

2002 — Emergence of the Gas-to-Liquids Industry: a Review of Global GTL Developments

T. H. Fleisch*, R. A. Sills*, M. D. Briscoe

BP Upstream Technology Group, P.O. Box 3092, Houston, TX 77253, USA

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Abstract: This paper reviews the status of the gas-to-liquids (GTL) industry — including current commercial plants, announced projects and the technologies that are likely to be implemented in these future projects. Today, only 35,000 B/D of GTL products (0.1% of market) are manufactured from commercial gas-based plants. Advances in technology have lowered the cost of plants to the point where GTL plants can be profitable at crude oil prices of \$16/B. The advanced stage of development of several proposed GTL projects and attractive integrated economics, for both the gas field and plant, show that GTL can be a significant alternative for monetizing natural gas in the 21st century. GTL technologies includes more than Fischer–Tropsch technology and extends to other liquid fuels, especially in the oxygenate family (methanol, dimethyl ether, etc.).

Key words: gas-to-liquids (GTL), syngas, Fischer–Tropsch, oxygenates, methanol, dimethyl ether

1. Introduction

“Gas-to-Liquids Projects Gaining Momentum as Process List Grows” is the title of an article published in the June 23, 1997 issue of the *Oil & Gas Journal*. This article describes the reasons for the resurgence of interest in gas-to-liquids (GTL) at that time, as well as the major contenders; that is, Shell, Sasol, Exxon (now ExxonMobil) and Syntroleum, to build the next wave of commercially viable, full-scale GTL plants. However, since 1997 none of these major contenders have actually started construction on a commercial-scale GTL plant. On July 11, 2001, the *Oil Daily* said: Conversion of natural gas-to-liquids may have been pushed to the backburner by the resurgence of liquefied natural gas (LNG) over the past year, but efforts to bring the radical technology to commercial fruition are continuing.

This paper reviews the:

(1) Current status of GTL projects, not only those using Fischer–Tropsch (FT) technology but also those

aimed at the oxygenate market;

(2) Key FT technologies and syngas conversion technologies to produce oxygenates that are likely to be used in GTL projects to be built in the near-term;

(3) Keys for success — the reasons why today’s commercial activities are likely to be successful.

A key message is that although none of the proposals listed in the 1997 *Oil & Gas Journal* article have started construction, the GTL industry appears to be entering a significant growth period during which GTL capacity could increase from 35,000 B/D to 1–2 million B/D by 2015 [1,2].

2. GTL drivers and definition

Several factors are converging to drive the growth in the GTL industry:

(1) Desire to monetize existing stranded gas reserves;

(2) Energy companies keen to gain access to new gas resources;

* Corresponding authors. E-mail: FleiscTH@bp.com and sillsra@bp.com.

(3) Market demand for cleaner fuels and new cheaper chemical feedstocks;

(4) Rapid technology development by existing and new players;

(5) Increased interest from gas rich host governments.

These drivers can be best expressed in the context of the *Gas Economy* [3] — a vision for the future of an economy powered by natural gas.

2.1. The Gas Economy

The world's plentiful gas supply sources, continued technological innovation, the desire for less carbon — intensive fuels, and the need for cleaner air in urban areas, will continue to ensure an increase in the importance of natural gas to the development of world, regional and country economies. Looking into the future one can now envision an economy powered principally by natural gas. This *Gas Economy* would be supplied from a truly global market consisting of large gas reservoirs geographically spread but linked to consumers by such options as gas pipelines and LNG but also by large tankers carrying liquid or solid products manufactured from gas via gas conversion

(Figure 1). In this world, the role of gas-to-liquids is not only to provide another option to monetize gas for existing markets, but also to create new markets.

Having found and produced the natural gas at the lowest cost, it is necessary to deliver it from the well-head to the customer who can be separated from the source of the gas by many thousands of kilometers. Most of the world's gas production is brought to the market via pipelines but the high cost of gas pipelines limit the connection of gas resource and market to less than about 5,000 kilometers. The only other commercially viable transport means today is LNG where methane is liquefied at $-162\text{ }^{\circ}\text{C}$, shipped to market in heavily insulated tankers and regasified for use in conventional gas markets such as power generation and domestic applications. Another new means of transport is Gas By Wire. Electricity is generated at the point of the gas resource, AC voltage is converted into DC, transported up to a few thousand kilometers to the customers where the DC voltage is converted back into AC. Although transmission losses are significantly lower for DC than AC, current Gas By Wire has so far found limited applications for distances smaller than about 5,000 km.

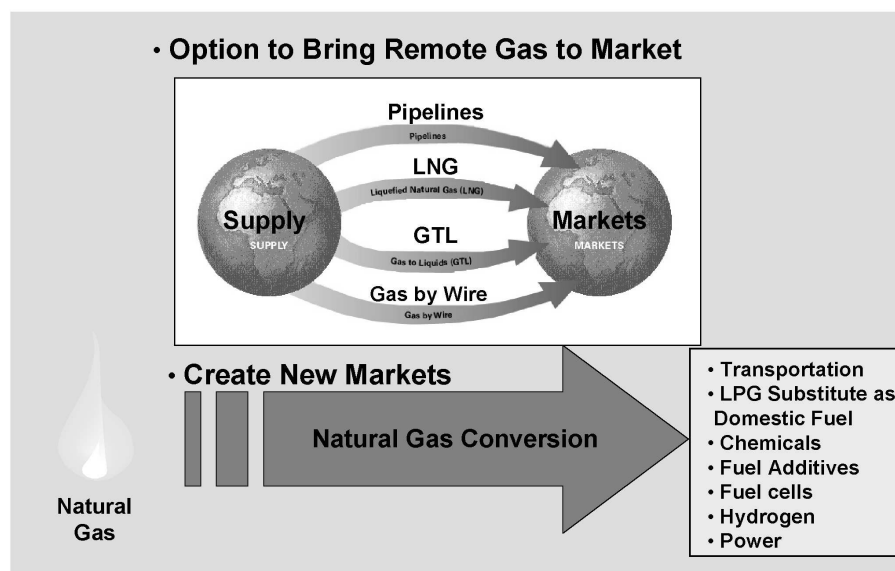


Figure 1. The role of GTL in the *Gas Economy*

GTL will provide another important means to bring remote gas resources to far away markets. Liquid hydrocarbons, paraffinic distillates, methanol or (dimethyl ether) DME can be easily and cheaply

shipped over large distances similar to the refined petroleum products of today. These natural gas derived fuels have to compete with conventional fuels in the market place that pays little to nothing of a

premium for the cleaner GTL fuels. However, up until very recently, gas derived fuels could not compete with the conventional fuels because chemical conversion of gas has been and still is expensive. The methane molecule is chemically very stable and requires significant amounts of energy and sophisticated catalyst systems to break and convert into higher molecular weight, liquid products. Significant cost reductions from improved technologies and economies of scale have moved GTL to the point of commerciality today. On-going efforts in all gas transport options are driving costs for all options down thereby allowing us to economically form new linkages between major gas resources and key regional markets. Trinidad, Qatar and Australia are examples of where several gas-to-liquids market options are being used and/or actively considered.

2.2. What is GTL

GTL has become synonymous with the FT route for producing liquid fuels, petrochemical feedstocks and other products from natural gas. However, GTL also includes production of oxygenates [4] (Figure 2). Today, the route to liquid, higher value products from gas is through conversion via synthesis gas (syngas).

Two basic types of liquid products can be manufactured, namely hydrocarbons via Fischer–Tropsch synthesis and oxygenates such as methanol and DME. Today, gas conversion is the basis of sizable industry consuming the equivalent of 4 TCF of gas a year, which is about the same amount as is monetized in the LNG industry. The major product is hydrogen for both use in refineries and for use in the production of fertilizer (ammonia/urea). It is a little appreciated fact that natural gas conversion to fertilizer is critical for the feeding of the world's 6 billion people. Methanol is the other key product manufactured commercially for many decades currently serving the high value chemicals and fuel additives market in the production of formaldehyde, acetic acid and (methyl tertiary butyl ether) MTBE. DME is a small volume special chemical today used predominantly as an environmentally-benign aerosol propellant replacing the ozone depleting chlorofluorocarbons used in the past. It is anticipated, however, that these oxygenates will eventually serve many large fuel markets including the electrical power market, the transport and the domestic fuel market. These oxygenates can also serve as key building blocks for a gas-based chemical industry.

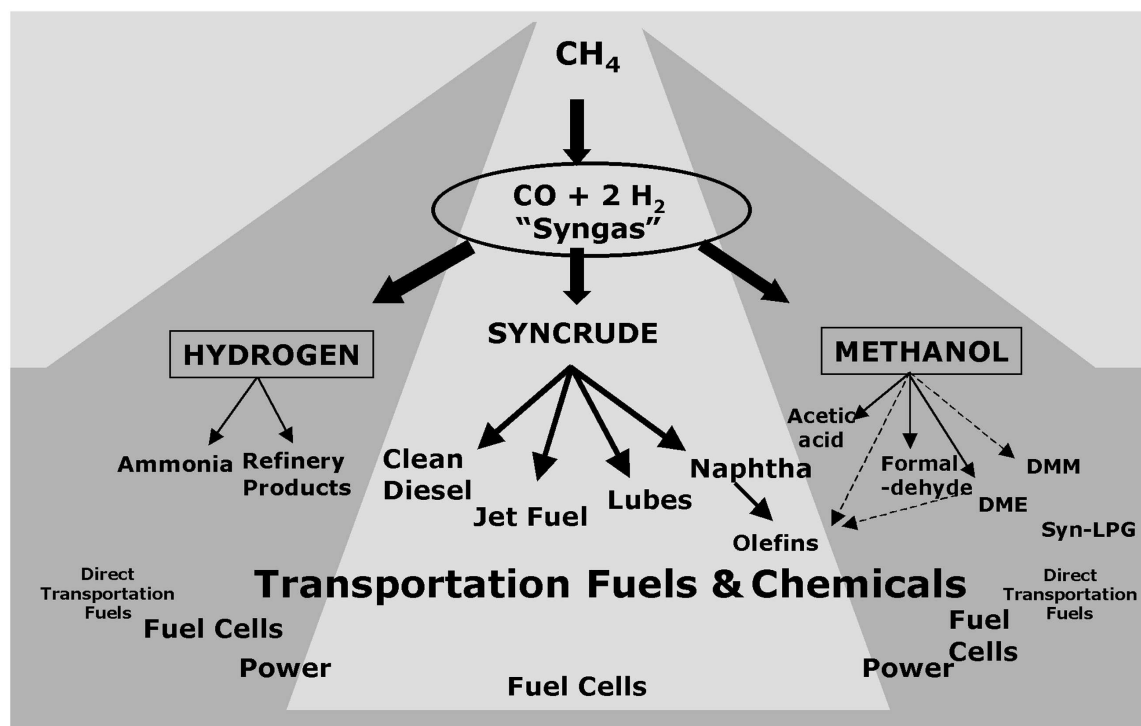


Figure 2. GTL options.

3. Global commercialization activities

A review of global commercialization activities, as shown in Table 1, indicates that today's operating and announced GTL projects represent about 1 million B/D capacity via FT, of which 35,000 B/D is operating, and about 125,000 B/D COE for oxygenate production. The geographical locations that have the most projects are Qatar with 330,000 B/D to 480,000 B/D, and Australia with about 200,000 B/D total from both the FT (60%) and oxygenate (40%) routes. One GTL plant that started up in 1985 is now making methanol for the traditional chemical markets.

These plants are listed by geographical area; and by GTL category, that is, GTL-FT or GTL-oxygenate; and by stage of development, that is, commercially operating, front end engineering design (FEED), or study.

Of the numerous companies on the path toward commercializing GTL, the Sasol Chevron Joint Venture and Shell have made the most aggressive statements. Sasol Chevron Joint Venture says it anticipates investments in excess of \$5 billion over the next 5–10 years. At \$20,000–25,000 per B/D, this investment is equivalent to 200,000–250,000 B/D. Shell has stated that it plans to commit to four large scale GTL plants by the end of 2010, which would be equivalent to a total capacity of about 300,000 B/D.

The construction and operation of commercial and pilot/demonstration scale plants has enhanced the level of GTL experience. Several companies have large-scale plant operating experience.

(1) Shell's experience is primarily due to its GTL plant in Bintulu, Malaysia.

(2) Sasol has very extensive and large-scale experience with several coal-based FT processes. Mossgas, a Sasol licensee, also has GTL operating experience.

(3) ExxonMobil has experience due to both the New Zealand gas-to-gasoline plant (as Mobil), and its 200 B/D Baton Rouge demonstration plant.

(4) Other companies such as BP, Syntroleum, Rentech and Conoco have or are in the process of acquiring experience with large-scale 70–400 B/D pilot plants.

3.1. GTL-Fischer-Tropsch

3.1.1. Commercial operations

3.1.1.1. Shell in Bintulu, Malaysia

The Shell Middle Distillate (SMDS) plant in Bintulu converts natural gas into high quality synthetic oil products and specialty chemicals, which are paraffinic and colorless. The plant converts 100 MM-SCFD (million standard cubic feet per day) of natural gas into 12,500 B/D of middle distillates (gasoil, kerosene, naphtha) and specialty products (lubricant feedstocks, detergent feedstocks, solvent feedstocks, various grades of waxes, and drilling base fluids). The plant started operations in May 1993. In 1997, an explosion in the air separation unit damaged the plant. The plant was rebuilt and production restarted in mid-2000. Since then the plant has been operating at full capacity.

3.1.1.2. Mossgas in South Africa

Mossgas, the State-owned gas-to-liquids producer, uses the Fischer-Tropsch gas-to-liquid process to produce a range of high quality sulphur-free and environmentally friendly fuels in the largest GTL facility in the world [5]. In January 1993, the plant went into full production. Mossgas produces 22,500 B/D of finished products from natural gas. Liquid products are produced from syngas using FT technology licensed from Sasol. Mossgas produces petrol, diesel, kerosene, liquid petroleum gas (LPG) and fuel oil, as well as a range of anhydrous alcohols. The alcohols are used in solvent blends, paint thinner formulations, de-icing and windscreen wash applications in sub-zero temperature conditions and as a carrier in the printing ink industry.

3.1.1.3. Sasol in South Africa—FT synthesis from coal-derived syngas

Sasol has successfully produced liquid fuel from syngas derived from coal since 1955 in South Africa. Although the syngas is not generated from natural gas, commercialization of liquids from syngas using FT technology is very relevant to the development of gas to liquids technology. At both Sasolburg and Secunda, all synthesis gas is produced from coal using Sasol/Lurgi fixed bed dry bottom gasifiers. Future GTL plants using Sasol FT technology would use autothermal reforming technology supplied by Haldor Topsoe. Sasol produces about 135,000 B/D of synthetic fuels from coal-derived synthesis gas, shown in Table 2.

Table 1. Global GTL commercialization activities

Country	Company/Technology Provider and Location	Project	Capacity Plant (B/D)	Status	Comments
Argentina	Shell	GTL-FT	75,000	Study	
Australia	Syntroleum,Barrup Peninsula	GTL-FT	11,500	FEED	a.k.a Sweetwater; seeking financing
	Shell,NW Shelf	GTL-FT	75,000	Study	
	Sasol Chevron	GTL-FT	30,000	Study	
	GTL Resources	GTL-FT	10,000	Study	Floating offshore plant — NW Shelf
	Methanex, Darwin	GTL-CH ₃ OH	24,000*	FEED	
	DME International Ltd	GTL-DME	10,000–20,000 *	Planning	
	Japan DME Int'l	GTL-DME	20,000–35,000*	Study	Consortium of 8 companies lead by NKK Corp, includes TotalFinaElf Mitsubishi Gas Chemical, JGC, Itochu and Mitsubishi Heavy Industries
Bolivia	GTL Bolivia/Deane Group	GTL-FT	10,000	Study	FT technology from Rentech
Chile	Syntroleum,Puntas Arenas	GTL-FT	10,000	Study	Empresa Nacional del Petroleo (Chile) and Advantage Resources (Denver, CO)
Egypt	Shell	GTL-FT	75,000	Study	
Iran	Shell	GTL-FT	70,000	Study	
	Narakangan	GTL-FT	34,000	Study	
	GTL/Sumitomo				
India	India DME Consortium	GTL-DME	26,000	Study	Indian Oil Corp; Gas Authority of India and IIP. Plant Location could in the Middle East/Gulf Region
Indonesia	Shell	GTL-FT	75,000	Study	
Italy	EniTechnologie and IFP,Sannazzaro de Burgondi	GTL-FT	20	Operating	Pilot Plant
Japan	NKK, Kushiro	GTL-DME	25	Operating	NKK Corp, Taiheiyu Coal Mining Co and Sumitomo Metal Industries
Malaysia	Shell, Bintulu	GTL-FT	12,500	Operating	May 1993 startup. 1997 temporary shutdown. Restarted May 2000.
New Zealand	Mobil/NZ Synfuels Corp(Initially)	GTL-G	14,500(Gasoline)		Stopped making gasoline in late '90s. Converted to producing 4,400 TPD
	Methanex (current)	GTL-CH ₃ OH	16,000* (CH ₃ OH)	Operating	Methanol for chemicals market
Nigeria	Sasol Chevron	GTL-FT	34,000	FEED	
Peru	Syntroleum	GTL-FT	5,000	Study	
Qatar	Sasol	GTL-FT	34,000	FEED	Feb. 2002 announced FEED completed; seeking EPC Bid
	ExxonMobil	GTL-FT	80-90,000	Study	June 2001 Letter of Intent signed
	Ivanhoe Energy	GTL-FT	80,000–185,000	Study	Using Syntroleum GTL technology
	/Mitsui & Co				
	Shell	GTL-FT	75,000–110,000	Study	Letter of Intent signed in 1Q 2002
	Conoco	GTL-FT	60,000	Study	Capacity expansion up to 250,000 B/D
South Africa	Marathon	GTL-FT	N.A.	Study	Capacity not available
	Mossgas	GTL-FT	22,500	Operating	Reached full production January 1993
	Sasol, Secunda and Sasolburg	Coal-FT	150,000	Operating	
Trinidad & Tobago	Rentech/Forest Oil	GTL-FT	10,000	Study	
	Atlas Methanol	GTL-CH ₃ OH	20,000 *	Under construction	
	Shell	GTL-FT	75,000	Study	
United States	BP, Nikiski Alaska	GTL-FT	300	Under construction	2Q 2002 startup
	Conoco, Ponca City, OK	GTL-FT	400	Under construction	Late 2002 startup
	Syntroleum, Port of Catoosa, OK	GTL-FT	70	Under construction	2003 startup; DOE Clean-Fuels Program with Syntroleum and Marathon Oil
	Rentech, Sand Creek CO	GTL-FT	1,000		
	ANGTL, Prudhoe Bay, Alaska	GTL-FT	50,000	Study	Using Sasol technology; Proposed at Cook Inlet, integrated IGCC/GTL
Venezuela	PDVSA	GTL-FT	15,000	Study	
Totals		GTL-FT	954,500–1,104,500		
		GTL-Oxygenates	116,000–141,000		
		Total	1,069,500–1,244,500		

* Conversion factors:

5.2 Bbl crude oil equivalent per MT DME; 3.71 Bbl crude oil equivalent per MT methanol.

Table 2. FT synthesis of Sasol from coal-derived syngas

Location	FT process reactor	Capacity, B/D
Secunda, South Africa	8 Sasol advanced synthol	124,000
	1 Slurry phase distillate	3,000
Sasolburg, South Africa	1 Sasol advanced synthol	3,500
	6 Arge fixed bed	3,200
Total		133,700

3.1.2. Proposed projects that have reached the FEED stage

Starting construction of several new GTL plants in the next 1–2 years is critical to the development of a significant GTL industry consisting of many large-scale commercial operations producing more than one million barrels per day of premium liquid products by 2015 [2]. The projects at an advanced stage and most likely to be the next to be constructed are described below.

3.1.2.1. Sasol Chevron Global Joint Venture in Nigeria

The Sasol Chevron Global Joint Venture is progressing plans to build a 34,000 B/D GTL plant on a site adjacent to the Escravos River in Nigeria [6]. The plant is designed to convert 300 MMSCFD of gas into 22,300 B/D of ultra-clean diesel, 10,800 B/D of naphtha and 1,000 B/D of LPG.

The GTL plant will use technology provided by the Sasol Chevron Global Joint Venture. Topsoe will provide the gas reforming technology. Sasol will provide the slurry-phase FT technology and Chevron will provide the product workup hydroprocessing technology.

Project status: The project received formal project recognition, which codifies the fiscal and tax terms, from the Nigerian Government in September 2000. Front end engineering design (FEED) began in 2001. The EPC contract was put out for open bid in early 2002. The construction contract is due for award by the end of 2002, with startup in 2005.

3.1.2.2. Sasol in Qatar

Sasol and Qatar Petroleum are progressing plans to build a GTL plant in Ras Laffan Industrial City, Qatar. The plant is designed to convert 330 MM-

SCFD into 24,000 B/D fuel, 9,000 B/D of naphtha and 1,000 B/D of LPG. The technology is likely to be similar to that used in the Escravos GTL Plant.

Project status: Discussions between Qatar Petroleum and Sasol began in 1996. A Joint Venture Agreement was signed in July 2001. Also in 2001, the Sasol and Qatar Petroleum Joint Venture awarded the FEED contract for the estimated \$800 million GTL project to Foster Wheeler. The scope of work includes preparation of the FEED, selection of long lead package vendors, and preparation of the invitation to bid. Foster Wheeler is also responsible for prequalifying engineering, procurement and construction (EPC) contractors, and to assist in the selection of bidders, lender evaluation and award of the EPC contract. In early 2002, the EPC contract was put out for bid. The bidding process is expected to take several months. Commercial production is expected in 2005.

3.1.2.3. Shell

Shell has or is in the process of conducting studies for GTL plants to be located in eight locations. Shell has stated that it plans to commit to four large-scale (70,000 B/D or greater) GTL plants by the end of 2010, which would be equivalent to a total capacity of about 300,000 B/D. The next generation facility will convert 600 million SCFD into 75,000 B/D of products using the Shell middle distillate synthesis (SMDS) process.

Project status: In September 2001, Shell selected Kellogg, Brown & Root and JGC Corporation as contractors for the first large-scale GTL project. JGC built Shell's existing SMDS plant in Malaysia. The location for the large-scale plant is yet to be determined, but an investment decision is expected by the end of 2002. The engineering design activities (similar to FEED) will be conducted over an 18 month period.

3.1.2.4. Syntroleum in Australia

The Sweetwater project [7] is an 11,500 barrels per day plant that will employ the Syntroleum Process to convert natural gas into ultra-clean, high-performance, sulfur-free synthetic specialty products, such as lubricants, industrial fluids and paraffins, as well as synthetic transportation fuels. The plant is to be located on the Burrup Peninsula in Western Australia.

Project status: In September 2001, Syntroleum completed an agreement with Tessag Industrie Anlagen GmbH. The EPC contract covers engineering, procurement, construction, pre-commissioning, commissioning and testing of the plant, plus personnel training for \$600 million. The contract provides for a schedule of 35 months to mechanical completion and start-up within 5 months of mechanical completion. In January 2002, Syntroleum said that efforts to complete the debt and equity financing are progressing.

3.2. GTL-oxygenates

3.2.1. Commercial operations: gas-to-gasoline plant in New Zealand (currently producing methanol)

The world's first gas-to-liquid fuels plant was originally owned and operated by the New Zealand Synthetic Fuels Corporation. The company's shareholders were 75% New Zealand Government and 25% Mobil. The plant was started up in October 1985. Full production was achieved in April 1986, producing 14,500 B/D of premium gasoline via the Mobil methanol to gasoline process. It was constructed to convert natural gas to gasoline, with methanol as an intermediate step in the process.

The methanol facility consists of two identical 2,200 t/d units designed by Davy-McKee. In 1997, the gasoline production facility was permanently idled. Now, the entire crude methanol production is distilled into chemical grade methanol. The plant is owned and operated by Methanex.

3.2.2. Commercialization activities

An emerging GTL option is the large-scale production of oxygenates, primarily methanol and DME, for the fuel/chemical markets [4]. Traditionally, methanol plants with capacities of up to 2,500 MT/D (9,300 B/D COE equivalent) have supplied the industrial chemicals market as a feedstock for making pri-

marily MTBE and formaldehyde. However, increasing the size of the plants to 5,000 MT/D and greater lowers the cost sufficiently to begin opening up a new market as a fuel. Likewise, large-scale production of DME [8], a derivative of methanol, facilitates a new market for this oxygenate as a fuel.

A review of global GTL-oxygenate activities, as shown in Table 1, indicates that today's operating and announced GTL projects represent about 125,000 B/D COE for oxygenate production. Although some of GTL-methanol/DME projects, particularly those producing methanol, are to supply the traditional chemicals market some of the production could be used as a fuel. These projects include three projects being promoted by DME International Ltd. in Australia, Japan DME International in Australia, and the India DME Consortium for the Indian market, for a total DME production equivalent to 56,000 to 81,000 B/D COE.

4. GTL technology

GTL processes consist of three major processes:

- (1) Production of syngas,
- (2) Conversion of syngas to a syncrude or oxygenate, and
- (3) Upgrading of syncrude by hydroprocessing to marketable products.

This paper focuses on reviewing recent technology developments in syngas conversion processes.

4.1. GTL-FT technology developments

Sasol and Shell are the leaders in commercial GTL experience. Several other companies have or are obtaining extensive demonstration unit experience, such as ExxonMobil, BP, Syntroleum, Conoco and Rentech.

4.1.1. Sasol/Mossgas

Sasol has almost 50 years of experience with FT technology [9]. FT fuels production exceeds 1 billion barrels.

The process has been operated at commercial scale since the 1950s by Sasol, and has undergone significant advancements [10]. The initial process, the Arge Process, involved low temperatures (200–250 °C), pressures at 20–30 bar, and a fixed catalyst bed. The Arge process primarily produces a linear paraffin wax, which are used as petrochemical feed-

stock and also for transport fuels after further processing. This process was the only process available until the 1950s/1960s when the Sasol Synthol process was developed. This process involved high temperatures (300–360 °C) and pressures of 20–30 bar, but used a circulating fluidized bed to produce light olefins for chemicals production and gasoline components. This process has recently been updated to the Advanced Synthol process.

The latest development of FT technology is the Sasol slurry phase reactor, which is an integral part of Sasol's slurry phase distillate (SSPD) Process, and carries out the synthesis reaction at low temperatures (200–250 °C) and pressures of 20–30 bar. The process involves bubbling hot syngas through a liquid slurry of catalyst particles and liquid reaction products. Heat is removed from the reactor via coils within the bed producing medium pressure steam. Liquid products are removed from the reactor, and the liquid hydrocarbon wax separated from the catalyst. The gas stream from the top of the reactor is cooled to recover light hydrocarbons and reaction water. The Sasol slurry phase technology has undergone several developments primarily concerned with catalyst formulations. Initial development used an iron-based catalyst, but recent developments have used a cobalt-based catalyst, giving greater conversion.

Recent Sasol developments have focused on using a slurry reactor design rather than a tubular fixed bed design. In general, slurry reactor technology offers capital cost and operational advantages of fixed bed reactors. Slurry reactors have higher maximum capacities, allow good temperature control; however, require unique catalyst-production separation technology.

Sasol has operated both iron-based and cobalt-based slurry catalysts in a 100 B/D demonstration reactor commissioned in 1990. The slurry phase FT process was commercialized May 1993 in Sasolburg at 2,500 B/D (5 m diameter) scale with an iron-based catalyst. A 99% reactor availability was sustained during the first 7 months of operation. This is the only commercially operating slurry phase FT reactor. Using a highly active and stable cobalt catalyst, Sasol has stated that the nominal capacity of a single slurry reactor is 15,000 B/D [9]. Mild recycle provides high conversion. This higher capacity design requires fewer reactors and therefore lowers capital investment.

Sasol Proposed Qatar and Nigerian GTL plants will use Sasol's slurry phase distillate process that

uses a proprietary cobalt-based FT catalyst. Sasol and Engelhard developed the FT catalyst. A commercial catalyst plant has been built with Engelhard in de Meern, Holland.

4.1.2. Shell

Shell is the other leader in commercial GTL experience due to its GTL Plant in Bintulu. Shell's approach to FT syngas conversion differs from that of Sasol's latest design. Rather than using a slurry reactor, Shell uses a tubular fixed bed reactor containing a proprietary cobalt-based catalyst with mild recycle.

The Shell middle distillate synthesis (SMDS) process [11] includes:

- (1) Syngas production uses a non-catalytic reforming process using oxygen,
- (2) Heavy paraffin synthesis uses a tubular, fixed-bed reactor with cobalt clays, and
- (3) Hydrocracking to make finished products.

In the original designed used in Bintulu, the capacity of each of the four reactors is about 3,500 B/D. In the rebuilt plant, Shell has said that it is using a significantly higher activity catalyst.

The SMDS products target the markets for clean conventional fuels, petrochemical feedstock, niche applications and specialties (base oils/chemicals).

4.1.3. ExxonMobil

ExxonMobil's advanced gas conversion technology 21st century (AGC-21) FT hydrocarbon synthesis process [12] converts syngas using an advanced FT synthesis step, in which hydrogen and CO are converted to heavy hydrocarbons in the presence of a high-performance cobalt-based catalyst, suspended in a novel slurry reactor. A substantial fraction of these heavy hydrocarbons is mostly linear paraffinic, containing substantial levels of 650 °F plus boiling material. This material is converted to the desired final products in an upgrading step.

The syngas conversion and upgrading steps are integrated for each specific application to capture synergies, which minimize the cost of steam and power generation as well as water treating.

The syngas conversion process uses a slurry reactor design, with a proprietary cobalt based FT catalyst with a rim thin layer design that improves selectivity to desired products. The catalyst is designed to avoid diffusion limitations associated with intraparticle mass transfer, which is especially important when

operating at high productivities. The isothermal reactor design also enables high selectivity. A multistage reactor design provides high conversion.

This technology is ready for commercialization based on the two years experience with its integrated 200 B/D demonstration unit in Baton Rouge, La. Recent technology advances have increase the reactor productivity more than two-fold over that with the original catalyst. This improvement is achieved by controlling the interplay of three-phase hydrodynamics, process conditions and catalyst properties.

The AGC-21 hydrocarbon synthesis technology is protected by about 1200 patents. In 1999, Exxon-Mobil prevailed at a major European patent opposition proceeding regarding its slurry FT bubble column process patent.

ExxonMobil is exploring several commercialization options, including those in Qatar and Alaska, USA.

4.1.4. BP

BP has been working to advance GTL technologies since the 1980s. BP is investing \$86 million in a GTL test facility in Nikiski, Alaska, where the company plans to test new technology that would convert gas into synthetic crude at lower capital costs.

The test facility will convert about three million cubic feet of natural gas into an estimated 300 barrels of synthetic crude a day. The main process steps consist of the compact reformer and an FT converter using a proprietary BP catalyst. The facility is scheduled to begin operations during the second quarter of 2002.

The compact reformer syngas technology to be tested has been developed at the BP research centers in Warrensville, Ohio, USA and Sunbury, UK in collaboration with Davy process technology (formerly Kvaerner process technology).

4.1.5. Syntroleum

Syntroleum's GTL process has been under development since the 1980s. Syntroleum has developed proprietary highly active cobalt-based FT catalysts to convert syngas produced from a proprietary air-fed autothermal reactor. Catalysts have been developed for a multi-tubular fixed bed reactor, used in the design for the Sweetwater GTL Project in Australia, and for a slurry reactor.

Syntroleum has successfully tested the catalyst in

a slurry reactor in the 70 B/D pilot plant operated at the BP (formerly ARCO) Cherry Point Refinery, in 2000–2001, for more than 4,500 hours. This pilot plant has been dismantled and is being reassembled for GTL operations in Oklahoma, USA. Tests with tubular fixed bed reactors are conducted at Syntroleum's 2 B/D pilot plant in Tulsa, Oklahoma that has been operating since 1991.

Because of the nitrogen diluent, the air-based FT synthesis reactor is one-pass resulting in a lower thermal efficiency to liquid products. However, plant capital costs are lower due to avoiding the need for an air separation unit to produce oxygen.

4.1.6. Conoco

Conoco has recently started significant GTL efforts to develop catalyst and reactor technology, in part based on its relationship with DuPont, which owned Conoco until 1998.

In 1997, Conoco and DuPont initiated an FT catalyst development program. Shortly, thereafter, syngas testing was begun. A 400 B/D pilot plant, located in Ponca City, Oklahoma, was approved in early 2001. The plant uses a catalytic partial oxidation process (CoPOXTM) for syngas production and a slurry phase reactor with a proprietary cobalt-based catalyst for FT conversion. High carbon efficiencies of 85% are expected due to process integration. The plant is scheduled to operate from late 2002 through 2003.

4.1.7. Rentech

Rentech is focused on the development of iron-based catalyst/slurry-phase process GTL technology to be able to utilize syngas derived from not only natural gas but also solid or liquid hydrocarbon feedstocks. The Rentech process [13] was verified in a 235 B/D facility built in Pueblo, Colorado in 1993. This plant had two 6 ft diameter/55 ft high FT reactors. The plant was design to use gas extracted from the Pueblo, Colorado landfill. Although the conversion technology performed as expected, the landfill did not produce sufficient gas and the plant operations were suspended.

Rentech will license their technology. Rentech has stated that they are working on numerous potential GTL projects around the world, including one in Bolivia, with a total capacity of 150–200,000 B/D.

4.2. GTL-oxygenate technology developments

4.2.1. Methanol, DME and other oxygenates

Today, methanol is a major chemical building block used to manufacture formaldehyde, MTBE, acetic acid and a wide range of other chemical products. Methanol production processes are currently available under license from many companies including ICI, Haldor Topsoe, Lurgi, MW Kellogg, and Mitsubishi. DME production technology is available from Haldor Topsoe, Mitsubishi, Lurgi and Toyo Engineering.

Tomorrow's market for methanol could include conversion to ethylene and propylene, which are major chemical building blocks. Since the market for ethylene and propylene are large, the impact of this new use on methanol demand would be dramatic. Processes for conversion of methanol to olefins (MTO) have been developed both by UOP and Norsk Hydro, and ExxonMobil. MTO was developed as a second step in a two-step process to convert low-cost natural gas to ethylene and propylene. DME could also be converted to ethylene and propylene using this technology [4].

The potential new market for oxygenates could be many times greater than the current market [4]. These new markets for oxygenates are possible due to recent technology/engineering advances permitting the design of large-scale plants; that is, 5,000 MT/D methanol equivalent or greater, producing low-cost oxygenates [8,17].

Another oxygenate investigated as an alternative fuel for diesel engines is di-*n*-pentyl-ether (DNPE) [14]. DNPE can be produced by a multi-step process from butane and methane.

The International DME Association was formed, in early 2001, to promote the public awareness and use of DME [15]. The Methanol Institute serves as the voice of the methanol industry in the USA [16].

4.2.2. Large-scale oxygenate production technology

The technology to product both methanol and DME in a large-scale plant is similar [15,17]. This technology can be described by using Haldor Topsoe technology for making DME [18] as the example.

The idea of using DME as an alternative fuel for compression ignition engines, the feasibility of large-scale manufacture, and the first engine tests were published by BP (as Amoco Corporation), Haldor Top-

soe A/S, NAVISTAR and AVL List GMBH during the 1995 SAE Congress in Detroit [8,19,20]. Since then, due to the versatility and benign characteristics, DME has emerged as a clean multi-purpose fuel suitable for a number of other applications, including as a LPG substitute and a fuel for power generation. Several ventures are currently examining the feasibility of DME ventures, and it anticipated that DME will be available in fuel quantities by 2005 or 2006.

The Topsoe DME process combines the production of methanol from natural gas and the conversion into DME in a single plant, with an integrated synthesis section. The DME process includes the Topsoe autothermal reforming process followed by a proprietary synthesis design. The DME synthesis technology takes place in gas phase in fixed bed reactors.

Both the autothermal reformer technology and the DME synthesis technology accommodates very large single line capacities, and thus permit significant economies of scale. Single line capacity exceeding 7,000 MTPD DME is possible.

Another process for making DME is being developed by NKK Corp. using a slurry reactor for DME synthesis [21].

4.2.3. ExxonMobil MTG

An alternative approach to FT synthesis is the methanol to gasoline process (MTG) developed and commercialized by Mobil (now ExxonMobil) in 1985. In this process, methanol is converted to high-quality gasoline that requires only minor further processing to a finished product.

5. GTL products

GTL-FT plants produce a slate of products that is significantly different from that produced from a typical crude oil refinery (Figure 3). GTL plants are capable of producing a slate of products with highly desirable properties [2,11], including lube basestocks, premium fuels, petrochemical naphtha and waxes — all of which are sulfur free. These products meet or exceed virtually all product requirements and, therefore, are fully fungible with conventional petroleum-derived products. The value of a GTL barrel is estimated to be about \$30/B, compared to about \$25/B for a refinery barrel, with \$20/B crude oil. The product slate and, therefore, the product values from both GTL plants and refineries can vary.

6. GTL plant efficiencies

The thermal efficiencies of today's proposed GTL-FT plants range from 60% to 65%. However, 77% to 83% of the carbon in the feed gas is converted to saleable products — with the balance being converted to CO₂ (Figure 4).

From a theoretical perspective and selecting a single hydrocarbon as an average representative for the full range of GTL-FT hydrocarbons formed, the overall reaction can be represented as the following equation. When X is zero, the maximum thermal efficiency

is 78%. The remaining 22% of the input energy went into making water. Also, at this maximum thermal efficiency, the methane carbon conversion into liquid products is 100%. However, at today's thermal efficiencies ranging from 60% to 65%, X will range from 2.4 to 3.6 and resulting carbon conversions efficiencies of 77% to 83%. Therefore, when considering energy rejection in the form of CO₂ emissions, carbon conversion efficiencies should be used.

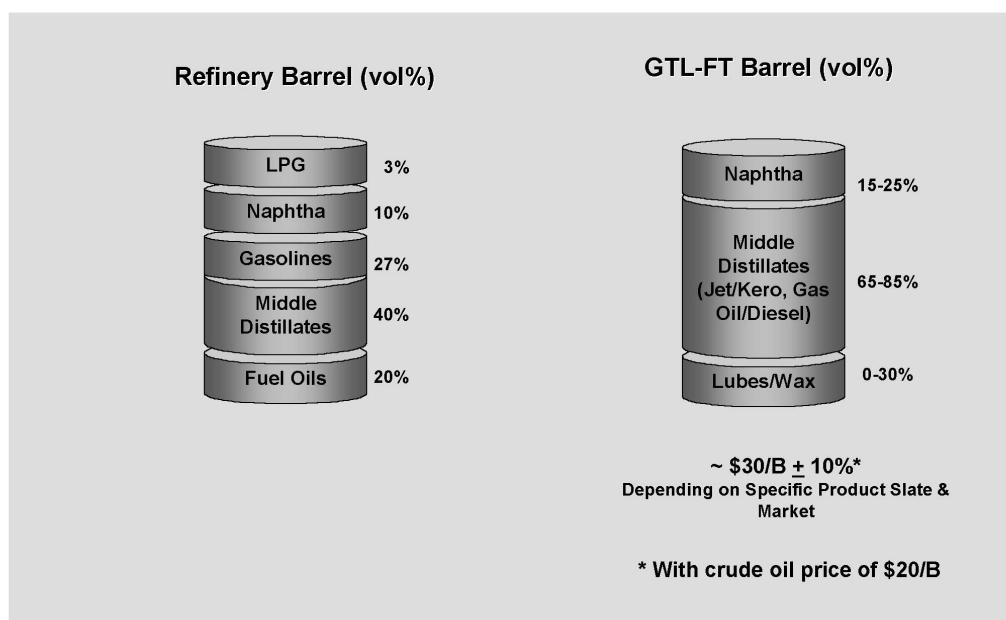
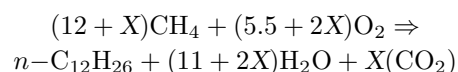


Figure 3. Comparison of the GTL-FT barrel vs. conventional refined barrel.

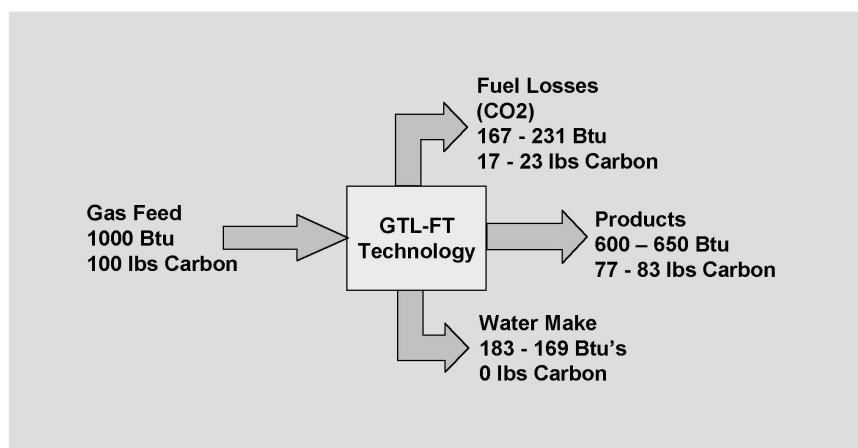


Figure 4. GTL-FT overall energy and carbon balance.

7. Economics for GTL projects

The business opportunity provided by GTL-FT should primarily be viewed as a gas monetization option rather than only a stand-alone business based on GTL plants that convert purchased gas to high-value liquid products.

GTL-FT plant generic rates of returns can range from 10%–28%, depending on Brent crude prices (Figure 5). These economics are presented for illustrative purposes. The economics assume a gas field with ample resources located in a low-cost location, with leveraged project financing, accelerated capital recovery from short-term deferred taxes and local market gas/product pricing.

The economics for the upstream gas field that the GTL plant monetizes are even more attractive than those for a stand-alone plant. Upstream IRR associated with monetizing the gas to the GTL-FT plant range from about 30% to 45%, depending on Brent crude prices. The high IRR is primarily due to revenue from LPG and condensate that is extracted from

the gas before routing the residue gas to the GTL-FT plant. However, even a leaner gas field would have more attractive economics than the GTL-FT plant.

Today, GTL projects (like LNG projects) will likely be sanctioned based upon integrated (both upstream and downstream) economics. However, in the future, GTL projects using technological advances that significantly reduce capital costs could be stand-alone businesses.

The reasons why proposed commercialization activities are likely to be successful are, GTL:

- (1) Produces high-value products including premium fuels, petrochemical naphtha and lube basestocks;
- (2) Capital and operating costs for plants are decreasing [2,22];
- (3) Integrated economics, with the upstream gas resource, are attractive.

These advantages more than offset plant thermal and carbon efficiencies of 60%–65% and 77%–83% respectively.

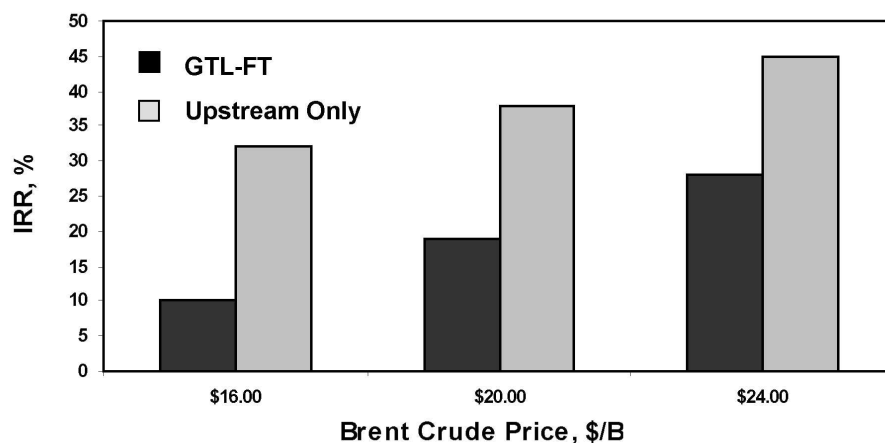


Figure 5. Upstream and GTL-FT plant generic IRR for a liquids rich gas field.

8. Key messages

(1) GTL will become the third major option to monetize natural gas along with pipelines and LNG.

(2) GTL includes making Fischer–Tropsch as well as oxygenates products from gas.

(3) The construction and operation of commercial and pilot/demonstration scale plants has enhanced the level of GTL experience. Several companies have high levels of experience:

a. Shell's experience is primarily due to its GTL plant in Bintulu, Malaysia.

b. Sasol has very extensive and large-scale experience with several coal-based FT processes. Moss gas, a Sasol licensee, also has GTL operating experience.

c. ExxonMobil has experience due to both the New Zealand gas-to-gasoline plant (as Mobil), and its 200 B/D Baton Rouge demonstration plant.

d. Other companies such as BP, Syntroleum, Rentech and Conoco have or are in the process of ac-

quiring experience with large-scale 70–400 B/D pilot plant.

(4) Projections are that GTL production will be in the range of 1–2 million barrels per day by 2015 [1].

(5) GTL capacity growth prospects have been enhanced by:

a. Significant reductions in capital cost. Today's \$25,000 per B/D capacity will quickly drop to \$20,000 per B/D by 2005 and to \$15,000 per B/D by 2015.

b. Value of high quality clean fuels and products.

c. Huge quantities of remote, low-cost natural gas; market constraints in LNG and costs of long-distance pipeline. GTL plants could monetize potentially 900 TCF gas reserves (equivalent to 15 million B/D) [1].

d. Visions for the *Gas Economy*.

(6) GTL capacity growth could be moderated by:

a. Lower oil prices than expected. Oil prices are unpredictable and volatile. Current projections are based on \$16/B.

b. Higher plant construction costs than anticipated. Current projections are based on costs of \$25,000 per B/D today decreasing to \$15,000 per B/D by 2015.

c. Technology risks. Although the technology risks are low and manageable, the first several large-scale plants in range of 50,000 B/D to 100,000 B/D may encounter financing challenges.

d. Competition with other more-established and conventional options for monetizing gas such as LNG, and for producing products such as conventional refineries.

9. Conclusions

GTL plays a vital role in the *Gas Economy* vision: a world powered by natural gas — a cleaner, economic stepping-stone to the world of renewables and hydrogen. GTL is an important option for moving natural gas to market. GTL options include not only the well-known production of FT liquids but also the production of oxygen containing fuels, fuel additives and chemicals, such as methanol and DME.

Based on both the announced GTL plants and a reasonable projected rate of plant construction, GTL production could reach 1–2 million B/D by 2015. GTL can be a major alternative for monetizing natural gas in the 21st century.

Disclaimer

The authors have tried to ensure that all data and information provided in this paper is correct. Sources of information include presentations at recent GTL conferences, published papers and press releases. The authors do not guarantee the completeness and accuracy of the information. Reference herein to any specific commercial products, process, or service by trade name, trademark, and manufacturer or otherwise, does not constitute its endorsement or recommendation.

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