenced in 2003 and it was finally commissioned in 2007 and 2008 (The Gulf Intelligence, 2011), following significant project delays and cost overruns to its US$1 billion budget. Operational teething problems followed with a significant issue associated with excessive fine material produced in the F-T reactors took some time to resolve. That plant has a nameplate design capacity of 32,400 barrels /day, but is believed to have produced at significantly less than that capacity for much of its operating life to date. The water produced as a bi-product from the GTL plant is used for irrigation purposes in Qatar.

Sasol was involved in a GTL feasibility study with Texaco in 1998 to build a plant in the Niger Delta. A FEED study for the Escravos project was completed in 2002, which resulted in an agreement between Sasol, Chevron Corporation and Nigerian National Petroleum Company (NNPC) to build a plant of the same design as the one under construction at that time in Qatar. Construction contracts were awarded for the plant in 2005 with high expectations for the plant (Fraser, 2005), but the project has been subject to a number of delays and cost overruns. By the end of June 2011, construction of the Escravos GTL plant was reported to be some 69% complete with the overall Engineering, Procurement and Construction work some 76% complete (Ezeah, 2012).

The Escravos GTL plant in Nigeria according to 2011 reports (Reuters, 2011) was expected to cost some US$8.4 billion and to become operational by 2013 (Bala-Gbogbo, 2011). It is reported to have an initial capacity of 32,400 barrels/day, i.e. similar in scale and design to the Oryx plant in Qatar. The project is now being developed by Chevron Nigeria Limited (75%) and NNPC (25%). Due to increased cost and delays, Sasol withdrew from the project in 2009, although its F-T technology will be used under licence there. Current cost estimates suggest that the Escravos GTL plant will deliver GTL at a unit capital cost of some US$180,000/ barrel/day of capacity.

Sasol is currently in the planning stages for projects to build GTL plants in Uzbekistan, United States and Canada. In Uzbekistan a joint venture between Uzbekneftegaz, Sasol and Petronas formed in 2009 conducted a feasibility study for a 38,000 barrels / day GTL plant

and signed an investment agreement to build such a plant in 2011. That plant will produce GTL products, specifically diesel fuel for the local land-locked Uzbekistan market. Sasol has further developed its F-T reactors in recent years from the 16,000 barrels/day throughput per reactor deployed in Qatar to 24,000 barrels/day for the same reactor vessel size to be deployed in plants currently being planned (Sasol, 2011) and expects to further increase throughput capacity per vessel in the short-term.

14.2 Shell GTL Plants

Shell commissioned what it claims to be the World's first commercial GTL plant in Bintulu Malaysia in 1993 at a capital cost of some US$850 million (US$68,000/ barrel/day). The plant is a joint venture composed of four shareholders: Shell (72%), Mitsubishi (14%), Petronas, the national oil company of Malaysia (7%), and Sarawak State (7%). The Bintulu GTL plant had an initial design capacity of 12,500 barrels / day. This used the Shell Middle Distillate Synthesis (SMDS) process. Production at the Bintulu GTL plant was interrupted for more than two years by a fire in the air separation unit in 1997, but was upgraded to a capacity of 14,700 barrels/day in 2003 and is operated by a staff of some 380.

Shell used its experience at Bintulu to design an order of magnitude scale up of its GTL technology for what would ultimately become the Pearl plant in Qatar. In 2003 when the pre-feed stage for a large GTL plant in Qatar was announced, Shell's expectation was that it would be able to deliver a 140,000 barrel/day plant for some US$4 billion plus US$ 2 billion for the associated offshore field development. Shell were not alone, in the period 2002 to 2004, when the industry's expectation for GTL F-T technology development was that scale up could in the short-term reduce F-T GTL unit costs to the US$20,000/barrel/day of capacity level.

Following large-scale F-T GTL plant FEED studies in Qatar by Shell, ExxonMobil and ConocoPhillips it became clear that capital costs would be much higher. ExxonMobil withdrew from its Qatar Palm GTL project in 2006 citing high costs, but Shell elected to proceed with Qatar Petroleum to develop the Pearl GTL project with a budget of around US$18 billion. Construction of the Pearl GTL plant started in February 2007. At the peak of construction the project was reported to have employed some 52,000 workers. It represents Shell's single largest project investment ever and is one of the largest oil and gas facilities ever built worldwide. The Pearl GTL plant was eventually brought into production in 2011 for a total project cost reported to be in the region of US$19 billion (including NGL production). De Klerk (2012) estimates the GTL capacity component of the Pearl Plant to be some US$110,000/barrel/day of capacity, excluding the cost of NGL processing from the feed gas.

The Pearl gas-to-liquids (GTL) plant, jointly owned by Qatar Petroleum and Shell, located in Ras Laffan Industrial City, sold its first commercial shipment of GTL Gasoil in June 2011 (Oil Review Middle East, 2011). The second train of the plant became operational in late 2011 and the plant was scheduled to reach full capacity by mid-2012 (Shell, 2011). Once fully operational, Pearl GTL is designed to consume some 1.6 billion cubic feet of gas per day

(bcfd) from the North Field, which will be processed to deliver an expected 120,000 bpd of condensate, LPG and ethane and an expected 140,000 bpd of GTL products.

15. Cash Flow Analysis Methodology to Evaluate the Commerciality of GTL Projects

There are several factors that determine the cash flow and income streams associated with GTL plants. The key factors required for a methodology that analyses the commercial attractiveness of a GTL plant in a multi-year cash flow model include:

- Cost of feedstock (natural gas, coal, petroleum coke or biomass)
- Prices of the petroleum products and chemicals produced and sold from the plants. Those product prices are in most cases strongly influenced by benchmark crude oil prices. GTL products generally trade in price ranges that reflect prevailing refinery and petrochemical plant crack spreads. Sometimes GTL products trade at small premiums to refinery derived products because of their superior quality (i.e. low sulphur, low aromatics in the case of diesel and gasoline)

- If the GTL project is an integrated project then revenue from natural gas liquids extracted from the feed gas stream need to be included in the project cash flow and income calculations

- Capital costs to construct the GTL plant, which can be usefully compared by the unit US$/ barrel/day of plant product throughput capacity

- How capital costs are offset, recovered and/or depreciated over time and deducted as part of a taxable income methodology

- GTL plant efficiency (i.e. unit quantities of feedstock required to produce one unit of product) on an energy and/or mass basis

- GTL plant annual utilisation rate (days/year) based upon maintenance and turnaround requirements

- GTL plant operating and maintenance costs including the costs of catalysts, chemicals, utilities.

- Offsite costs including access to port or other export loading terminals and/or storage facilities

- Cost of transportation (shipping) between the GTL plant and the market in which the products are sold

- Fiscal deductions applied which vary significantly from jurisdiction to jurisdiction, but typically include some or all of:

- Regressive taxes levied along the GTL supply chain (e.g. property taxes, royalties, etc.)

- Progressive taxes levied on profits generated from the sale of the GTL products

- Tax allowances, credits, holidays and/or capital cost uplifts that reduce the fiscal burden for a period of time

- Accelerated depreciation mechanisms that promote faster cost recovery / offset and improved time value of the income stream for the investor

More detailed cash flow analysis models would also consider inflation, financing structures, interest rates, exchange rates and a detailed breakdown of the product slate (i.e., percentages of products produced and their individual prices) with price forecasts and escalation factors applied over time, if appropriate.

Because there are so many variables involved in determining commerciality it is usually not possible to simplify commerciality to terms that express it just as a breakeven oil price – feed gas price combination, below which a certain GTL technology becomes sub-commercial. To make comparisons on such terms it is necessary to apply some general assumptions about several of the above factors (e.g. assume constant / generic fiscal and cost recovery terms and indicative efficiency, operating and supply chain costs). Table 1 illustrates indicative input base case assumptions required for a multi-year cash flow and income analysis of a hypothetical F-T GTL project. Readers should be aware that the assumptions made in this table are likely to differ from those applying to specific plants.

Table 1. Base case input assumptions for a multi-year cash flow and income analysis of a hypothetical F-T GTL plant integrated with upstream feed gas supply and NGL yield.

Table 2 provides a sensitivity analysis table in terms of calculated internal rate of return (IRR%) for a range of oil prices, feed gas prices and plant capital costs, while maintaining all the other base case assumptions listed in Table 1 constant. Clearly changing any of the other base case factors from those values listed in Table 1 would lead to changes in the IRR's calculated and listed in Table 2. Hence, the commerciality comparisons provide an approximate guideline only. Decision making would require more in depth analysis calculating net present values, discounted payback periods and risk adjustments. Stochastic models involving Monte Carlo simulation using input distributions for the key price and cost input uncertainties would be used by most organisations to provide further insight from such cash flow models.

Table 2. Post-income-tax cash flow sensitivity analysis of the hypothetical GTL (F-T) plant (50,000 barrels of product produced/ day) expressed as IRR (%) in terms of a range of oil prices, capital costs and feed gas costs applied while maintaining the other base case input assumptions listed in Table 1.

The sensitivity results presented in table 2 suggest that the commerciality of an F-T GTL plant is particularly sensitive to oil price and capital costs per unit of plant throughput

capacity and less sensitive to feed gas prices. However, different fiscal structures from those assumed in the hypothetical plant example could change the valuations significantly. Tax incentives such as accelerated depreciation, periods of exemtion from certain fiscal elements (e.g. tax holidays) or tax credits might all improve the commerciality of the example provided. Similarly improved plant efficiency due to technology improvements and lower shipping costs due to proximity to market could also lead to improvements in the project's cash flow performance from an investor's perspective.

16. North American GTL Opportunities

The large prevailing natural gas to oil price differential that has persisted in North America (2009 to 2012), driven by increased shale gas production, has sparked renewed interest in building large-scale GTL plants there. At low (i.e. <US%4/mmbtu) natural gas prices and high crude oil prices (>US$75/barrel) a good commercial case can be made for GTL technologies. GTL is likely also to increase its appeal in North America as greater restrictions on gas flaring and fugitive emissions from oil and gas production and hydraulic fracture stimulation operations, introduced in 2012 by the U.S. Environmental Protection Agency (EPA) in 2012, take effect by 2015 (Reuters, 2012).

Over the past year pre-feasibility studies for three GTL projects to be based in North America have been announced.

1. In June 2011 Sasol agreed to pay more than US$2 billion to join Talisman in its Montney Shale gas play, acquiring interest in both the Farrell Creek and Cypress A assets. Jointly Sasol and Talisman committed to a feasibility study to determine if a proposed gas-to-liquids facility in Western Canada could be commercially viable and open up new markets for the Montney Shale production. The technical feasibility study was completed late in 2011 by Foster Wheeler who was then mandated to develop a detailed cost estimate for a 48,000 barrels / day (~2 million tons per annum -mtpa) plant before the end of 2012. If the cost estimates make sense and market conditions hold up then a final investment decision for that project is expected in 2014 with operations commencing in 2017/2018 (Calgary Herald, 2011). Talisman suggested that the project was provisionally expected to cost between US$4 billion and US$ 5 billion. After participating in the feasibility study for a GTL (gas-to-liquids) facility, Talisman Energy decided in June 2012 not to proceed with the next phase of the project. That decision placed the immediate future of the project in doubt.

2. Sasol also announced in September 2011 that it had chosen the south-western region of the State of Louisiana as the site for a planned gas-to-liquids (GTL) facility. It sanctioned an 18-month feasibility study to evaluate the building of GTL facility in Calcasieu Parish, Louisiana with capacities of either 2 mtpa or 4 mtpa (i.e. up to about 96,000 barrels / day). When announced it represented the first large-scale GTL project in the United States. This followed an announcement by Sasol In December 2010, to evaluate building the world's first Ethylene Tetramerization Unit, also to be located in Calcasieu Parish, Louisiana.

3. In April 2012 Shell announced its own plans to build a GTL plant in Louisiana of similar scale to its Pearl Plant in Qatar (i.e. ~140,000 barrels / day). That project is in the feasibility phase with provisional cost estimates likely to be in excess of US$10 billion.

These and other potential North American GTL projects are all vulnerable to natural gas price increases. If natural gas prices stay low and oil prices remain relatively high GTL projects are likely to be commercially attractive if capital costs can be held below about US$ 100,000 / barrel/day capacity, which neither Shell nor Sasol appear to have achieved in their recent GTL projects. The opportunities for GTL in North America using shale gas feed gas are significant, but so are the price risks (for feed gas and products) and project cost risks.

17. Other Countries to Which GTL Technologies are Likely to Grow in Appeal

For gas-resource-rich countries in remote locations with small indigenous gas consumption, GTL technologies offer diversification of markets from those that can be reached by pipeline (if possible) or LNG supply chains, which direct supply only into natural gas-consuming markets. By offering the ability to target supply into global-liquid-fuel-transportation markets GTL plants significantly diversify market opportunity and help to smooth financial returns in volatile conditions where gas markets prices and oil and petroleum product market prices become decoupled (Figure 5).

Figure 5. GTL and LNG are processing gas for sale into two distinct markets: LNG supplies gas primarily for city gas and power-generation markets; GTL supplies synthesized petroleum products (middle distillates, naphtha, and lubricants) primarily into transportation fuel markets. Source: updated from Wood, 2005.

Australia, with its vast coal and natural gas resources for many years has conducted research in GTL and CTL process technologies recognising the desirability of producing low-emission liquid fuels from coal and/or natural gas (Trimm & Pullar, 2005). CSIRO (Commonwealth Scientific and Industrial Research Organisation) continues to fund GTL technology research (CSIRO, 2010), but no commercial scale GTL projects are in planning. The significant capital commitments to LNG projects currently under construction in Australia, and the cost inflation that they have driven, is likely to dampen enthusiasm for the construction of GTL projects in the medium term. However, in the long-term many gas-resource-rich countries (e.g. Algeria, Australia, Bolivia, Russia, and Central Asia etc.) are likely to reconsider the viability of GTL in diversifying the gas monetisation strategies. Positive investment decisions for GTL projects in those countries will undoubtedly depend upon the differential between natural gas, crude oil and petroleum product prices and the unit capital costs of building large-scale GTL plants. China, which has already developed CTL and DME plants and is likely to scale-up its GTL plans and diversify its GTL technologies, especially when it exploits its shale gas and CBM resources on a larger scale.

Gas-rich landlocked countries, such as Bolivia and certain Central Asian republics (e.g. Uzbekistan – in which Sasol and partners are now constructing a plant - and Turkmenistan), are potential niche markets for GTL. They do not require very large plants and have limited potential to export the GTL products. However, because their oil supply is primarily very light oil and condensate they cannot produce enough diesel and middle distillates in their conventional oil refineries to meet local demand. In the case of Bolivia it has to import diesel, which involves expensive transportation and a GTL plant could avoid that (e.g. Velasco et al., 2010).

Figure 6 highlights the main opportunities and challenges confronting would-be GTL developers.

Figure 6. The GTL Industry: A summary of its opportunities and challenges.

18. Conclusions

GTL technologies offer the potential to reduce global dependency on crude oil-derived transportation fuels. They also offer substantial opportunities for the owners of stranded gas to diversify the markets into which they deliver their gas-derived liquid products, particularly targeting the large and rapidly growing global middle distillate markets. However, the technologies are complex, costly and tightly held by a few companies holding patents for the key process steps, which present significant barriers to entry for building large-scale plants. This also renders the building of large-scale plants challenging for the gas resource holders in terms of capital costs, access to technology and long-term transfer of GTL technologies.

At the current time Fischer-Tropsch (F-T) technologies dominate GTL applications for large scale- plants. Technology breakthroughs are required if methane-to-gasoline or methane-to-olefin plants are to displace traditional refinery and petrochemical routes to those products. On the other hand dimethyl-ether (DME) has a growing market in Asia, particularly in China, which is likely to expand if the one-step process, avoiding the production route via methanol, is successfully scaled up as planned, and transportation fuel markets are developed for DME.

The GTL industry is also exposed to significant oil and gas price risks as it requires a significant differential between feed gas costs and petroleum product prices. Volatile crude oil and natural gas markets make it difficult for companies to sanction the capital investment for new GTL projects that will enter the market some four years in the future not knowing whether those future markets will render the plant commercially viable or not. Whereas refineries are exposed to oil price volatility, GTL plants are exposed to both oil and gas price fluctuations. For F-T GTL to be commercial at oil prices of less than about $40 / barrel, plant capital costs, operating costs and feed gas costs all have to be substantially lower on a unit basis than large-scale plants built in recent years have been able to deliver. If the unit capital cost of an F-T GTL plant is close to US$100,000/barrel/day, the operating cost of that plant is close to US$20/barrel of product and the feed gas costs in the vicinity of

US$5.00/MMBtu the liquid products would cost in the vicinity of US$100/barrel and the economics of such a plant do not look so inviting in 2012 market conditions. The industry has to achieve lower plant and feed gas costs to be economically attractive.

Opportunities to scale-down the GTL technologies for modular plants to use associated gas and avoid flaring, in remote onshore and offshore oil fields, are being pursued. Tougher rules restricting flaring and fugitive emissions from hydraulic fracture stimulation are likely to boost interest in the small-scale technologies. Unit cost and process reliability are likely to determine the uptake of these technologies.

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Figures and Captions

Figure 1
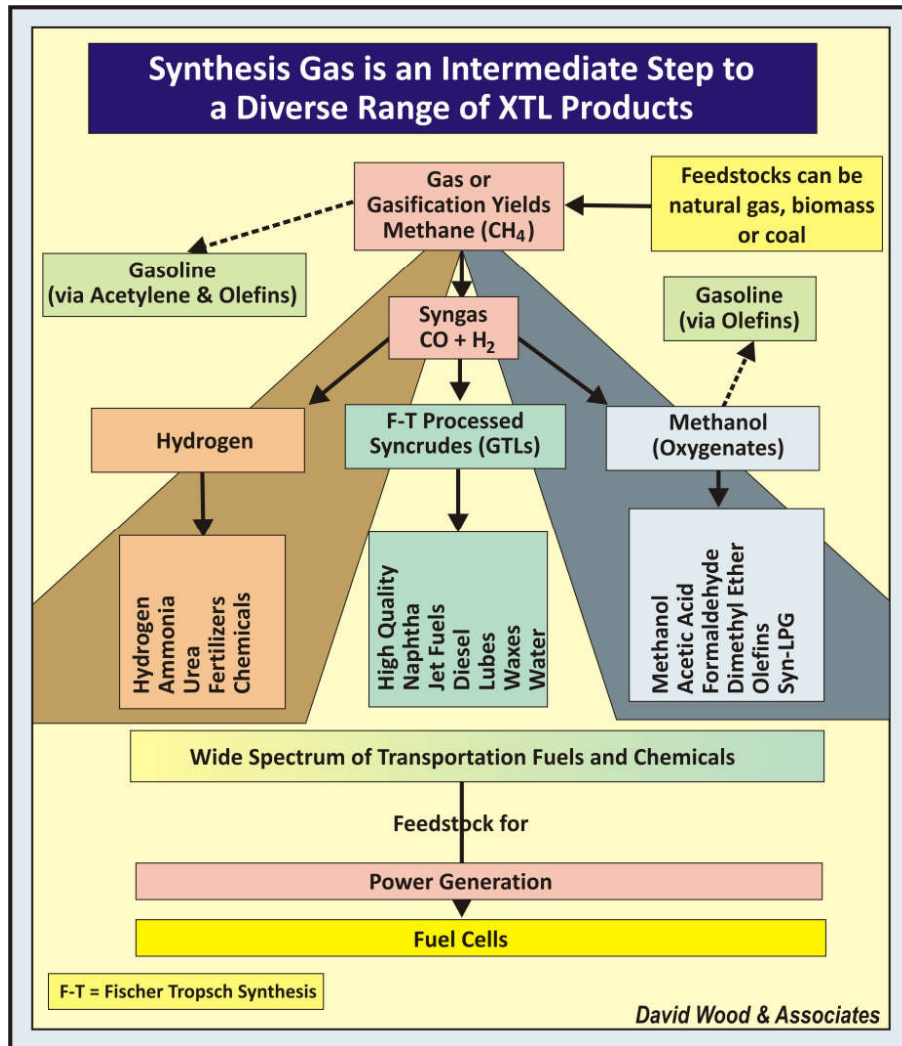
Figure 1. Methane can be converted into a range of liquid and gaseous chemicals via the synthesis gas process route. Methane itself can be derived from natural gas resources or generated by the gasification of coal and various biomass resources. Source updated from Wood et al., 2008.

Figure 2
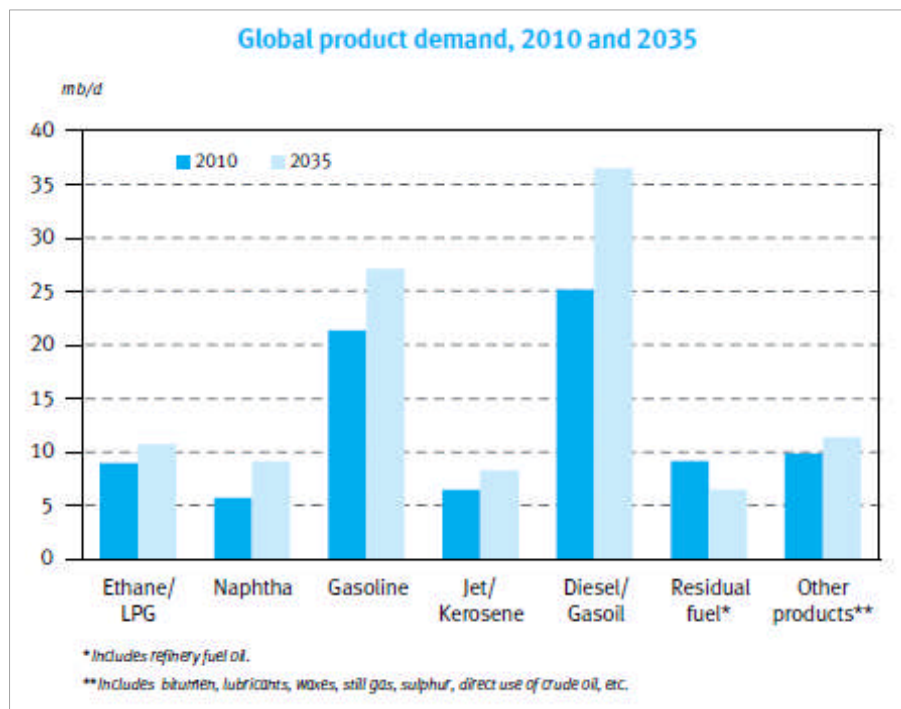
Figure 2. OPEC's Global petroleum product demand forecast emphasizes the significant growth expected over the next two decades, especially for middle distillates. Source OPEC, 2011.

Figure 3
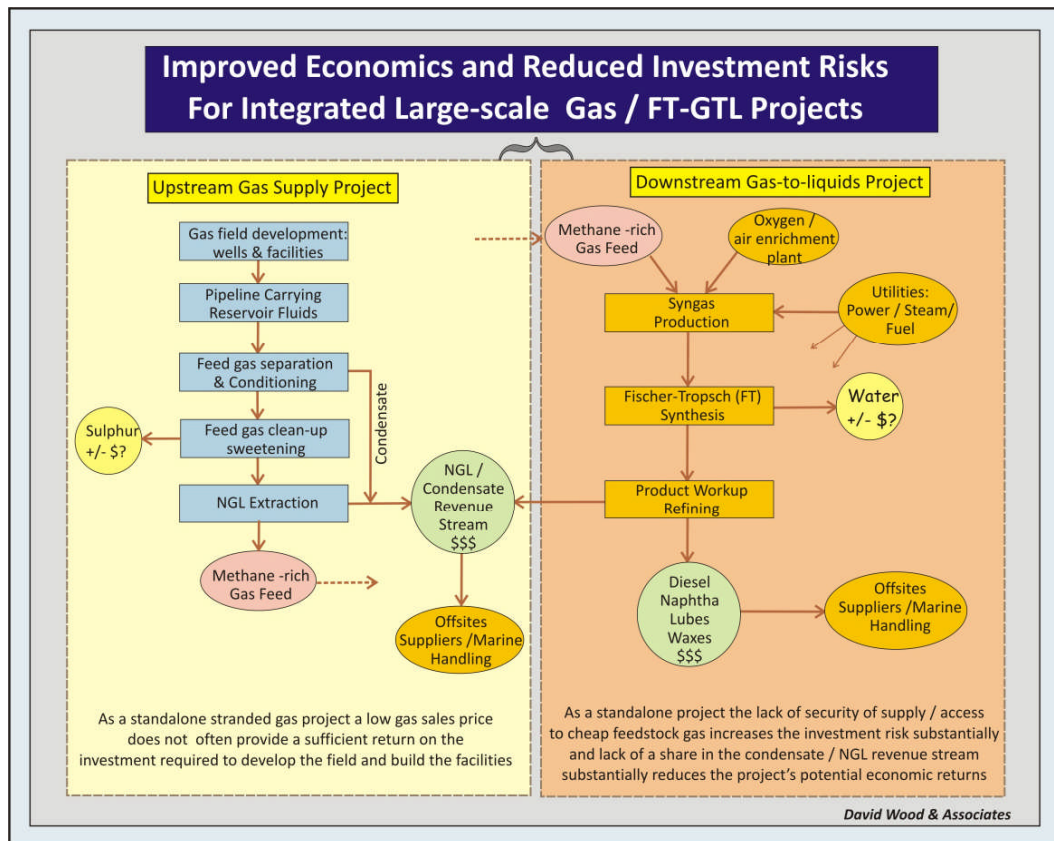
Improved Economics and Reduced Investment Risks For Integrated Large-scale Gas / FT-GTL Projects

Figure 3. Large-scale F-T GTL projects become more economically robust for the developer if they involve integrated upstream and downstream components securing feed gas supplies and additional revenues from NGL and condensate extracted from the feed gas. Source updated from Wood & Mokhatab, 2008.

Figure 4

Figure 4. The products derived from upgrading syncrude produced by F-T GTL differ significantly from those produced by refining a barrel of crude oil. Notably F-T GTL produces more high-value, zero-sulphur products, especially middle distillates. On the other hand refining crude oil, particularly heavy oil produces substantial quantities of low-value fuel oil, i.e. more than prevailing markets can consume. Source modified from Fleisch et al., 2003.

Figure 5
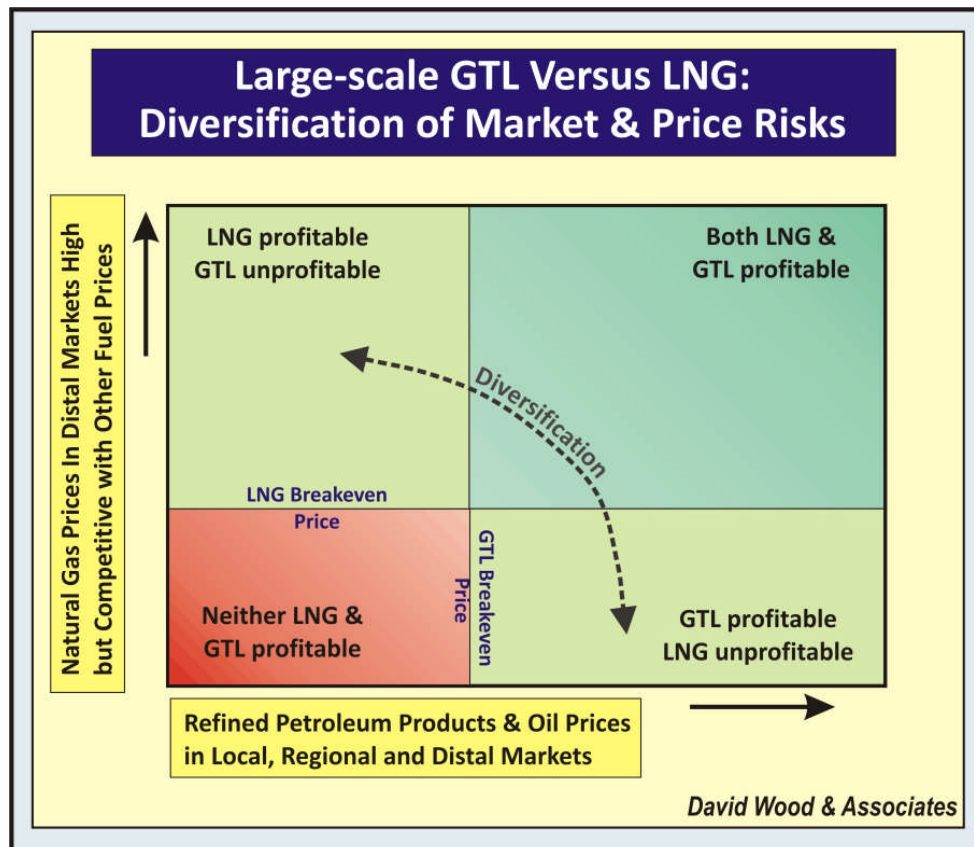
Figure 5. GTL and LNG are processing gas for sale into two distinct markets: LNG supplies gas primarily for city gas and power-generation markets; GTL supplies synthesized petroleum products (middle distillates, naphtha, and lubricants) primarily into transportation fuel markets. Source: updated from Wood, 2005.

Figure 6

The GTL Industry: Opportunities & Challenges

Markets to Target	Hurdles to Cross	Risks to Overcome
Global liquid transport fuels	Access to technology	Low future oil prices
Isolated liquid fuel markets in land-locked regions	Process complexity	High future gas prices
Avoid flaring of associated gas in producing oil fields	Scaling-up processes	Capital cost escalation
LPG substitute and blendstock	Process efficiency	Rise in catalysts costs
Power generation liquid fuels in remote markets	Process reliability	Poor plant reliability
Base petrochemicals	GTL plant emissions	High maintenance downtime
Petrochemical feedstock	Integrating upstream gas supply	New competing technologies
Speciality lubricants	Providing transport infrastructure	Cheaper alternative products
	Training skilled operations teams	Insecurity of feed gas supplies
	Meeting market specifications	Fiscal instability

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Figure 6. The GTL Industry: A summary of its opportunities and challenges.

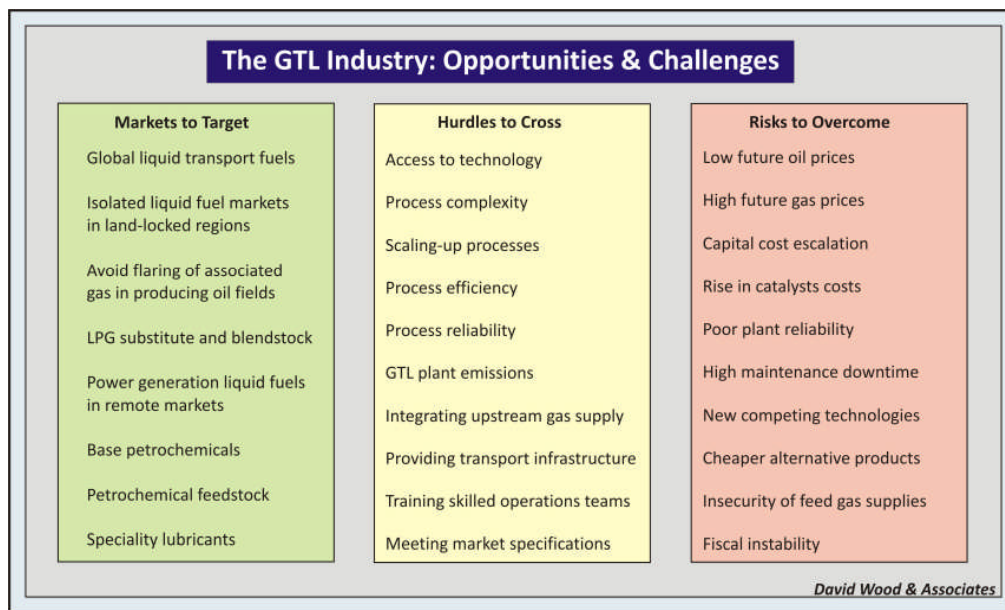| Base Case Assumptions for Hypothetical GTL (F-T) Plant		
Plant Capacity and Utilisation		
GTL plant throughput (product output capacity)	Barrels/day	50000
Plant uptime (days /year)	days	350
Oil and Product Prices		
Oil price	US$/barrel	100
Product slate average positive (negative) margin to oil price	%	12.0%
Feed Gas Quantities and Costs		
Unit feed gas costs	US$/MMBtu	1.5
Plant energy efficiency	%	60.0%
1 BOE defined to contain an energy quantity of	Btu	5600000
Energy content (MMBtu / Boe) feed gas	MMBtu	5.6
Energy content (MMBtu / barrel) average GTL product	MMBtu	5.7
MMBtu of Feedgas consumed / barrel of GTL produced	MMBtu	9.5
Energy content (Btu / cf) of feed gas)	Btu	1060
Wet to dry gas shrinkage factor	%	10.0%
Volume of feed gas / boe of product	cf	9958
Feed gas cost / barrel of GTL product	US$/barrel	14.25
Capital Costs		
Unit capital cost (US$/barrel/day GTL plant throughput)	US$/barrel/day	110000
Total capital costs	US$ millions	5500
Capital costs incurred over number of initial project years	years	4
Operating & Transportation Costs		
Annual operating & maintenance costs (% of capex)	%	0.075
Operating & maintenance costs per unit of plant capacity	US$/barrel/day	8250
Annual operating & maintenance costs	US$ millions	412.5
Unit variable offsite costs	US$/ barrel	1.00
Annual fixed offsite costs (% of capex)	%	0.5%
Annual offsite costs (fixed plus variable)	US$ millions	45
Unit shipping costs	US$/barrel	5.00
Annual shipping costs	US$ millions	87.5
Fiscal, Cost Recovery & Capital Depreciation Terms		
Pre-income tax fiscal components to government	US$/barrel	3
Income tax annual rate % of positive income	%	40.0%
Capital cost straight line depreciation period	years	10
Uplift allowance of capital costs	%	10.0%
Annual capital cost depreciation allowance	US$ millions	605
Integrated Project with NGL Yield?	yes	
NGL yield from wet feed gas	barrels/million cf	15
NGLs sold at price premium (or -ve discount) to crude oil	US$/barrel	3
Timing Assumptions		
Project start year	year	1
Production start year	year	5
Duration of production	years	30
Production final year	year	35
Discount rate applied for analysis	%/ year	10.0%
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Table 1. Base case input assumptions for a multi-year cash flow and income analysis of a hypothetical F-T GTL plant integrated with upstream feed gas supply and NGL yield.

Post-income-tax Cash Flow Sensitivity Analysis of Hypothetical GTL (F-T) Plant (50,000 barrels product/ day) Expressed as IRR(%)							
Unit Capex (US$/barrel/day) ⟶		**50,000**	**80,000**	**110,000**	**140,000**	**170,000**	**200,000**
Oil Price (US$/barrel) ↓							
50.0	a	11.8%	5.5%	0.7%	<0	<0	<0
	b	7.7%	0.7%	<0	<0	<0	<0
	c	0.7%	<0	<0	<0	<0	<0
75.0	a	20.9%	13.6%	9.3%	6.1%	3.2%	0.7%
	b	18.2%	11.3%	7.3%	3.7%	0.7%	<0
	c	15.2%	8.8%	4.4%	0.7%	<0	<0
100.0	a	28.0%	19.3%	14.3%	11.0%	8.5%	6.3%
	b	25.8%	17.5%	12.8%	9.6%	7.1%	4.7%
	c	23.4%	15.6%	11.1%	8.0%	5.3%	2.9%
125.0	a	34.0%	24.0%	18.5%	14.8%	12.0%	9.9%
	b	32.1%	22.5%	17.2%	13.6%	10.9%	8.8%
	c	30.1%	20.9%	15.8%	12.3%	9.8%	7.7%
150.0	a	39.2%	28.3%	22.1%	18.0%	15.0%	12.7%
	b	37.6%	26.9%	20.9%	17.0%	14.1%	11.8%
	c	35.8%	25.5%	19.7%	15.9%	13.1%	10.9%
175.0	a	44.0%	32.1%	25.4%	20.9%	17.7%	15.2%
	b	42.4%	30.9%	24.3%	20.0%	16.8%	14.4%
	c	40.9%	29.6%	23.2%	19.0%	16.0%	13.6%
200.0	a	48.2%	35.6%	28.4%	23.6%	20.2%	17.5%
	b	46.9%	34.5%	27.4%	22.8%	19.4%	16.8%
	c	45.4%	33.3%	26.4%	21.9%	18.6%	16.0%
Feed Gas Costs ($/MMBtu): a = 1.5; b= 2.5; c= 3.5							*David Wood & Associates*

Table 2. Post-income-tax cash flow sensitivity analysis of the hypothetical GTL (F-T) plant (50,000 barrels of product produced/ day) expressed as IRR (%) in terms of a range of oil prices, capital costs and feed gas costs applied while maintaining the other base case input assumptions listed in Table 1.