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**Gas to Liquids:
Historical Development and Future Prospects**

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Preface

While GTL or Gas to Liquids is frequently referred to in natural gas circles, apart from project-specific summaries produced by the sponsoring companies there is little in the way of contemporary literature to set the context for GTL against the backdrop of today's increasingly connected global gas situation.

As with many technological advances, 'necessity was the mother of invention' for the Fischer Tropsch Gas to Liquid (FTGTL) process in Germany during World War II and in South Africa during the long period of OPEC and UN oil sanctions. This paper reviews the genesis of the process in these countries and also subsequent related applications in Malaysia, New Zealand and Alaska. The major expansion in FTGTL production in Qatar can be seen as a strategic push to diversify market monetisation channels by this major gas resource holder. The Oryx project in particular provides sufficient cost and operating data from which the wider economic characteristics of FTGTL can be broadly assessed.

Olga Glebova's paper represents the latest example of OIES Gas Programme research which sets out to probe the potential for the role of natural gas outside of the mainstream market fundamental and geo-political foci. I am pleased to add this paper to the expanding list of our programme's working papers.

Howard Rogers

Oxford, 2013

Contents

Acknowledgments	iii
Preface	iv
Introduction	1
Chapter 1. Historical review of industrial-scale GTL production	2
1. Industrial production of synthetic hydrocarbons	2
1.1 Production of synthetic liquid fuels in Germany to 1945.....	2
1.2 Production of synthetic liquid hydrocarbons in the Republic of South Africa and other countries from 1945 to 1995	3
1.3 Trial production of synthetic hydrocarbons	5
1.4 Production of synthetic hydrocarbons and fuels in Qatar 2006-2012.....	6
Chapter 2. FTGTL production	12
2.1 The Fischer-Tropsch Synthesis	12
2.2 FTGTL products	12
2.3 Consumption of natural gas in FTGTL production and product output.....	14
Chapter 3. Economics of FTGTL	19
3.1 Introduction	19
3.2 Energy market fundamentals	19
3.3 FTGTL project economics.....	25
3.3.1 Introduction	25
3.3.2 Modelling assumptions	28
Chapter 4. Comparative project economics – FTGTL and LNG	35
Chapter 5. Conclusions	39
Bibliography	40
Glossary	45

Tables

Table 1: Capacities of SLH production in Germany	2
Table 2: Capacities of operating SLH plants.....	10
Table 3: Indicators of FTGTL kerosene quality.....	13
Table 4: Indicators of FTGTL diesel quality	13
Table 5: Natural gas feedstock consumption for existing and possible FTGTL projects.....	15
Table 7: Barrels of FTGTL products and FTGTL product mixture in one tonne	17
Table 8: Barrels of the Top 5 World oil grades in a tonne	18
Table 9: Average refined product prices for 12 years (2000-2011) on the basis of two markets (FOB MED Italy and FOB Singapore)	23

Table 10: Scaling ratio Brent Crude Oil Price vs GTL products.....	23
Table 11: Index values for DCCI and DOCI - 2000 to 2011	27
Table 12: GTL CAPEX.....	27
Table 13: Initial data for calculation of efficiency of industrial GTL production.....	28
Table 13: Wholesale gas prices of the Federal Tariff Service in 2011 (the estimated calorific value 7,900 kkal/m ³ or 33080 kJ/m ³).....	31
Table 14: The most effective FTGTL production in Russia by results of the analysis.....	32
Table 15: Technical and economic characteristics of FTGTL and LNG production (capacity of 10 billion m ³ /year).....	36

Figures

Figure 1: Moss gas Plant, Mossel Bay.....	4
Figure 2: Bintulu GTL Plant.....	5
Figure 3: Oryx Plant, Qatar	7
Figure 4: Schematic diagram of GTL production at Oryx GTL plant	8
Figure 5: Pearl GTL Plant, Qatar	9
Figure 6: Schematic diagram of GTL production on the Pearl GTL plant.....	9
Figure 7: Fischer – Tropsch Reaction.....	12
Figure 8: Oil and Gas Prices 2007 – 2013.....	19
Figure 9: Brent Crude Oil Price vs Oil Product Prices, FOB MED Italy (2000 -2011)	21
Figure 10: Brent Crude Oil Price vs Basket of Oil Products-Analogues, FOB MED Italy (2000 – 2011)	22
Figure 11: Global Upstream, Refining and Petrochemical Sector Capital Cost Indices.....	26
Figure 12: Sensitivity of Oryx GTL project analogue	29
Figure 13: The possible location of future FTGTL plants in Russia.....	30
Figure 14: Unit Liquefaction Costs by Year of Production Start	35
Figure 15: Comparison of breakeven economics for three LNG projects, assuming Japan as destination market.....	37
Figure 16: The influence of Brent price on FTGTL project economics	38

Introduction

Natural gas in 2012 represented 23.9% of global primary energy consumption¹ and was used mainly in space heating, power generation, industry and transport. While pipeline gas and LNG represent the more familiar routes to market, this paper focuses on a third route, specifically the production of synthetic liquid hydrocarbons (SLH) that are derived from natural gas using Fischer-Tropsch Gas to Liquid technologies (FTGTL).

Pipeline transport and LNG frequently have logistical constraints due to the geography (and sometimes geopolitics) of the main gas pipelines routes and the restriction to coastal locations for LNG regasification facilities. The demand for these channels of gas transportation and monetization is also subject to future uncertainties, e.g. long-term shale gas production growth in the USA, assumptions on the pace of coal to gas substitution in China's energy mix and the rate of development of renewables capacity and other alternatives to natural gas-fired generation in Europe and other parts of the world.

Qatar, which after Russia and Iran is the third largest natural gas reserves holder in the world, has successfully implemented a diversified global LNG marketing strategy. In 2006 and 2011 Qatar also brought into commercial operation two FTGTL production plants: Oryx GTL and Pearl GTL based on Sasol and Shell technologies. This represented a step-change in commercial scale GTL production and potentially marks a transition to more widespread adoption of GTL as a primary channel for natural gas monetization in the future.

At this juncture it is important to be clear on what we define as GTL. There are a variety of processes which produce synthetic liquid hydrocarbons from other hydrocarbon or biomass feedstocks. These include Gas to Liquid (GTL); Coal to Liquid (CTL); Biomass or Biogas to Liquid – biofuels (BTL).

As this paper is concerned with Gas to Liquids based on the Fischer-Tropsch process it is important to avoid potential confusion with other natural-gas based processes from which the product is in the liquid phase (including in the widest interpretation LNG, Natural Gas Liquids (NGLs) and dimethyl ether (DME). We will therefore use the more specific FTGTL abbreviation (in place of GTL) in order to focus on the process of synthesising liquid hydrocarbons from natural gas through the Fischer-Tropsch Synthesis (FT-synthesis).

The mix of hydrocarbons produced by the Fischer Tropsch synthesis is often termed synthetic crude oil or nonconventional oil which contains components which do not occur in natural oil products. Synthetic crude oil also lacks certain components that are common in natural oil: aromatics, naphthenic hydrocarbons and others. In addition, synthetic crude oil cannot be transported in undiluted form by pipeline as it contains high levels of long-chain paraffins (waxes), exceeding admissible values by a factor of 11². Thus the term 'synthetic oil' is not strictly suitable for products of FT synthesis.

Chapter 1 will review the genesis of GTL technology and processes and describe the main FTGTL plant in operation today. Chapter 2 describes the Fischer-Tropsch Synthesis process, Chapter 3 examines the economic sensitivity of the process, based on a generalized model of the Oryx project, Chapter 4 compares the technical and economic characteristics of FTGTL and LNG production and Chapter 5 contains the paper's summary and conclusions.

¹ BP (2013), 'Primary Consumption by Fuel' spreadsheet

² Dancuart (2006); pp. 482 – 532.

Chapter 1. Historical review of industrial-scale GTL production

1. Industrial production of synthetic hydrocarbons

Before reviewing and assessing the present day opportunities for FTGTL from natural gas and the underlying economic and strategic considerations, we will begin by reviewing the historic development of the industrial-scale production of synthetic liquid hydrocarbons by FTGTL technology broadly in chronological sequence.

1.1 Production of synthetic liquid fuels in Germany to 1945

During the course of World War 2 Germany found it increasingly difficult to source conventional oil and refined product supplies for its war effort and was thus incentivized to develop alternative options.

The first production of Synthetic Liquid Hydrocarbons (SLH) had been effected from syngas (a mixture of carbon monoxide and hydrogen) in Germany by F. Fischer and G. Tropsch in 1926³. By 1944, based on Fischer-Tropsch technology (FT-synthesis), Germany had developed this to an industrial scale with 9 plants producing some 600 thousand tonnes/year (t/y) (or 14,000 b/d)⁴. The capacities of the first SLH plants are presented in table 1.

Table 1: Capacities of SLH production in Germany⁵

No	Name of the city where plant situated	thousand t/y
1.	Castrop-Rauxel	40
2.	Dortmund	45
3.	Horst-Gamburg	70
4.	Oberhausen-Holten	60
5.	Litzendorf	30
6.	Odertal	34
7.	Ruhland-Schwarzheide	180
8.	Eckel	55
9.	Bergkamen	80
	Total production:	594

Source: compiled by the Author, specific sources in footnote.

³ Fischer (1926a), pp.193-197., Fischer (1926b), p.p.276-285.

⁴ Belikov and Gordon (1945) p. 95, Stranges (2007);, pp.1-27.

⁵ Belikov and Gordon (1945).p.95.

1.2 Production of synthetic liquid hydrocarbons in the Republic of South Africa and other countries from 1945 to 1995

Apartheid was proclaimed as the official policy of the Republic of South Africa government following the general election in 1948. In addition to an arms embargo imposed by the United Nations from the 1960s, OPEC members also imposed an oil embargo from 1973 onwards⁶. This was followed by a United Nations oil embargo resolution passed in 1980.

In 1955 the Sasol company built the Sasol-1 plant in Sasolburg which produced some 5,600-8,000 b/d (or 240-340 thousand t/y)⁷ of synthetic hydrocarbon liquids. Syngas for the Sasol-1 plant was produced from brown coal produced locally. Since 2004 syngas at Sasol-1 plant has been manufactured from natural gas delivered by pipeline from Mozambique. As a consequence of this change of feedstock, the products of FT synthesis, were termed FT gas to liquid products (FTGTL).

The prompt rise in oil prices as a consequence of the 1973 and 1979 oil crises and the impact of sanctions compelled the Republic of South Africa to develop large scale national programs directed to the production of alternative synthetic fuels.

Accordingly, in 1980 and 1983 South Africa commissioned two synthetic liquid hydrocarbon (SLH) plants: Sasol-2 and Sasol-3 in Secunda city⁸. In addition to SLH these enterprises are at the present time manufacturing various chemical products (alcohols, acids, monomers, polymers and many others). Sasol-2 and Sasol-3 still use local brown coal as the raw material for syngas production.

Available data on the capacity of the Sasol-2 and Sasol-3 plants differs. The total capacity of the two plants is estimated at 124-154 thousand b/d (or about 5.3-6.6 million t/y)⁹, with their relative sizes in the ratio 40:60. Total investment for the construction of Sasol-2 was of the order of \$3.2 billion; for Sasol-3 it was around \$2.8 billion.

In comparison with the Sasol-1 plant, Sasol-2 and Sasol-3 have key technological differences in the separation and processing of FT-synthesis products. More detailed descriptions of the technologies of these plant are available in the literature¹⁰.

In 1991 PetroSA, the national oil company of the Republic of South Africa, constructed the Mossgas plant based on Sasol technology (22.5 thousand b/d of GTL¹¹) in Mossel Bay city on the Indian Ocean coast. It was the first commercial GTL plant using natural gas as a raw material for syngas production. Natural gas is sourced from the gas-condensate Mossel Bay field located some 100 km offshore. The Mossgas enterprise is a fully integrated complex including gas and gas condensate production, transportation via sub-sea gas pipeline, gas processing and GTL production. Around 13.5 thousand b/d of gas condensate is processed at the oil refinery, which is a part of the Mossgas complex. Thus, the total capacity of hydrocarbon output from the Mossgas plant amounts to 36 (22.5+13.5) thousands b/d¹². The plant produces a wide range of products including liquefied petroleum gases, unleaded gasoline, kerosene, diesel and boiler fuels, alcohols and other products.

⁶ Levy (1999), P. 3

⁷ Dry (1986), pp.161-208; Dry and Steynberg (2006), pp.406-481; Waddcor (2003), pp.8-10.; Sasol Facts (2006), p 120.; www.syntheticfuel.com/gtl_za_rubezhom

⁸ Dry (1986), pp.161-208.

Dry M.E.and Steynberg (2006), pp.406-481., Waddcor(2003), pp.8-10., [Sasol facts\(2006\). p.120](#)

⁹ Subhanish (date??), P.27 ; Synthetic fuels: a long-term vision.- Petroleum Economist-2009.-N.2-p.3.; Eni (2011), p 155 , www.syntheticfuel.com/gtl_za_rubezhom; www.technip.com/en/technip-coflexip-desing-and-build-gtl

¹⁰ Dry (1986) pp.161-208., Dry and Steynberg (2006), pp.406-481.; Rahmim (2008), pp.22-31.; Vosloo (2001), pp.149-155.

¹¹ Waddcor (2003), pp.8-10.

¹² Couvares (2003), P 4.; Falbe J., p.25;

Figure 1: Moss gas Plant, Mossel Bay



Source: Syntroleum Presentation

Malaysia

The Bintulu GTL plant in Malaysia is situated on Sarawak Island in Bintulu and since 1993 has produced the following products: liquefied petroleum gas (up to 5%), naphtha (up to 30%), diesel fraction (up to 60%) and paraffin (up to 5-10%). Natural gas from the fields offshore Sarawak is used as the syngas feedstock. The initial capacity of the GTL plant was 12,500 b/d with an investment level of about \$850 million. After expansion and refurbishment in 2005 the capacity of the plant increased to 14,700 b/d of GTL or about 530 thousand t/y. The plant has one process train with 4 parallel multi-tubular reactors. The productive capacity of each reactor is 3,700 b/d.

The design and construction of Bintulu GTL plant was carried out by the JGC Corporation engineering company (Japan). Only RD Shell company technologies were used at the plant: the SMDS technology (Shell Middle Distillate Synthesis), including Shell Gasification Process (SGP) – for syngas production; Heavy-Paraffin Synthesis (HPS) – for producing GTL by the Fischer - Tropsch method and Shell Heavy Paraffin Conversion (HPC) - for GTL hydro-upgrading.

The shareholders of Bintulu GTL plant are: RD Shell (72%); Petronas and Mitsubishi (28%)¹³.

¹³ Fabricius (2005), pp.17-19.; Waddcor (2003), pp.8-10.; <http://www.shell.com>

Figure 2: Bintulu GTL Plant



Source: The Oil Drum, November 2010, <http://www.theoil Drum.com/node/7118>

Russia

After the end of the Great Patriotic War of 1941-1945 a plant producing GTL from syngas by the Fischer-Tropsch method with a capacity of about 50 thousand t/y was transported from Germany to the USSR - The Rostov Region Novocherkassk (now the JSC Novocherkassk Plant of Synthetic Products). The plant was brought into operation in 1952 and made various GTL products. Up to 1960 syngas at the plant was produced from Donetsk coal, and then subsequently from natural gas. In the late nineties GTL production ceased¹⁴.

New Zealand

In 1985 ExxonMobil brought onstream a plant producing gasoline from methanol (Methanol to Gasoline technology (MTG) or "Mobil-process") in New Zealand (New Plymouth city) with a capacity of about 14,500 b/d of synthetic gasoline. The shareholders of the New Plymouth plant are the Government of New Zealand (75%) and ExxonMobil (25%). The MTG technology is considered as an alternative to Fischer-Tropsch synthesis.

The syngas for methanol production is produced by gasification of locally mined coal. The plant produced gasoline during the period 1985-1995 but at present it produces only methanol because of the economic inefficiency of the MTG technology and because the gasoline product contained up to 2.0-2.2% aromatic hydrocarbon (1,2,4,5-tetrametilbenzol) which from an ecological point of view is much more damaging than benzene, which is contained in refinery-sourced gasoline. (According to the European standard EN-228 it should not exceed 1%)¹⁵.

1.3 Trial production of synthetic hydrocarbons

The Republic of South Africa

In 2002 the partnership "GTL.F1AG" was created to construct a pilot GTL plant at the Mossgas plant complex in Mossel-Bay. Its shareholders became: Statoil (Norway) -37.5%; PetroSA (Republic of South Africa)-37.5%, Lurgi (Germany) -25%). Technology developed by Statoil is used at the plant

¹⁴ Loktev (1982), pp.123-133.

¹⁵ Gorshteyn (2008), P. 21

for manufacturing GTL. The GTL installation was constructed between 2002 and 2004 with a productive capacity of 1,000 b/d. Building the GTL installation as a 'brown-field' project at the already operating Moss gas plant resulted in significant investment economies.

PetroSA acted as the project client, while the general designer was Technip SpA (Italy) under an EPC contract (Engineering, Procurement, Construction – design, delivery of material resources and the equipment, i.e. "turnkey" construction). Total project investment was about \$70-80 million. The initial fixed price to Technip SpA under the EPC contract was about \$26 mln.

The USA

ConocoPhillips owns a Synthetic Liquid Hydrocarbon (SLH) installation with an output of 400 b/d at Ponca City (Oklahoma). Capital expenditure for this plant was about \$75 million¹⁶.

BP-Davy, a partnership of British Petroleum (BP) and Davy Process Technology (Davy) built the SLH installation in Nikiski city (Alaska, USA) with a capacity of 300 b/d in 2004 with a capital investment of about \$86-100 million. The installation is used for researching natural gas and associated petroleum gas-based processes and for receiving input data from the SLH plant¹⁷. One important consideration in Alaska is the very significant gas cap and associated gas reserves at the giant Prudhoe Bay oil field which in (2012) had no viable means of accessing a market¹⁸.

Other Areas

Due to the focus on plant and processes of commercial scale, this paper is not concerned with research installations with capacities less than 100 b/d such as those of Syntroleum and Rentech (USA), CompactGTL (Great Britain), JOGMEC (Japan Oil, Gas & Metal National Corporation, Japan) and others.

1.4 Production of synthetic hydrocarbons and fuels in Qatar 2006-2012

Qatar Petroleum/Sasol

Qatar has built and commissioned significant GTL production capacity during the period from 2006 to 2012. Given its emergence in the same period as the world's largest LNG producer while at the same time developing its domestic industrial sector based on gas feedstock, it is reasonable to ask why Qatar also undertook the construction of the world's largest GTL facilities at this time.

Firstly, Qatar has reserves of 25 Tcm of natural gas concentrated generally within one giant offshore gas-condensate structure - the North Field, located in the Persian Gulf, with reserves estimated at nearly 900 Tcf (or about 25.5 Tcm). Liquefaction plant for the production of 62 mtpa of LNG, including 42 mtpa for QatarGas, has been constructed in Qatar on the basis of this field¹⁹.

Qatar's rationale for the development of the GTL industry is probably based on a desire to diversify away from reliance entirely on LNG for monetizing its gas resource. With natural gas prices in North America and Europe diverging from oil and oil product prices since the mid to late 2000s, converting a

¹⁶ Waddcor (2005), pp.46-49.

¹⁷ Couvares (2005), P.9.; Freide et al (2007), pp.37-44.; Waddcor (2005), pp.46-49.; Waddcor (2003), pp.8-10.

¹⁸ Falbe (2005), p.25 ; Statoil (2006); Hansen et al (2001), pp.405-410.; Schanke et al (2004), pp.43-48.; GTL Technology Joint Venture//2005.-p.4. <http://www.petrosa.co.za>

¹⁹ [Qatargas Corporative Citizenship report.-p.92. www.qatargas.com](http://www.qatargas.com)

gas resource to hydrocarbon liquids provides a revenue stream with is insulated from regional gas market supply and demand fundamentals.

Qatar's GTL industry began in 2001 with the creation of a "QP/Sasol" partnership between Qatar Petroleum (51%) and Sasol Synfuels International (49%) for the construction of the Oryx GTL plant in Ras Laffan city. The raw material for syngas production is natural gas from the North Field, which is processed onshore. Sasol and Shell technologies are used at these GTL plants,²⁰ which have a nameplate capacity of 34 thousand b/d and an output of 32.4 thousand b/d assuming a 95% uptime²¹.

Figure 3: Oryx Plant, Qatar



Source: New York Times, December 2012

The main products of the Oryx GTL plant are: a kerosene-diesel fraction and naphtha in the ratio 3:1 totaling 95%, and liquefied petroleum gas (LPG) that consists of 25% propane and 75% N.butane²².

Capital investments in the Oryx GTL project incurred cost overrun and were about \$900-950 million by the time it became operational in 2006²³.

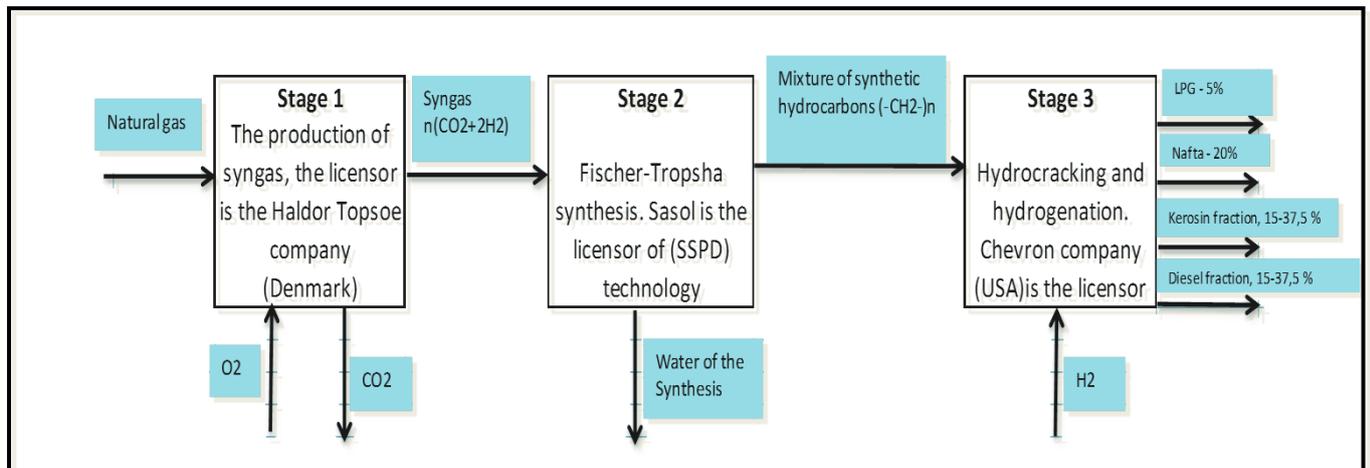
²⁰ Fedeli (2005), pp.15-16.; Turner (2005), pp.10-12.

²¹ Moonsamy (2012), p.2.; Sasol strategy update North America and GTL focus.-2011 14 April.-p.74 <http://www.sasol.com>

²² Dry and Steynberg (2006), pp.406-481.

²³ Chedid et al (2007), pp.4799-4811.; Stoppard et al (2007) , p.1.

Figure 4: Schematic diagram of GTL production at Oryx GTL plant ²⁴



Source: compiled by the Author

From Figure 5 it is evident that GTL production consists of three main stages:

- Stage 1 – the production of syngas, the licensor being the Haldor Topsoe company (Denmark);
- Stage 2 – the Fischer-Tropsch synthesis is carried out using the Sasol Slurry Phase Distillate (SSPD) technology where a mix of gaseous, liquid and solid hydrocarbons with mainly normal structure and small impurities of unsaturated hydrocarbons (olefins) and oxygen-containing constituents (alcohols and others) is produced. The licensor of SSPD technology is the Sasol Synfuels International Company. The production of GTL products is carried out in two parallel trains. Each train contains one Slurry Reactor with a capacity about 17,000 b/d.
- Stage 3 is the hydrocracking of long-chain synthetic paraffin hydrocarbons to produce hydrocarbons with smaller molecular weight (diesel fraction and naphtha) and also the hydrogenation of olefins and alcohols to paraffin hydrocarbons. The licensor of this technology is the Chevron Company (USA)²⁵.

Besides the main products (diesel fraction, kerosene fraction, naphtha and LPG) the Oryx GTL plant generates synthetic water, steam and electric power, which are sold for use in nearby processing plant.

Qatar Petroleum/Shell

In 2006 the QSGTL partnership (Qatar Petroleum-75% and Shell -25%) was established for the construction and operation of the Pearl GTL project. It is located 75 km from the capital of Qatar in Ras Laffan city. Shell was responsible for providing the capital investment ²⁶.

Unlike Oryx GTL, Pearl GTL is a completely integrated project "from offshore well to GTL products". It includes gas production, processing of gas and FTGTL production. The plant feedstock is 1.6 bcf/d (or 45.3 mmcm/d.) of natural gas from the gas-condensate North Field.

²⁴ Chedid et al (2007), pp.4799-4811.; Turner (2005), pp.10-12.

²⁵ Olschar et al (2007), pp.187-193.

²⁶ Taylor and Azeez (2011), p.8.

The initial feedstock of 45.3 mmmcm/d of raw gas yields 120 thousand b/d of gas condensate and dry gas. This subsequently yields 140 thousand b/d of GTL. Thus, the total liquid hydrocarbon product capacity is 260 (120+140) thousand b/d²⁷.

The first train of the Pearl GTL plant with a GTL capacity of about 70 thousand b/d was started up in 2011. The second train with the same capacity came onstream in 2012.

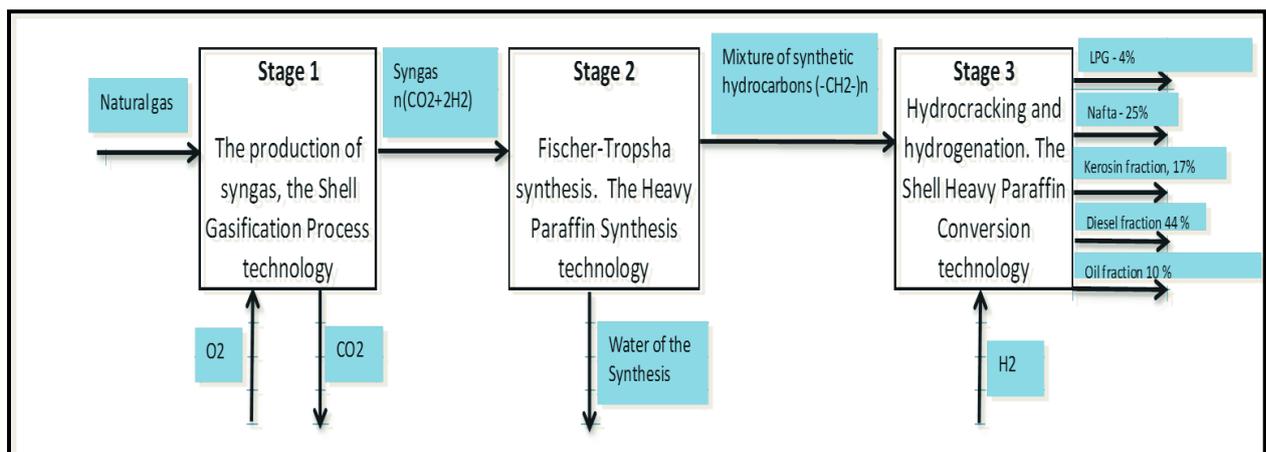
Figure 5: Pearl GTL Plant, Qatar



Source: <http://www.shell.com/global/aboutshell/major-projects-2/pearl/overview.html>

"JGC/KBR" (a consortium of JGC Corporation (Japan) and Kellogg Brown & Root (KBR, Great Britain) designed and constructed the plant using Shell technology – SMDS (Shell Middle Distillate Synthesis) for GTL receiving in 3 stages. Shell technology is used in each production stage and is protected by more than 3500 patents. The same technology is used on the Bintulu GTL plant in Malaysia.

Figure 6: Schematic diagram of GTL production on the Pearl GTL plant



Source: compiled by the Author

²⁷ Stoppard et al (2007), p.1 ; Taylor and Azeez (2011) p.8;
http://www.shell.com.ru//home/content/rus/aboutshell/our_business_tpkg/perl/

The 3 stages of The Shell Middle Distillate Synthesis (SMDS) technology are²⁸:

- the 1st Stage is syngas production from natural gas. It is carried out through the Shell Gasification Process (SGP) technology;
- the 2nd Stage is the Fischer-Tropsch synthesis, carried out using Heavy-Paraffin Synthesis (HPS) technology where the mix of gaseous, liquid and waxy hydrocarbons with mainly normal²⁹ structures and small impurities of unsaturated hydrocarbons (olefins) and oxygen-containing components (alcohols and others) is produced. On each train the synthesis of hydrocarbons is carried out in 12 tubular reactors. The capacity of each reactor is 5,800 b/d resulting in 70,000 b/d of GTL for the train.
- the 3rd Stage uses the Shell Heavy Paraffin Conversion (HPC) technology and includes three processes: hydro-upgrading of GTL (hydrogenation of unsaturated components and alcohols), hydrocracking and hydro-isomerization of firm synthetic paraffin hydrocarbons and splitting them into hydrocarbons with lower molecular weight.

Trains I and II were constructed between 2006 and 2011, and Train 2 started up in 2012, The total Pearl GTL project investment is estimated at \$19-25 billion.

The capacities of operating SLH plants are specified in Table 2³⁰.

Table 2: Capacities of operating SLH plants

Country	FTGTLPlant	Capacity, b/d
South Africa	Sasol I, asolburg	5,600-8,000
	Sasol II & Sasol III, Secunda	124,000-154,000
	Mossgas, Mossel Bay	22,500
Malasia	Bintulu GTL, Bintulu	14,700
Qatar	Oryx GTL, Ras Laffan	32,400
	Pearl GTL, Ras Laffan	140,000
Total:		339,200-371,600

Source: compiled by the Author

²⁸ Taylor and Azeez (2011), p. 8.

²⁹ The term normal refers to straight chain paraffins (alkanes) in contrast to branched molecules.

³⁰ Nicholls (2008), p.2.; Oil & Gas Journal.- 2011.-V.109.11a.-pp.3-4.;

[http://www.shell.com.ru//home/content/rus/aboutshell/our_business_tpkg/perl/;](http://www.shell.com.ru//home/content/rus/aboutshell/our_business_tpkg/perl/)

[Will Pearl GTL push into a new era? - PFC Energy Memo Gas competition service. – 2011 - 7 Nov.- p.3-5. www.pfcenergy.com.](http://www.pfcenergy.com)

Capacities of operating SLH production plants (including GTL)

From Table 2 the aggregate capacity of all SLH production plants worldwide is between 339.2 and 371.6 thousand b/d or 14.3-15.6 million t/y.

Qatar became the world's second largest SLH producer (after the Republic of South Africa) with the implementation of the Pearl GTL project, and became the world leader in making these products from natural gas (GTL production) with total output capacity of 172.4 thousand b/d³¹.

Analyses of data from the literature allow us to conclude that the availability of licenses for the industrial FTGTL technologies is currently limited to just two companies - Sasol and Shell. Cooperation between Qatar and the specified licensors is through the creation of joint ventures between Qatar Petroleum and Sasol (Oryx GTL) or Shell (Pearl GTL).

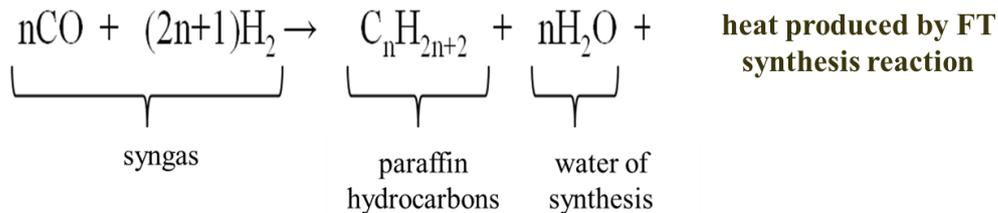
³¹Braginskiy and Shlihter (2004), pp.3-12

Chapter 2. FTGTL production

2.1 The Fischer-Tropsch Synthesis

FTGTL products are formed via the Fischer-Tropsch Synthesis from a feedstock comprising carbon monoxide (CO) and hydrogen (H₂), which is called syngas³²: As described above the syngas is formed from a reaction between methane and oxygen.

Figure 7: Fischer – Tropsch Reaction



Source: compiled by the Author

The FT-synthesis reaction products are a mixture of paraffin hydrocarbon compounds in whose molecules the carbon atoms number up to 100. In addition co-products such as water of synthesis, unsaturated hydrocarbons and oxygen-containing compounds (alcohols and others) are generated.

In industrial-scale production the mixture of synthetic hydrocarbons produced is divided into the following product categories: liquefied petroleum gases (LPG)³³, naphtha, kerosene and diesel fractions. Of these products LPG and naphtha, being primarily consumed as petrochemical feedstock, should not be regarded as 'liquid fuels', i.e. the primary objective of the FTGTL process. Our primary focus is on the kerosene and diesel FTGTL fractions.

2.2 FTGTL products

FTGTL kerosene fraction

Some indicators of FTGTL kerosene quality and those of aviation fuel in accordance with the brand Jet A-1 are presented in Table 3³⁴.

Table 3 shows that the density and temperature at the onset of crystallization of FTGTL kerosene does not meet the standards for Jet A-1 aviation fuel. Nevertheless there are three means by which FTGTL kerosene can be utilized despite the disparity in density relative to the Jet A1 specification used.

The first is to alter the quality characteristics of the fraction (density and crystallization temperature of the fraction³⁵ in order to comply with the standards, by refining synthetic crude oil at an oil refinery

³² Cozukova and Krilova (2008), p. 221; Dry and Steynberg (2006), pp.406-481.

³³ LPG comprises Propane and Butane with propylene, butylene and other hydrocarbons present in small concentrations.

³⁴ Lamprech and Roets (2005), p.4; Schroeder (2012), p.16

blended with natural crude. To this end it is possible to dilute the kerosene and diesel fraction at an oil refinery.

Table 3: Indicators of FTGTL kerosene quality

Indicators of oil kerosene	Jet A-1	FTGTL kerosene
Density 20°C, kg/m ³	Not less than 775	740-747 (out of range)
Temperature at the beginning of crystallization, °C	Not higher than minus 47	Minus 48

Source: compiled by the Author

The second approach is to compound or blend the kerosene fraction with aviation fuel produced from oil refining. This is only possible if the refinery product is sufficiently within the specification standards to allow for volumetric mixing.

The third approach is to use the FTGTL kerosene fraction as an additive for blending winter grades of diesel fuel.

An example of successful implementation of the second approach is the use of an FTGTL kerosene mixture (the proportion in the fuel being 35-50%) in 2008 and 2009 as aviation fuel used by Qatar Airways planes (A380 and A340) on the Doha-London-Doha route with 240 passengers onboard³⁶.

FTGTL diesel fraction

Some indicators of FTGTL diesel quality and diesel fuel are given in Table 4 in accordance with the standard EH 590:2004³⁷.

Table 4: Indicators of FTGTL diesel quality

Indicators of oil diesel	EH 590:2004	FTGTL diesel
Density 20°C, kg/m ³	820-845	766 (out of range)
Greasing ability:	No greater than 460	567-617 (out of range)

Source: compiled by the Author

It is clear that FTGTL diesel fraction does not conform to the standard of the diesel fuel in either its density or greasing ability.

The mismatch with established standards for both FTGTL diesel and kerosene fractions requires that they be blended with refinery-derived product prior to utilization. FTGTL products cannot be regarded as stand-alone commodities.

³⁵ Countries can have various standards for density and temperature at the beginning of crystallization. For example in Russia there is a TC – 1 standard where the temperature at the beginning of crystallization is Minus 60. To achieve the required standards it is possible to utilize the dewaxing process at an oil refinery.

³⁶ Schroeder (2012), p.16; http://www.shell.com.ru/home/content/rus/aboutshell/our_business_tpkg/per/

³⁷ Lamprech and Roets (2005) p.4, Morgan et al (1998), pp.9.- 19; Schaberg et al (2001) , pp. 9. 11-13

FT-synthesis co-products

The by-products which are formed by the industrial production of FTGTL are shown in Figure 6: synthetic water, fuel gas, carbon dioxide (not shown on the scheme) and heat of FT-synthesis. The heat of FT-synthesis is used to generate process steam and for electric energy production, some of which is used in the production plant.

2.3 Consumption of natural gas in FTGTL production and product output

The natural gas consumption for Oryx GTL, Pearl GTL and other FTGTL projects are shown in Table 5. This table is a mixture of actual built plants and estimates for potential projects studied in various sources.

Table 5: Natural gas feedstock consumption for existing and possible FTGTL projects

№	Operating plant or FTGTL project plant	Capacity FTGTL, thousand bbl/d	Natural gas feedstock consumption				
			f ³ / bbl	MMBTU/ bbl	m ³ /bbl	m ³ /t	billion m ³ /y
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1.	Plant «Oryx I GTL» ³⁸	32.4	9 250	9.25	262.0	2270	3.09
2.	Plant «Pearl GTL» ³⁹	140	11 400	11.4	322.6	2790	15.6
3.	Project (estimation) ⁴⁰	100	10 000	10	283.2	2460	9.8
4.	Project (estimation) ⁴¹	126	9100	9.1	257.5	2230	11.2
5.	Project (estimation) ⁴²	146	7000	7.0	198.8	1720	10.0
6.	Project (estimation) ⁴³	60.3	8200	8.2	233.0	2020	4.85
7.	Project (estimation) ⁴⁴	64.3	7900	7.9	225.4	1950	5.0
8.	Project (estimation) ⁴⁵	163.3	9400	9.4	266.2	2300	15
9.	Project (estimation) ⁴⁶	12.6	8100	8.1	230.0	2000	1.0
		37.8	8100	8.1	230.0	2000	3.0
		125.6	8100	8.1	230.0	2000	10.0
		339.3	8300	8.3	234.0	2030	27.4
10.	Project (estimation) ⁴⁷	163	7500	7.5	213.4	1850	12.0
11.	Project (estimation) ⁴⁸	23.5	9500	9.5	268.9	2330	2.2
12.	Project (estimation) ⁴⁹	15	10 000	10.0	283.2	2460	1.5
		25 and larger	9 250	9.3	261.8	2270	2.3 and larger

Source: compiled by the Author

³⁸ Gas-to-liquids. A Reserve ready to be tapped.- IHS CERA. - 11.07.2011.p.16. [http:// www. ih. com. products /cera /energy-report; Gas-to-liquids-GTL.-2011.-p.3](http://www.ih.com/products/cera/energy-report;Gas-to-liquids-GTL.-2011.-p.3). <http://www.natgas.info/html/gastoliquids.html>;
 Sasol Expects to Beat Design Capacity at Oryx GTL-02.07.2008.-1P. <http://www.greencarcongress.com/2008/7/sasol-expects-t.html>

³⁹ Gas-to-liquids-GTL.-2011.-3P. <http://www.natgas.info/html/gastoliquids.html>

⁴⁰ Patel (2005) p11

⁴¹ Bao (2008) p.103.

⁴² Kissel and Serebrovskiy (2003), pp.163-166.

⁴³ Uchkin (2004) p. 175.

⁴⁴ Kissel (2005), pp.19-22.

⁴⁵ Uchkin (2004), pp.73-75.

⁴⁶ Kissel and Khatton (2005), pp.69-71.

⁴⁷ Uchkin (2004) p.175. [or is this Uchkin 2005?]

⁴⁸ Sisley and Goswami (2003), pp.14-15.

⁴⁹ Gas-to-liquids. A Reserve ready to be tapped.- IHS CERA. - 11.07.2011.P.16. [http:// www. ih. com. products /cera /energy-report](http://www.ih.com/products/cera/energy-report)

From Table 5 the calculated ratio of raw natural gas to FTGTL product for the projects considered lies in the range of 1,720-2,460 m³/tonne (column 7). Differences in gas consumption between those actually recorded at the Oryx GTL plant (2270 m³/t)⁵⁰ and FTGTL projects currently at the design stage are in the range 76-112%. Differences in estimated ratios of raw natural gas to product for Oryx GTL and Pearl GTL plants (2,790 m³/t) are seemingly caused by the differences in FTGTL process technology design.

Focusing on the Oryx and Pearl plants, the fractions of the synthetic liquid hydrocarbons (SLH) and by-products are shown in Table 6.

Table 6: FTGTL product production at Oryx GTL and Pearl GTL plants

FTGTL products	FTGTL product output, b/d (%)		Density of FT-products ρ , kg/l	FTGTL product output, t/d		FTGTL product output, tonnes/m ³ natural gas	
	Oryx GTL	Pearl GTL		Oryx GTL [(2)*(4)* 159]/1000	Pearl GTL [(3)*(4)* 159]/1000	Oryx GTL ($\sum_{(5)} \cdot 365 / (3,09 \cdot 10^6)$)	Pearl GTL ($\sum_{(6)} \cdot 365 / (16,5 \cdot 10^6)$)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
LPG ⁵¹	1610 (5)	5600 (4)	0,54- 0,55	143	490	-	-
Nafta ⁵²	6490 (20)	35000 (25)	0,68	693	3781	-	-
Kerosene fraction ⁵³	12150 (37,5)	23800 (17)	0,747	1434	2827	-	-
Diesel fraction ⁵⁴	12150 (37,5)	61600 (44)	0,766	1470	7503	-	-
Diesel fraction ⁵⁵	-	14000 (10)	0,79	-	1759	-	-
Total amount ($\sum_{(1)}$)	32400 (100)	140000 (100)		3740	16360	0.441	0.362

Source: compiled by the Author

⁵⁰ Fraser (2005), pp.20-21.; [Sasol Expects to Beat Design Capacity at Oryx GTL-02.07.2008.-p.1. http://www.greencarcongress.com/2008/7/sasol-expects-t.html](http://www.greencarcongress.com/2008/7/sasol-expects-t.html)

⁵¹ www.nge.ru/g_p_51828-2002.htm

⁵² Cozukova and Krilova (2008) p 221;

⁵³ Monetizing gas using Sasol's technology. - Petroleum Economist.-2001. - V.68. - N9.- P.21-22.

⁵⁴ Schaberg et al (2001)

⁵⁵ Sisley and Goswami (2003), pp.14-15.

From Table 6 it is clear that the ratio of the output of all FTGTL products to natural gas feedstock supplied at operating GTL plants in Qatar is in the range of 0.362-0.441 t / thousand m³ of natural gas which is 58.0-70.7% of the theoretical output (0.624 t / thousand m³).

From Table 6 it follows that when processing 1,000 m³ of raw natural gas into FTGTL products, the physical volume of product is considerably less than that of the feedstock gas:

- the volume of an SLH mixture that is received from 1000 m³ of gas is approximately equal to 0.5-0.6 m³ $\approx (0.362-0.441)/0.726$. It is about 1,670-2,000 times $\approx [1,000 / (0.5-0.6)]$ less than a volume of raw natural gas feedstock.
- The volume of natural gas transported by pipeline under high pressure is 70-100 times less than that at atmospheric pressure,
- gas transported in the form of LNG by tankers is 600 times denser than its gaseous form at atmospheric pressure.

From these estimates the advantage of FTGTL product transportation in comparison with the volume of pipeline gas is apparent. This has obvious implications for the reduction in product transportation costs for FTGTL relative to pipeline gas and LNG as a channel for monetising natural gas.

The quantity of all FTGTL products (diesel fraction, kerosene fraction, naphtha and LPG) in barrels, and also the FTGTL product mixture (see Table 6) in 1 tonne is specified in Table 7.

Table 7: Barrels of FTGTL products and FTGTL product mixture in one tonne

No	FTGTL product	Density (ρ), kg/litre	Amount, bbl/tonne 1000/ρ/159
1	Diesel fraction	0.766	8.21
2	Kerosene fraction	0.747	8.42
3	Nafta	0.680	9.25
4	LPG	0.540	11.64
5	Product mixture 37,5% (1)+37,5(2)+20%(3)+5%(4)*	0.726	8.67

* Density of the product mixture is calculated on the equation:
 $\rho(5)=0.375\rho(1)+0.375\rho(2)+0.2\rho(3)+0.05\rho(4)=0.726$

Source: compiled by the Author

The reason for the lower density of FTGTL products in comparison with oil products (see Tables 3 and 4) is that oil refinery products contain naphthenic and aromatic hydrocarbons whose density is higher than that of paraffins produced from FTGTL processes⁵⁶.

The density of an FTGTL mixture in comparison with world oil grades is presented in Table 8⁵⁷.

Table 8: Barrels of the Top 5 World oil grades in a tonne

№	Oil grades	Density		Amount, b/t
		ρ, kg/l	API ^o *	
1	Brent (Europe)	0.831	39.0	7.56
2	WTI (West Texas Intermediate, USA)	0.827	39.6	7.60
3	Urals (Russia)	0.862	32.6	7.30
4	Siberian Light (Russia)	0.825	40.0	7.62
5	Arab Light (Saudi Arabia)	0.861	32.8	7.31
6	Mixture of FTGTL products	0.726	63.4	8.67

* API_o – oil density in degrees - API (American Petroleum Institute), where $API_o = (141.5/\rho) - 131.5$.

Source: compiled by the Author

It is clear from Table 8 that the FTGTL mixture, having a density of 0.726 kg/l, is significantly less dense than world oil grades.

⁵⁶ Petrov (1984), p 264;

⁵⁷ <http://www.topneftgaz.ru/analysis/7727>; http://www.uptrading.ru/main/internet_trejdng_na

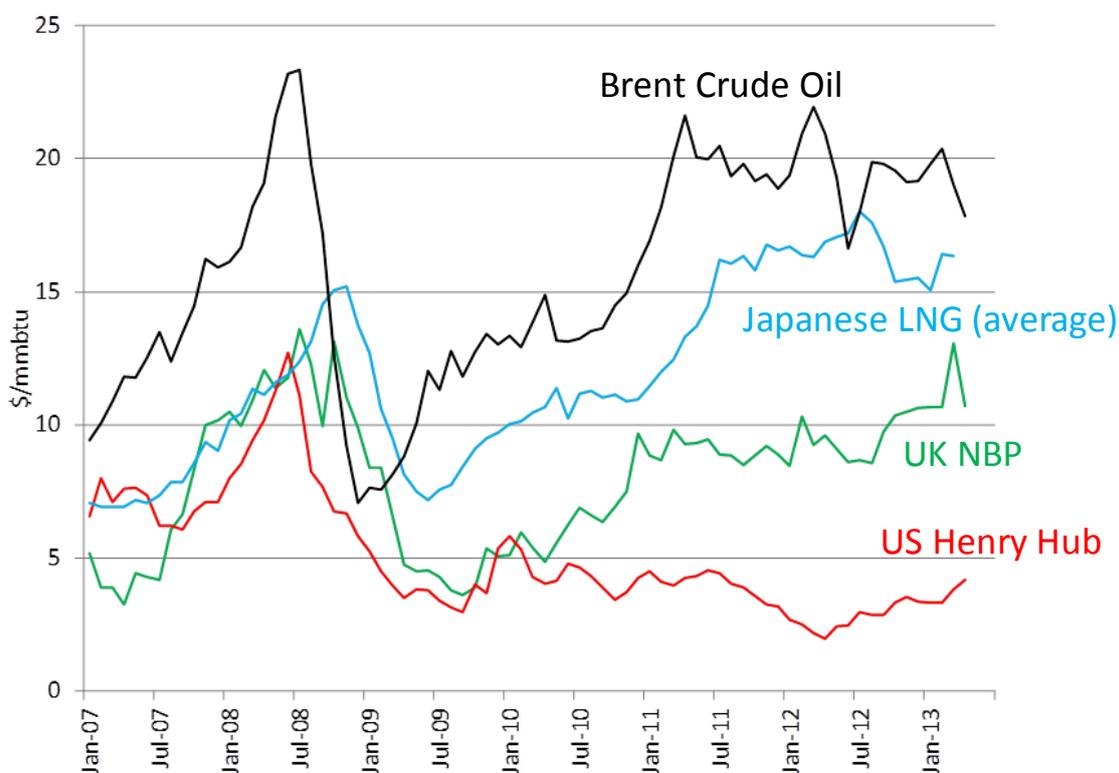
Chapter 3. Economics of FTGTL

3.1 Introduction

The purpose of this chapter is to explore the underlying economics of the FTGTL process in general based on the limited data available on the projects in Qatar. With suitable caveats this may provide us with information about key considerations regarding project economics of GTL projects in general in the current energy market context.

3.2 Energy market fundamentals

Figure 8: Oil and Gas Prices 2007 – 2013



Sources: Platts, Argus, EIA

From Figure 8 we make the following observations:

- the ramp-up in all price series in the period from 2007 to the fourth quarter of 2008, commonly referred to as the 'commodities bull run',
- The subsequent fall in prices associated with the financial crisis and subsequent economic recession,
- The sustained diversion between price series from 2009 onwards.

The Brent crude price recovered from its post-financial crisis lows and since early 2011 has been around \$19/MMBTU (\$110/bbl). Japanese LNG is imported under long term contracts in which the LNG price is related to recent crude price levels so that, whilst the terms of individual contracts vary, it is not surprising to see the LNG price line bearing a strong relationship to crude price, albeit with a lag. The UK NBP price has been around \$9/MMBTU since late 2010. This reflects an ongoing market

expectation that increasing demand growth for LNG in Asia would require Europe to increase imports of pipeline gas from Russia. At the moment this has been tempered by declining demand for natural gas in Europe due to the economic recession, the growth of renewable energy and the loss of market share in the power sector to coal. (The price of coal has fallen largely as a consequence of lower US gas prices allowing gas to win market share from coal in the US power sector, leading to higher coal exports to Europe). Finally shale gas production has caused US natural gas production to grow faster than demand and so depress Henry Hub prices. Although since early 2012 Henry Hub has been on a rising trend, in April 2013 the price was still lower than the long-run marginal cost of dry shale gas, estimated to be in the range \$5 - \$7/MMBTU⁵⁸.

In such markets as the US and Europe where the price of natural gas on trading hubs is primarily driven by supply and demand fundamentals it is clear that there is limited linkage to oil price. This has been commented upon extensively by Stern⁵⁹ and others. Natural gas has increasingly substituted for coal and petroleum products in the space heating sector. Furthermore, since the widespread adoption of the Combined Cycle Gas Turbine in the 1990s, gas has almost completely displaced oil products in the power sectors of North America and Europe.

Figure 8 also shows that the trend of Brent crude oil is higher by 2-3 \$/MMBTU than the Japanese average LNG price, by 5-6 \$/MMBTU than the UK NBP gas price and by almost 12 \$/MMBTU than the US Henry Hub gas price in April 2013.

It is important to note that on traded markets there are no quotations for FTGTL products. Consequently, one of the purposes of this paper is to suggest a methodology to determine prices of FTGTL products, relative to crude oil and refined products in order to evaluate the economics of FTGTL projects.

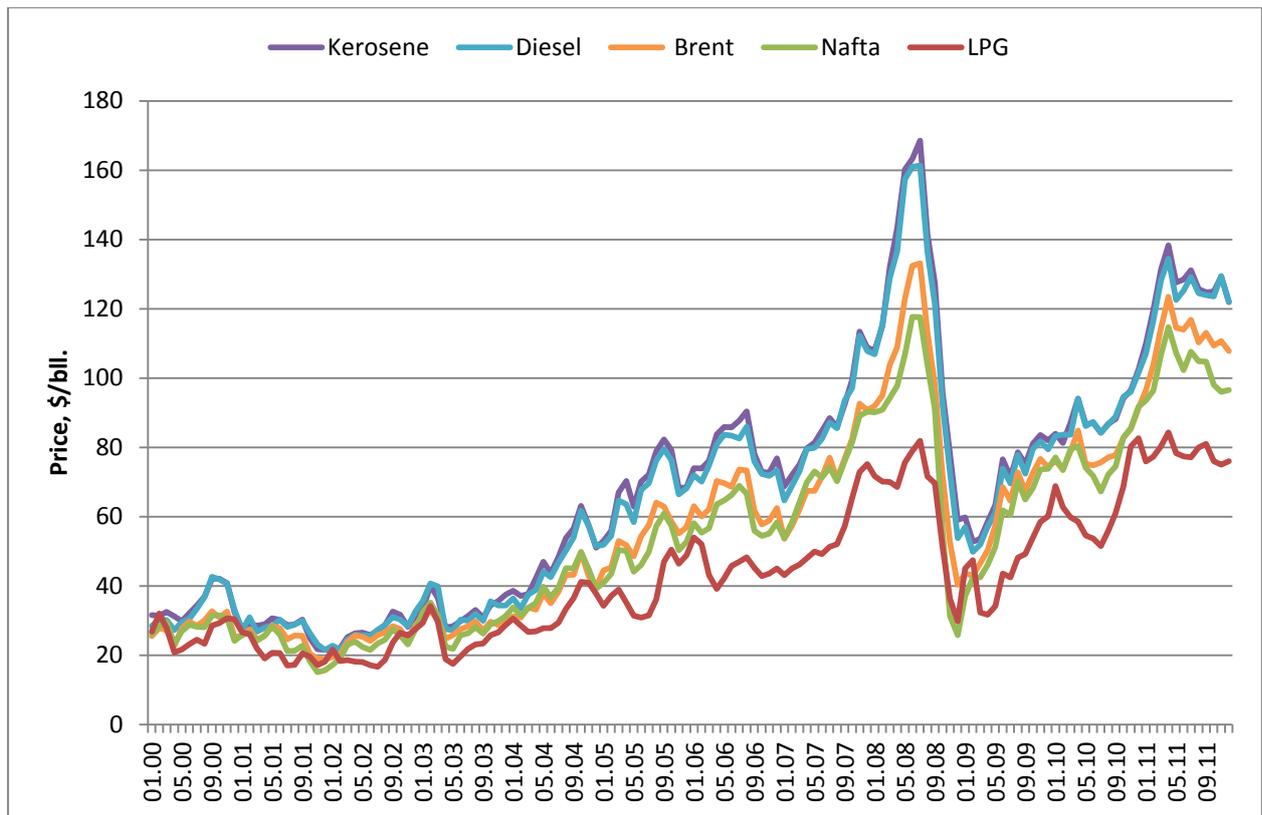
In Chapter 2 final FTGTL products were shown to be reasonably similar to petroleum product analogues in their broad characteristics relating to intended end use. The relationship between the prices of Brent crude and refined products has been analysed, with results shown in Figures 9 and 10.

Figure 9 shows the trend of Brent crude oil and oil product-analogues to FTGTL products on two delivery bases: FOB MED Italy. It can be observed that the price dynamics of oil products are similar to those of Brent with a spread of several \$/bbl, depending on the specific product.

⁵⁸ Henderson (2012), p. 44 -47

⁵⁹ Stern (2011)

Figure 9: Brent Crude Oil Price vs Oil Product Prices, FOB MED Italy (2000 -2011)

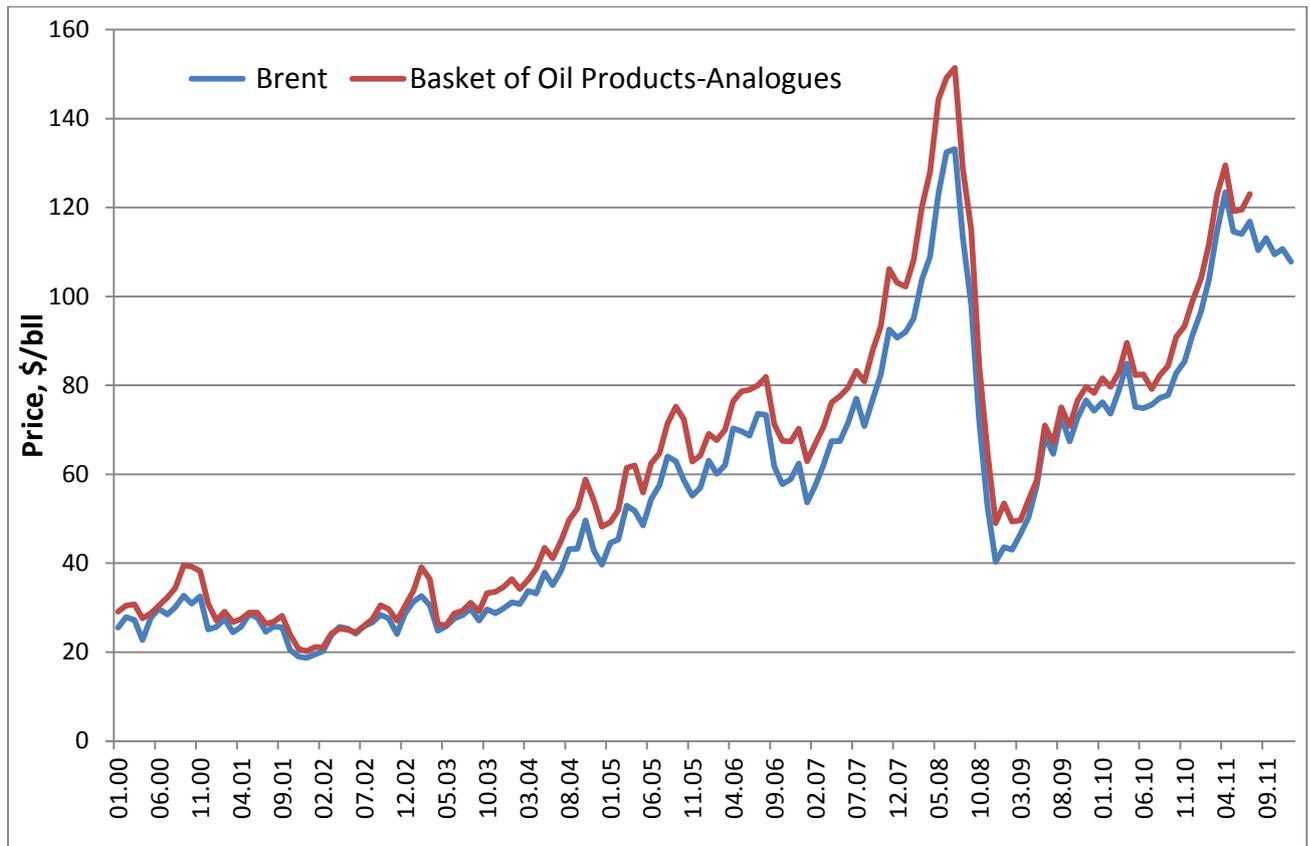


Sources: Platts⁶⁰

As was mentioned previously, the average FTGTL product basket according to the Figure 5 would consist of: 37.5 % diesel fraction, 37.5 % kerosene fraction, 20 % naphtha and 5 % LPG. Using Platts data, the average percentage of FTGTL products in a basket, and the assumption that FTGTL products are similar to oil products, the price dynamics of oil products (as analogues for FTGTL products) to Brent were constructed. This is presented in Figure 10.

⁶⁰ <http://www.platts.com/IM.Platts.Content/ProductsServices/Products/Euromkscan.pdf>

Figure 10: Brent Crude Oil Price vs Basket of Oil Products-Analogues, FOB MED Italy (2000 – 2011)



Sources: Platts, Author calculations

Figure 10 shows that trend of a basket of oil product-analogues to FTGTL products is higher than Brent oil by several \$/bbl.

These data (Figures 9 and 10) show that the dynamics of oil product prices are similar to the dynamics of Brent prices over the period of 12 years (delivery basis: FOB MED Italy). This allows us to derive a future FTGTL product basket price based on a future Brent price assumption.

Prices of refined products on markets are usually determined in \$/tonne. As already discussed, the density of FTGTL products is lower than refined products, so the number of barrels in a tonne is higher (without taking into account additional margin for specific qualities such as the low sulphur content of FTGTL products).

The approach adopted in deriving a Brent-related FTGTL product price is as follows:

1. Determine the ratio of refined product analogue products on a \$/tonne basis and from their densities (tonnes/barrel) derive their average price in \$/bbl. The averages for these values for 12 years (2000-2011) on the basis of two markets (FOB MED Italy and FOB Singapore) is presented in Table 9.
2. In order to calculate prices of FTGTL products it is proposed to use the price of Brent oil, adjusted by the conversion factor (scaling ratio) which is put forward in this paper and presented in Table 10.

Table 9: Average refined product prices for 12 years (2000-2011) on the basis of two markets (FOB MED Italy and FOB Singapore)

FTGTL oil products – analogues	Average product price (2000-2011) \$/bbl		Quantity of bbl in a tonne
	FOB MED Italy	FOB Singapore	
LPG	41.76	41.14	11.64
Nafta	52.36	53.98	9.25
Kerosene	66.02	65.72	8.42
Diesel	64.44	64.05	8.21
Brent	55.28	55.28	7.56
FTGTL Basket	-	-	8.67

Sources: Author's calculations

Table 10: Scaling ratio Brent Crude Oil Price vs GTL products

FTGTL oil products – analogues	K^{GTLi}		Margin for quality, \$/bbl
	FOB MED Italy	FOB Singapore	FOB MED Italy
LPG	1.16	1.15	
Nafta	1.16	1.20	5.40
Kerosene	1.33	1.32	
Diesel	1.27	1.26	8.30
Brent	-	-	
Weighted average margin for quality. \$/bbl FTGTL Basket			4.00

Sources: Author's calculations

Naphtha feedstock is used for pyrolysis processes in the petrochemical industry. The output of ethylene from FTGTL naphtha is about 10% higher than from crude oil naphtha. This is because oil

naphtha (according to TU 38-001256-76⁶¹) has a wax content of about 55-60% , while FTGTL naphtha contains more than 99% of waxes with a density about 0.68 kg / l⁶². The yield of ethylene, calculated according to Mukhina T.N.⁶³ for FTGTL naphtha is approximately 4% higher than that derived from petroleum ⁶⁴. This means that during the pyrolysis of 1 tonne of FTGTL naphtha an additional 40 kg of ethylene is produced (1000 * (34-30) / 100 = 40). With the average world price of ethylene \$1,200-1,300/tonne⁶⁵, the additional margin from ethylene production could be around \$50. The estimated premium of naphtha at \$ 50/9.25 barrels ≈ \$5.4/per bbl. The additional premium to the price for FTGTL naphtha will be \$1/barrel ≈ (50/9.25) * 20 /100 (20% content FTGTL naphtha in FTGTL product mixture).

Thus, the value of the FTGTL product basket increases by about \$1/barrel due to the premium quality of naphtha.

The FTGTL diesel fraction has an average cetane number⁶⁶ (CN) equal to 73 units (compared to 51 units in diesel fuel according to EN-590 standard⁶⁷). The premium relating to FTGTL diesel is based on operational data from Russian refineries. The majority of Russian refineries use the cetane additive Dodicet- 5073 to bring the CN of diesel fuel within the requirements of standard EN-590. This requires the use of about 2 kg/t of diesel fuel⁶⁸. Taking into account the savings in the use of the Dodicet – 5073 additive when using FTGTL diesel product, the additional margin for the FTGTL product basket due to FTGTL diesel is about \$3/bbl⁶⁹.

Thus, a reasonable estimate for the additional margin for the FTGTL product basket compared with the value of refined product analogues is about \$4/bbl due to the quality characteristics of the naphtha and diesel fractions.

Therefore it is proposed to determine the Scaling ratio in the following way:

$$K^{GTLi} = (V^{GTLi} * P_{(2000-2011)}^{OPi}) / (V^{Brent} * P_{(2000-2011)}^{Brent}),$$

V^{GTLi} or V^{Brent} – number of barrels of FTGTL product or Brent in 1 ton;
 $P_{(2000-2011)}^{OPi}$ or $P_{(2000-2011)}^{Brent}$ average actual quotations of the prices of oil product – analogues to FTGTL products or Brent during 2000-2011, \$/bbl.

For clarification:

$$K^{GTLi} = (\text{Price of GTLi analogues in } \$/\text{tonne}) / (\text{Price of Brent in } \$/\text{tonne})$$

The Scaling ratio (K^{GTLi}) of each FTGTL product to Brent is also presented in Table 10.

⁶¹ Shkolnikova (1999)

⁶² Kozyukov and Krylov (2008)

⁶³ Mukhina (1987)

⁶⁴ Petrochemical Processes 2001. ABB Lummus. - Ethylene. <http://www.hydrocarbonprocessing.com>

⁶⁵ <http://www.platts.com> (average in 2012)

⁶⁶ Cetane number or CN is a measurement of the combustion quality of diesel fuel during compression ignition. It is a significant expression of the quality of a diesel fuel.

⁶⁷ www.nge.ru/g_p52368-2005.htm

⁶⁸ Mitusova (2009), pp.11-16.

⁶⁹ For Further details see Glebova (2012)

For the assumed future price of Brent the corresponding value of the final GTL products can be calculated utilizing the formula:

$$P_{20xx}^{GTLi} = P_{20xx}^{Brent} * K^{GTLi}$$

P_{20xx}^{GTLi} - Price of i FTGTL product (nafta, kerosene, disel, LPG) in 20XX \$/t;

P_{20xx}^{Brent} - Brent price in 20XX, \$/t;

K^{GTLi} - Scaling ratio of the price of 1 t of Brent in the price of 1 t of FTGTL product;

In addition, as discussed above, FTGTL products have premium qualities in relation to petroleum product analogues. This is due to their low content of sulphur, and high cetane number⁷⁰ of the diesel fraction, and high paraffin content for naphtha.

We will use a Brent price of 839 \$/tonne (average for Brent in 2011 FOB MED Italy) to which the scaling ratio is applied to derive the price for FTGTL products and subsequent economic evaluation. To this is added the additional special quality premium. The assumed future price of the FTGTL product basket is thus 1,073 \$/tonne corresponding to a Brent price of 110 \$/bbl.

3.3 FTGTL project economics

3.3.1 Introduction

The divergence between crude oil (and by extension oil products) and natural gas prices since 2008 in the US and other markets, which previously had regulated domestic natural gas prices at comparatively low levels, has stimulated much discussion in the energy media about the potential for investment in FTGTL as a form of arbitrage between gas and oil value chains. The Pearl project is the most recent manifestation of this and could potentially be used to quantify the economics of this arbitrage. Although the final cost range of the project is known and its feedstock and product flows and specifications are defined, there are still significant uncertainties which we should take into account. The main issue is that the project CAPEX includes that of offshore production facilities and those required to process the gas to meet input requirements for FTGTL plant. The split of upstream field production CAPEX and that associated with condensate removal vs the FTGTL plant costs are unknown.

For these reasons, the Pearl project cannot be used as the basis for calculation of FTGTL project economics. The key question is how to determine a reasonably representative 'base case' (specific indicators of capital and operating costs, the volume of source materials, amount of products produced, the cost of the products on the market) for analysing the economics of production of FTGTL liquid fuels?

The determination of an FTGTL plant base case characteristics was initially attempted through the analysis of available data on GTL industrial plants over the last 10 years. These fall into two categories:

⁷⁰ Cetane number or CN is a measurement of the combustion quality of diesel fuel during compression ignition. It is a significant expression of the quality of a diesel fuel.

Analysis of data from plants constructed since 2000

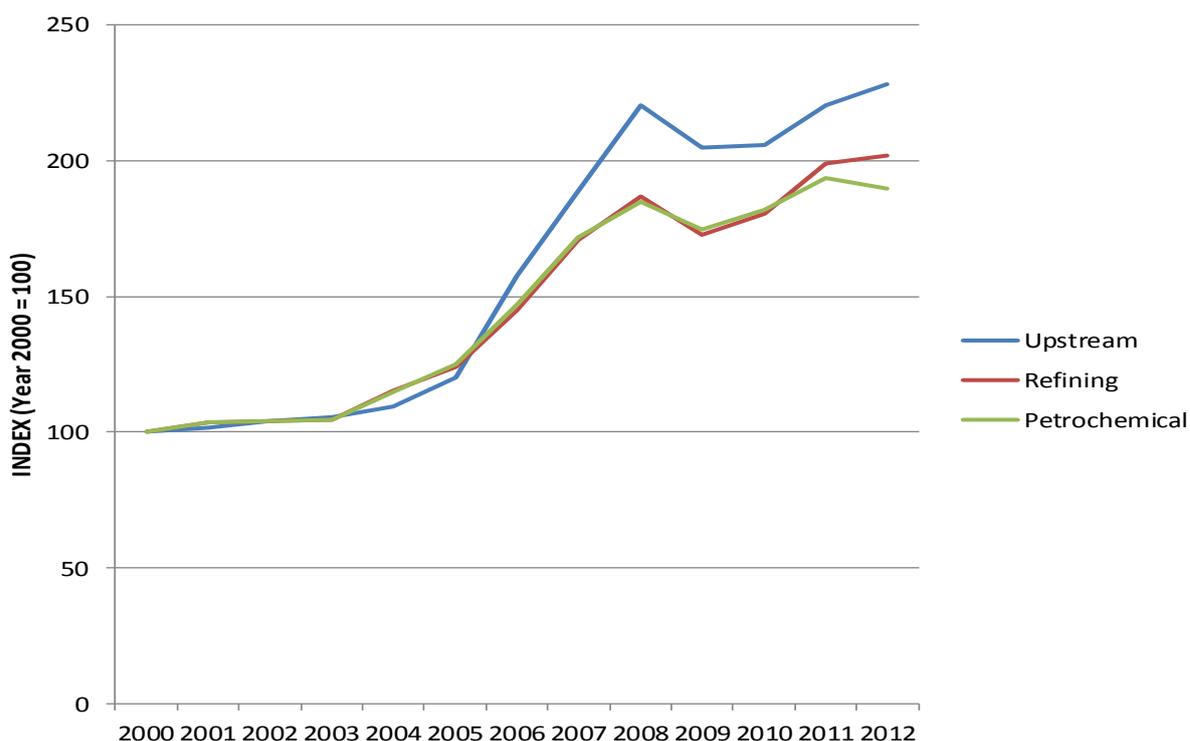
As mentioned above the new GTL plants for production of synthetic hydrocarbons from natural gas with capacity 32.4 and 140 thousand barrels/day were constructed in Qatar during the period from 2006 (Oryx GTL) to 2012 (Pearl GTL). However, as discussed above, because the FTGTL-specific costs cannot be determined for the Pearl Project, we are left just with the Oryx project as a data source in this category.

Analysis of data relating to potential future plants

Here we review available published data on potential FTGTL projects and derive their specific indicators to enable comparison with the Oryx plant. As a result of the analysis of the literature 11 projects were selected for the production of GTL, which formed the basis for deriving specific capital investments (CAPEX) and operating expenditures (OPEX). Many of these examples are technical studies for plants which have not been built. The results for these plants are presented in Table 12.

While making the comparison of these 11 projects it is important to note that the Pearl, Oryx and other project plant construction took place at a time of general cost inflation for all capital intensive process, power generation and upstream plant (see Figure 11).

Figure 11: Global Upstream, Refining and Petrochemical Sector Capital Cost Indices



Source: IHS CERA, <http://www.ihs.com/info/cera/ihsindexes/index.aspx>

Since the GTL projects considered in this analysis were constructed or had cost estimates made at different periods of time and had different throughputs, for the purposes of their comparative analysis it was necessary to adapt the data.

The cost data for these projects were converted to a 2011 basis, using the indexes of capital (Downstream Capital Cost Index (DCCI)) and operating costs (Downstream Operating Cost Index (DOCI)) which are presented in Table 11.

Table 11: Index values for DCCI and DOCI - 2000 to 2011⁷¹

Year	DCCI	DOCI	Year	DCCI	DOCI	Year	DCCI	DOCI
2000	100	100	2004	115	123	2008	187	182
2001	104	101	2005	124	132	2009	172	171
2002	104	103	2006	145	151	2010	180	173
2003	105	110	2007	154	168	2011	197	185

Source: IHS CERA, <http://www.ihs.com/info/cera/ihsindexes/index.aspx>

The next step was to list all projects on the basis of a standard capacity, to enable the comparison of projects. CAPEX for plants with a capacity from 37.8 to 125.6 thousand bbl/day was estimated from Oryx GTL costs using the Lang H.J. equation⁷²:

$$\text{CAPEX2} = \text{CAPEX1} * (\text{Q2/Q1})^{0.65}$$

The results of this calculation are presented in Table 12, which contains cost estimates for projects of different sizes (including many technical studies for plants which have not been built) after applying the Lang equation over the range of examples. This will help us to compare projects of different size and determine CAPEX utilizing analysis of data relating to potential future plant.

Table 12: GTL CAPEX

Plant, GTL project	Capacity thousand bbl/day	Year	CAPEX, \$/bbl/day (brought to capacity of 32.4 thousand bbl/day in 2011)	OPEX, \$/bbl
Oryx GTL» ⁷³	32.4	2006	51,000	10.0
GTL project ⁷⁴	100.0	2005	16,800	4.2
GTL project ⁷⁵	65.0	2005	28,300	6.1-8.1
GTL project ⁷⁶	64.3	2005	33,200	4.9
GTL project ⁷⁷	37.8	2005	38,000	4.4

Sources: Author's Calculations

From Table 12 it is evident that capital and operating costs of the existing Oryx plant exceed all estimates for potential plant, available from literature. This raises the question why the Oryx plant was so much more expensive on a unit of product basis compared to projects which were the subject of engineering studies/cost estimates, even though these have been normalised by the inflation indices relating to the date of cost estimation. One possibility is that the cost estimates in studies underestimated the complexity of construction of these projects, or that they expected costs to fall based on the 'learning experience' of Oryx and subsequent plants. The complexity of these projects and the risk of capital cost overrun is a theme often covered in the energy media⁷⁸.

For these reasons it was decided to use the Oryx GTL costs as the analogue for evaluating the economic viability of FTGTL production according to the actual cost and performance parameters. The package of initial project data for the calculation of GTL production is given in Table 13.

⁷¹ <http://www.ihs.com/info/cera/ihsindexes/index.aspx>

⁷² Couper et al (2008), p.2640; Dysert (2003), pp.22-30.; Remer and Chai (1990); L.H., pp.77-82.

⁷³ Chedid et al (2007), pp.4799-4811.; Stoppard et al (2007), p.1

⁷⁴ Patel (2005)

⁷⁵ Rahman (2008), pp.10-11.

⁷⁶ Kissel I. (2005), pp.19-22.

⁷⁷ Uchkin (2004), pp.73-75.

⁷⁸ <http://www.reuters.com/article/2012/11/26/column-kemp-natural-gas-idUSL5E8MQ79E20121126>

Table 13: Initial data for calculation of efficiency of industrial GTL production

Data	Values
Capacity, million.t/year (bbl/day)	1,364 (32,400)
FTGTL products, %, including:	100.0
Diesel fraction	37.5
Kerosene fraction	37.5
Nafta	20,.
LPG	5.0
Feed gas, billion cm/year (cf/bbl.)	3.09 (9,250)
CAPEX, (\$/bbl)	51,000
Construction period, years	5
Project life, years	25
Annual operating costs from total CAPEX, %	5

Source: compiled by the Author

3.3.2 Modelling assumptions

Integrated Economics

The economic analysis of the Oryx project analogue as described assuming \$110/bbl Brent – the average pricing of MED Italia basis according to Platts in 2011.

The prices for FTGTL products were calculated utilizing the Scaling ratio discussed above.

The feed gas price was assumed at a level about \$10/MMBTU (i.e. representing European hub prices over the period 2012 – 2013 to date).

The economic metrics of the project on this basis and assumptions are:

Rate of Return (nominal): 12.6 %

Net Present Value at 10% (nominal): \$326 million

Years to achieve payback after production start: 6.3 years

These project economics are not very attractive. However sensitivity analysis demonstrates the key factors driving project economics.

Figure 12: Sensitivity of Oryx GTL project analogue



Source: Author's Calculations

The Figure shows that in the case where gas price is 50% lower (i.e. \$5/MMBTU) the internal rate of return increases to 31.9%. Thus even after the application of profit sharing terms it is likely that the investing foreign company would see a rate of return well in excess of its cost of capital.

Based on the analysis and clearly on the assumption of a future Brent price of \$110/bbl, we can conclude that FTGTL economic indicators are viable only at feed gas prices broadly below \$8/MMBTU (IRR 21.5% before tax).

Indicative GTL project economics in Russia

The previous section generally shows the efficiency of GTL production on a NPV pre-tax basis.

The efficiency of GTL production using the same derived cost and production 'base case' as described above and the same methodology of price calculation can be used to assess the potential for future GTL projects in Russia. An analysis of 9 potential plant locations in 5 Federal Districts of the Russian Federation was carried out, as presented in Figure 13.

Figure 13: The possible location of future FTGTL plants in Russia



Source: Author's suggestions

Assumptions

The economics of these projects were calculated taking into account income and property taxes⁷⁹.

Feed gas price was determined depending on the region according to the Federal Tariff Service.

⁷⁹<http://www.economy.gov.ru>; <http://www.ocenchik.ru/docs/1062.htm>;

Table 13: Wholesale gas prices of the Federal Tariff Service in 2011 (the estimated calorific value 7,900 kkal/m³ or 33080 kJ/m³)⁸⁰

Regions	Wholesale gas price (excluding VAT)
	\$/1000 m3
Yamal-Nenets	57.21
Khanty-Mansiysk	67.53
Irkutsk Region	54.72
Sakhalin Region	48.71
Primorsky Krai	126.06
Krasnodar region	106.95
Orenburg region	87.56
Astrakhan region	84.97

Source: references⁸⁰

Calculations were made taking into account optimal delivery logistics of the final products.

Brent price was calculated on different delivery bases - FOB MED Italy and FOB Singapore (depending on plant location and delivery markets).

The additional margin for product quality described above was not taken into account.

The results of this analysis showed that the most attractive projects (internal rate of return is in the range from 16.5% to 25%) are in the areas of Sakhalin-2 and Sakhalin-1 (export-oriented products), as well as Angarsk, Novy Urengoi, and Surgut (delivery of GTL on the domestic market) (Table 14).

⁸⁰ http://www.gazprom.ru/f/posts/98/377922/prikaz_412-e_2.pdf
<http://irkobl.ru/sites/sti/prikaz/Gazosnabjenie/index>
<http://www.bestpravo.ru/rossijskoje/rx-pravila/f4o.htm>
<http://www.gazprom.ru/about/subsidiaries/list-items/gazprom-transgaz-surgut/>
 Prikaz FST RF №412-e/2 от 10.12.2010.-5C.

Table 14: The most effective FTGTL production in Russia by results of the analysis

№	Location of FTGTL plant (district)	FTGTL products	Logistics and delivery basis products FTGTL		Performance indicators		
			Exports	Russian market	IRR, %	Discount rate 15%	
						DPP ⁸¹ years	DPI ⁸²
1	Sakhalin-2	Products separately	FOB Prigorodnoe (transshipment, freight to port of Yokohama, Japan)	-	24.7	10.7	1.9
2	Sakhalin-1	Products separately	FOB the De Castries (transshipment, freight to p.Singapore)	-	24.5	10.8	1.8
3	Angarsk, Irkutsk region, Eastern Siberia	Products separately	-	FCA st.Suhovskaya-South Vost.Sib.zh.d.	19.3	14.7	1.3
4	New Urengoy, Yamal, West Siberia	Products separately	-	FCA st. Korotchaevo (LPG, nafta); FCA st.Surgut. (Gazprom Surgut processing)	18.8	15.3	1.3
5	Angarsk, Irkutsk region, Eastern Siberia	Products separately	By train p.Nahodka (transshipment, freight to Yokohama, Japan)	-	17.3	17.8	1.2
6	Surgut, Khanty-Mansiysk, West Siberia	Products separately	-	FCA st. Surgut (Gazprom Surgut processing)	16.6	19.5	1.1

Source: Author's Calculations

To set the context for future investment decisions on FTGTL projects the following SWOT-analysis (Strengths, Weaknesses, Opportunities & Threats) illustrates the factors that affect the feasibility of industrial GTL production in Russia.

⁸¹ Discounted Payback Period

⁸² Discounted Profitability index

SWOT-analysis

S - Strengths: the world's largest proven natural gas reserves and high reserves to production ratio; high geographic concentration of gas resources within Russia; a general expectation that the gap between oil and gas prices will persist.

W - Weaknesses: concerns regarding reserve maturity and lower future field size and economics; problems in attracting foreign investment for FTGTL; lack of qualified personnel in FTGTL sphere; construction of new greenfield production FTGTL (no precedent in the Russian Federation).

O – Opportunities: an opportunity to gain access to foreign FTGTL license technologies on acceptable terms; the output of high-quality products for the markets of the Asia - Pacific region; the opportunities for investment in the production and sale of environmentally friendly FTGTL products (sulphur content below 10 ppm).

T - Threats: high inflation, growth of tariffs/prices due to the strength of natural upstream monopolies; technological complexity of FTGTL projects, high capital intensity, complex logistics of delivery of heavy equipment; lack of infrastructure.

The combination of factors that provide the favorable conditions for FTGTL development can be summarized as follows:

Strategic factors:

- a) Diversification of transportation routes
- b) Possibility to monetize stranded and abundant gas reserves which may not be economically feasible by pipeline transportation (absence of pipelines or low-pressure reserves)
- c) Collaboration projects with the best international companies
- d) Creation of new centres of economic development and economic stimulation of surrounding regions.

Economic factors

- a) Crude oil prices at historically high level
- b) The development of shale gas

Environmental factors

- a) Legislation concerning low sulphur and clean burning fuels
- b) The necessity to utilize associated gas instead of flaring it

In summary, the key factors that affect the economic viability of FTGTL projects are:

- a) Location of the plant
- b) Presence of gas resources (the use of shale gas resources, offshore oil and associated gas of sufficient volume)
- c) Gas prices
- d) Oil prices

The above analysis generally supports the feasibility of the industrial FTGTL production in Russia.

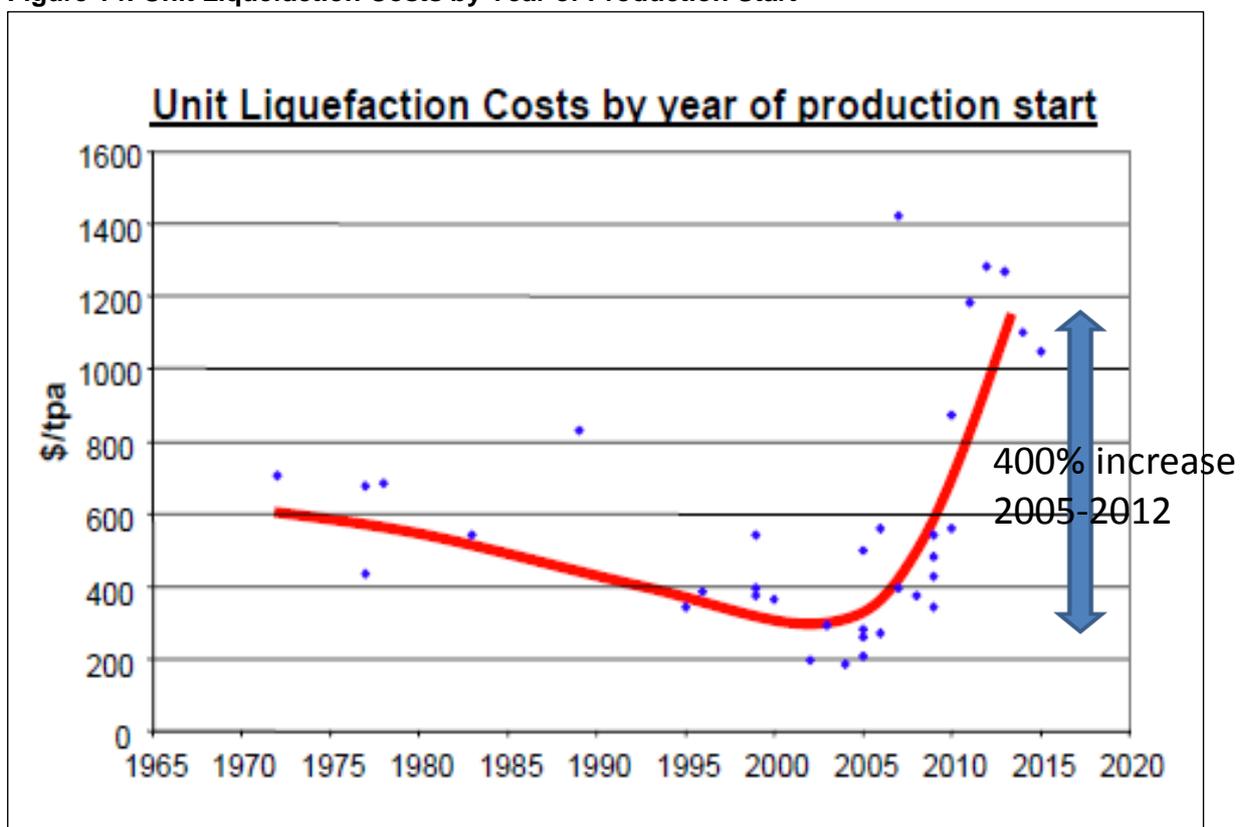
The total CAPEX of FTGTL plant is 51,000 \$/bbl. Although returns may be promising on paper, building an FTGTL plant still requires a large commitment of CAPEX. Given the cost overruns commented on in relation to Oryx this is another factor which makes investors wary and also means that it might be difficult raising project-specific bank finance.

Chapter 4. Comparative project economics – FTGTL and LNG

An alternative to the monetization of natural gas with the use of FTGTL technology is the production of liquefied natural gas (LNG) where it is possible to export it from coastal locations. Supplies of LNG to market are generally considered preferable to pipeline gas at distances of more than 2,000 - 2,500 km⁸³. According to Fleisch, in 2002 the economics of FTGTL products supply and LNG were similar, if the distance to destination markets exceeded 2,000 km, and the volume of supplied gas (for both FTGTL and LNG) was not less than 1-1.5 billion m³⁸⁴.

This section presents a comparison of FTGTL and LNG production economics. Table 15 shows the calculated technical and economic characteristics of the production of FTGTL and LNG capacity for processing 1 billion ft³/day (or about 10 billion m³/year) of natural gas in 2004⁸⁵. 2011 costs were inflated using the CERA DCCI (Table 11) taking into account that liquefaction projects also experienced inflation during the 2000s, as is shown in Figure 14.

Figure 14: Unit Liquefaction Costs by Year of Production Start



Source: GIIGNL

Apparent from Figure 14 is the scale of cost increases (400% compared with the 100% increase for upstream, refining and petrochemical sectors shown in Figure 11), and the variability of costs of individual projects.

⁸³ Fleisch et al (2002), pp.1-14.; Panahi and Skogestad (2010).

⁸⁴ Fleisch et al (2002), pp.1-14.; Panahi and Skogestad (2010)

⁸⁵ Patel (2005).

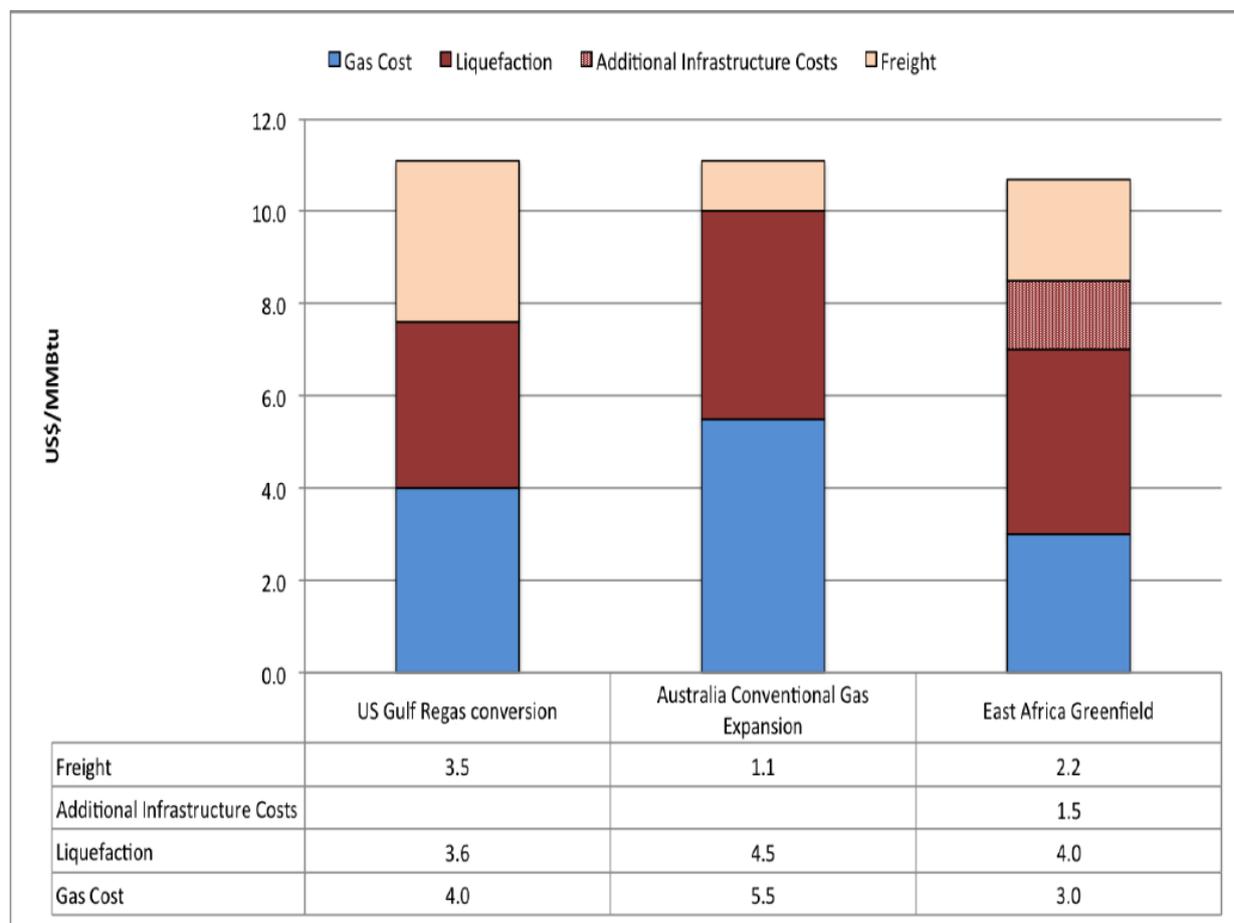
Table 15: Technical and economic characteristics of FTGTL and LNG production (capacity of 10 billion m³/year)

Characteristics	FTGTL	LNG
The number of production trains	6	2
Requirements for sulphur content of feed gas, ppm	Not more than 1	Not more than 20
Requirements for the disposal of CO²	Disposal of apart	Disposal of the total volume
Need for catalysts	All major installations require the use of catalysts and their periodic replacement	The process is carried out without catalysts
Steam and electricity	Production is fully supplied with steam production and own electricity generation, it is possible to export energy from the installation (OSBL)	No production of steam and electricity. Import of energy or use of part of the feed gas is required to ensure the operation of turbines and compressors.
The presence of berth, and ships for shipment of products	Liquid synthetic hydrocarbons are loaded on conventional berths and tankers for petroleum products	Requires special berths and loading systems for cryogenic products, as well as special tankers for transportation of cryogenic liquids
Factory area without common facilities	About 1 km ²	About 0.1 km ²
Time to construct the plant	38-48 months	36-38 months
Thermal efficiency, % define in footnote	60	85-88
The effectiveness of carbon, %	77	85-88
CAPEX, \$ billion	3.8 (depends on the location of the plant)	4.2 (coastal location of the plant)
Production of liquid hydrocarbon, bbl/d	100,000 (GTL products)	280,000 (LNG)
Consumption of natural gas for the production of liquid product, ft³/bbl.	10,000	3,570

Source: compiled by the Author

While stressing the difficulty of undertaking a strict economic quantitative comparison, we can take the directional findings from the Oryx analysis above and review prospective LNG projects for which assessments have been made.

Figure 15: Comparison of breakeven economics for three LNG projects, assuming Japan as destination market



Source: D. Ledesma, 'East Africa the Potential for Export', 2013, OIES, <https://www.oxfordenergy.org/2013/03/east-africa-gas-the-potential-for-export/>, P. 28

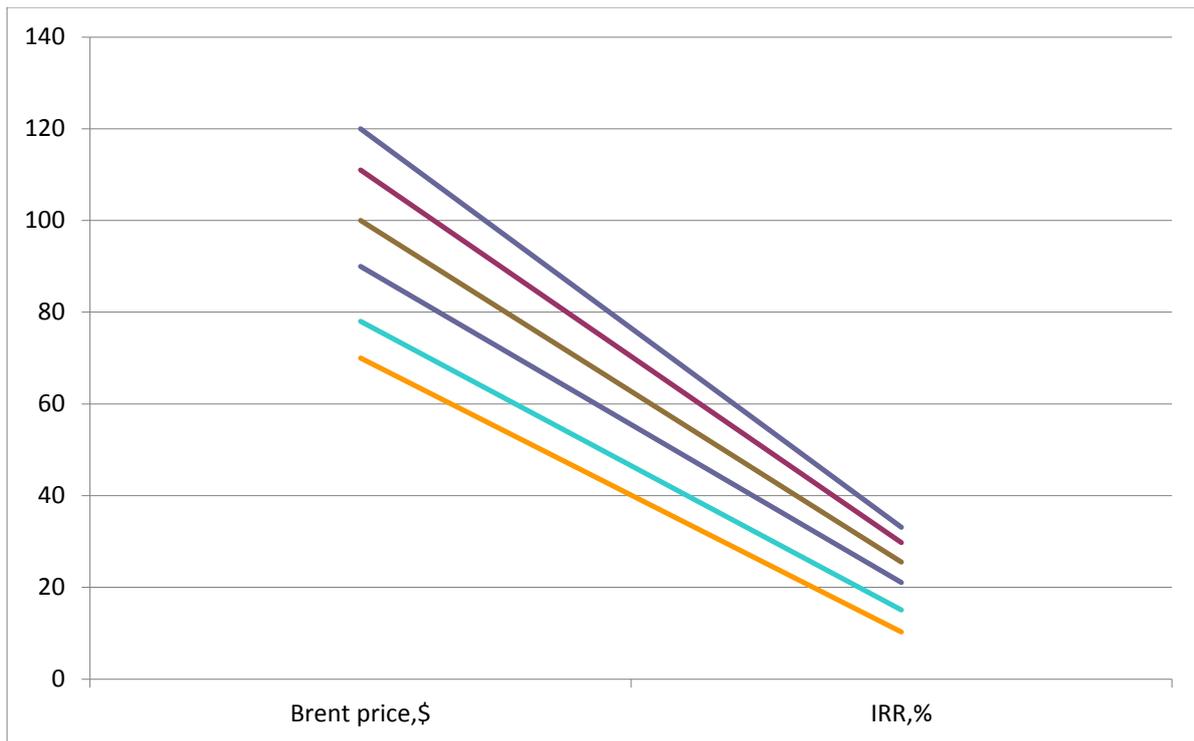
It is necessary to note from Figure 15 that all three example projects have a feed gas cost above \$3/MMBTU, but all achieve an acceptable IRR (assumed as 15%) at an LNG market price of around \$11/MMBTU (equivalent to \$64/barrel of oil equivalent).

If we take a feed gas price at a level of \$5.5 /MMBTU (Australia Conventional Gas Expansion) and run the FTGTL economic model using other assumptions in section 3.3.2 above, then the results suggest that:

An FTGTL project IRR of around 15% can be reached with a Brent price of about \$77/bbl without taking into account the additional margin for quality.

The correlation between Brent price and the FTGTL project IRR with fixed feed gas price around \$5.5/MMBTU is presented in Figure 16.

Figure 16: The influence of Brent price on FTGTL project economics



Source: Author's Calculations

Chapter 5. Conclusions

In conclusion we would like to summarise the main findings of the paper. FTGTL is a process which converts natural gas into liquid hydrocarbons. Major new FTGTL plants were brought online in Qatar in 2006 (Oryx GTL) and 2012 (Pearl GTL) with productive capacities of 32.4 and 140 thousand b/d respectively. During FTGTL synthesis the following set of products is produced: liquefied petroleum gas (LPG), naphtha, kerosene and diesel fractions. The FTGTL kerosene and diesel fractions do not conform to international standards on a number of qualitative characteristics, most importantly density and greasing ability, so there is a necessity to process the fuels further. The utilization of these two final products is possible only after altering the quality characteristics of the fraction to the required standards.

In this paper the methodology for calculating FTGTL product prices is presented. This is based on tracking the relationship of analogue refined products to the Brent crude price. This relationship is determined based on prices/tonne (rather than /barrel) in order to avoid the issue of FTGTL products having lower densities than their refined product analogues.

From a geographical point of view the areas of interest for FTGTL projects are countries with abundant resources of natural gas or 'stranded resources' (which means that reserves are located remotely from customers or are clusters of small reserves). FTGTL is also a possible way to monetize gas reserves and diversify transportation routes. The efficiency of FTGTL production is demonstrated in the example of Russia, where the most effective projects (financial internal rate of return is in the range from 16.5% to 25%) are in the areas of Sakhalin-2 and Sakhalin-1, Angarsk, Novy Urengoi, and Surgut.

Using selected examples, a comparison of LNG and FTGTL as two means for gas reserves monetization showed that they are broadly comparable from the technological and economical point of view.

Nevertheless, it should be recognized that FTGTL plants are large and complex (as illustrated in Figures 2,3,4 and 6) and in the case of Oryx and Pearl have been the subject of cost overruns in the construction phase. It remains to be seen whether, in a world where oil and natural gas prices remain de-linked, the experience of these and other projects will result in greater investor confidence in building significant new GTL capacity in the future.

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Glossary

1,2,4,5-tetrametilbenzol/benzene - is an organic compound with the formula $C_6H_2(CH_3)_4$. It is a colourless solid with a sweet odour. The compound is classified as an alkyl benzene. It is one of three isomers of tetramethylbenzene, the other two being prehnitene (1,2,3,4-tetramethylbenzene, m.p. $-6.2\text{ }^\circ\text{C}$) and isodurene (1,2,3,5-tetramethylbenzene, m.p. $-23.7\text{ }^\circ\text{C}$).

Aromatic hydrocarbon - An aromatic hydrocarbon is a hydrocarbon with alternating double and single bonds between carbon atoms forming rings. The term 'aromatic' was assigned before the physical mechanism determining aromaticity was discovered, and was derived from the fact that many of the compounds have a sweet scent. The configuration of six carbon atoms in aromatic compounds is known as a benzene ring.

b/d – barrels per day – a measure of (usually) liquid hydrocarbon flowrate. In the United States and Canada, an oil barrel is defined as 42 US gallons, which is equivalent to 158.987294928 litres or approximately 34.9723 imperial gallons.

Benzene - Benzene is an organic chemical compound with the molecular formula C_6H_6 . Its molecule is composed of 6 carbon atoms joined in a ring, with 1 hydrogen atom attached to each carbon atom.

billion cubic f/d - a measure of (usually) gaseous hydrocarbon flowrate – billion cubic feet per day.

Brown coal - often referred to as Lignite, is a soft brown fuel with characteristics that put it somewhere between coal and peat. It is considered the lowest rank of coal; it is mined in Bulgaria, Greece, Germany, Poland, Serbia, Russia, the United States, India, Australia and many other parts of Europe and normally used as a fuel for steam-electric power generation.

Diesel fraction – A product from the fractional distillation of crude oil between $200\text{ }^\circ\text{C}$ and $350\text{ }^\circ\text{C}$ at atmospheric pressure, resulting in a mixture of carbon chains that typically contains between 8 and 21 carbon atoms per molecule.

DPP, Discounted payback Period -This is the number of years taken to reach project payback on the basis of cashflows which have been discounted by the cost of investment capital.

DPI, Discounted Profitability Index -This is the ratio of the sum of discounted cashflow over the life of the project and the discounted negative cashflows during the project investment period.

Dodicet 5073 – An additive that enhances the flammability of diesel fuel and increases the cetane number.

Ethylene – (or ethene) is a hydrocarbon with the formula C_2H_4 or $H_2C=CH_2$. It is a colourless flammable gas with a faint "sweet and musky" odour when pure. It is the simplest alkene (a hydrocarbon with carbon-carbon double bonds), and the simplest unsaturated hydrocarbon after acetylene (C_2H_2).

FOB - FOB is an acronym for "free on board", meaning that the buyer pays for transportation of the goods. Specific terms of the agreement can vary widely, in particular which party (buyer or seller) pays for which shipment and loading costs, and/or where responsibility for the goods is transferred.

Henry Hub - The Henry Hub is a distribution hub on the natural gas pipeline system in Erath, Louisiana. Due to its importance, it lends its name to the pricing point for natural gas futures contracts traded on the New York Mercantile Exchange (NYMEX) and gas traded on the IntercontinentalExchange (ICE).

Hydrocracking - A hydrocracking unit, or hydrocracker, takes gas oil, which is heavier and has a higher boiling range than distillate fuel oil, and cracks the heavy molecules into distillate and gasoline in the presence of hydrogen and a catalyst. The hydrocracker upgrades low-quality heavy gas oils from the atmospheric or vacuum distillation tower, the fluid catalytic cracker, and the coking units into high-quality, clean-burning jet fuel, diesel, and gasoline.

Hydrogenation - Hydrogenation – to treat with hydrogen – is a chemical reaction between molecular hydrogen (H₂) and another compound or element, usually in the presence of a catalyst. The process is commonly employed to reduce or saturate organic compounds. Hydrogenation typically constitutes the addition of pairs of hydrogen atoms to a molecule, generally an alkene. Catalysts are required for the reaction to be usable; non-catalytic hydrogenation takes place only at very high temperatures. Hydrogenation reduces double and triple bonds in hydrocarbons

IRR% - Internal Rate of Return – is defined as the discount rate at which the discounted project cashflows sum to zero.

LNG - Liquefied natural gas - Liquefied natural gas or LNG is natural gas (predominantly methane, CH₄) that has been converted to liquid form for ease of storage or transport. The liquefaction process involves condensing natural gas into a liquid at close to atmospheric pressure by cooling it to approximately -162 °C.

LPG, Liquefied Petroleum Gas - Liquefied petroleum gas, also called LPG, GPL, LP Gas, liquid petroleum gas or simply propane or butane, is a flammable mixture of hydrocarbon gases used as a fuel in heating appliances and vehicles.

MMBTU – Million British Thermal Units. The British thermal unit (BTU or Btu) is a unit of energy equal to about 1055 joules. It is the amount of energy needed to cool or heat one pound of water by one degree Fahrenheit. In scientific contexts the BTU has largely been replaced by the SI unit of energy, the joule.

Naphtha - Petroleum naphtha is an intermediate hydrocarbon liquid stream derived from the refining of crude oil. It is most usually desulphurized and then catalytically reformed, which re-arranges or re-structures the hydrocarbon molecules in the naphtha as well as breaking some of the molecules into smaller molecules to produce a high-octane component of gasoline (or petrol).

Naphthenic hydrocarbon - A type of organic compound of carbon and hydrogen that contains one or more saturated cyclic (ring) structures, or contains such structures as a major portion of the molecule. The general formula is C_nH_{2n}. Naphthenic compounds are sometimes called naphthenes, cycloparaffins or hydrogenated benzenes.

NBP - the UK National Balancing Point, commonly referred to as the NBP, is a virtual trading location for the sale and purchase and exchange of UK natural gas. It is the pricing and delivery point for the ICE (IntercontinentalExchange) natural gas futures contract. It is the most liquid gas trading point in Europe and is a major influence on the price that domestic consumers pay for their gas at home.

NPV – The sum of discounted cashflows over the life of a project.

OPEC - is the Organization of the Petroleum Exporting Countries. It is an oil cartel whose mission is to coordinate the policies of the oil-producing countries. The goal is to secure a steady income for the member states and to secure oil supplies to consumers.

OSBL - Outside Battery Limits

Paraffin - Paraffin wax is a white or colourless soft solid that is used as a lubricant and for other applications. Paraffin may also refer to: Alkane, a saturated hydrocarbon; Kerosene, a fuel that is also known as paraffin and any of various colourless, odourless, light mixtures of alkanes in the C15 to C40 range from a non-vegetable (mineral) source, particularly a distillate of petroleum.

Pyrolysis - Pyrolysis is a thermochemical decomposition of organic material at elevated temperatures in the absence of oxygen (or any halogen). It involves the simultaneous change of chemical composition and physical phase, and is irreversible.

Syngas - Syngas, or synthesis gas, is a fuel gas mixture consisting primarily of hydrogen, carbon monoxide, and very often some carbon dioxide. Syngas is also used as an intermediate fuel in producing synthetic petroleum for use as a fuel or lubricant via the Fischer–Tropsch process and previously the Mobil methanol to gasoline process. Syngas has less than half the energy density of natural gas.

Unsaturated hydrocarbons - Unsaturated hydrocarbons are hydrocarbons that have double or triple covalent bonds between adjacent carbon atoms. Those with at least one carbon to carbon double bond are called alkenes and those with at least one carbon to carbon triple bond are called alkynes. The physical properties of unsaturated hydrocarbons are very similar to those of the corresponding saturated compounds. They are slightly soluble in water.

Water of synthesis – Water produced as one of the products of a chemical reaction.