The Greenhouse Gas Impact of Gas to Liquids (GTL)

An Industry Perspective

California Air Resources Board (CARB) Submission

November 2008

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1 Executive Summary

This chapter provides an executive summary of the GHG impact of GTL.

In order to achieve a reduction of at least 10 percent in the carbon intensity of California's transportation fuels by 2020, a diversity of alternative fuels will be required. Fair and comprehensive GHG emissions accounting methodologies are imperative to ensure all fuel pathways receive equitable treatment.

In this submission, Sasol Chevron has demonstrated how comprehensive accounting of GTL co-products can lead to a dramatically different GHG emissions life cycle analysis result compared to using the allocation methodology. It needs to be noted that this submission does not address the refinery diesel baseline currently used by CARB, which is also calculated using the allocation method.

This submission is forward-looking and models the likely GHG situation for the GTL industry in 2010 and 2020. A representative GTL plant for both periods was modeled taking an average GTL slate and supplying local base load demand for transportation fuel. The functional unit used in this study is 1 mile of travel in a mid-sized passenger car that uses a compression-ignition direct injection engine (CIDI) in California using GTL diesel.

Based on the set of assumptions outlined in this submission, when the GHG benefits of all GTL co-products are accounted in a comprehensive fashion, the carbon footprint of GTL diesel was estimated to be approximately 336 g CO_2e/mile in 2010 and 291 g CO_2e/mile in 2020, respectively. This represents a profound difference to results obtained for GTL using allocation methodology (454 g CO_2e/mile);

- A 15 % (2010) and 26 % (2020) decrease when compared to conventional diesel using allocation methodology (**Figure 1-1**).
- A 25 % (2010) and 35 % (2020) decrease when compared to GTL diesel using allocation methodology (**Figure 1-2**).
- These differences are due to the full consideration of the benefits of GTL co-products using the substitution method, in particular, GTL lubricant base oils (**Figure 1-3**).

Accounting fully for the co-production of GTL lubricant base oil is particularly important to this result;

- GTL lubricant base oil is a higher quality product than its refinery produced counterpart and its use to produce GTL lubricant oil has significant downstream benefits (carbon savings) that would otherwise be unaccounted for if applying the allocation method.
- In particular, GTL lubricant oil confers fuel efficiency savings in motor vehicles and allows an extended oil drainage interval when compared to refinery lubricant oil.

The results presented here are significant on two counts:

- Firstly, Sasol Chevron believes that a more comprehensive and fair accounting of GTL co-products are required. The full GHG benefits of GTL co-products are not captured using allocation methodology and therefore Sasol Chevron continues to favor the use of full substitution/system boundary expansion methodology for life cycle analysis leading to policy decisions.
- Secondly, this study highlights the potential for California regulators to achieve significant reductions in CO_2 emissions at the state level by encouraging the use of higher quality GTL lubricant oils over traditional lubricant oils.

GTL is an emerging industry and technology. An incomplete or incorrect Life-Cycle Assessment (LCA) has the potential to negatively impact the industry in a significant manner as it continues to develop. It is important that the Low Carbon Fuel Standard (LCFS) does not penalize emerging technologies, such as GTL, that are in the relatively early years of development.

Sasol Chevron recommends CARB develops a unique fuel pathway for GTL diesel; one that correctly accounts for, and gives full credit to, all GTL co-products in both a fair and comprehensive manner. Failure to do so would result in an incorrect assessment of the GHG impact of GTL diesel, which would unfairly damage an emerging industry.

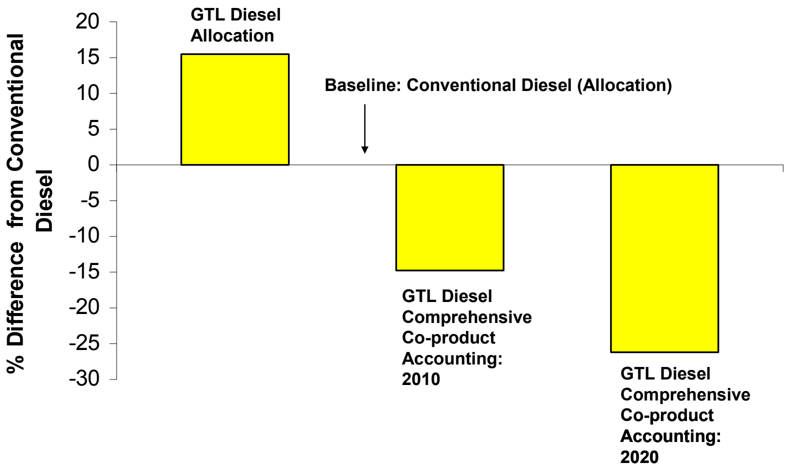

Figure 1-1: Percentage difference in GHG footprint of GTL diesel when the benefits of all GTL co-products are accounted for. Conventional diesel (allocation methodology) is used as a baseline.

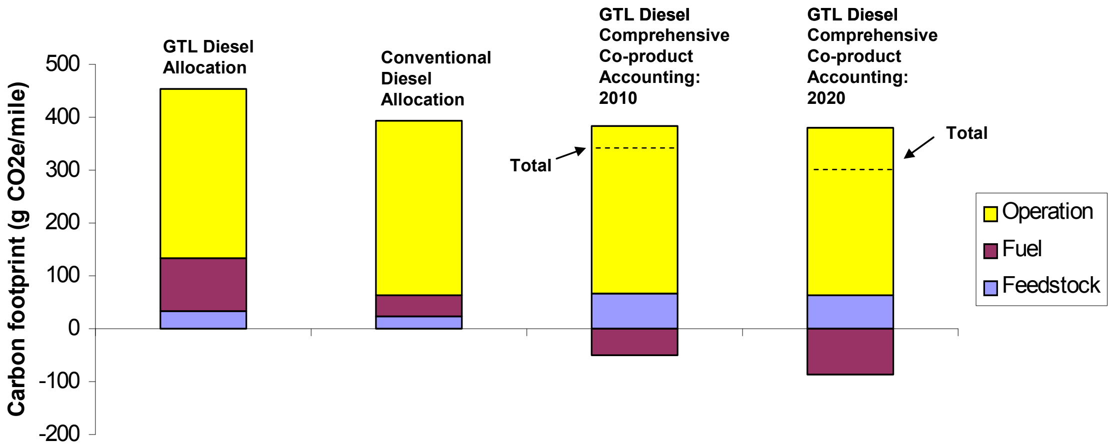

Figure 1-2: Comparison of the carbon footprint of GTL diesel when all GTL co-products are comprehensively accounted for with allocation results for GTL and conventional diesel. “Feedstock” refers to extraction and processing of the feedstock from the ground. “Fuel” refers to diesel production in the refinery. “Operation” refers to combustion of the fuel at the tailpipe of the motor vehicle.

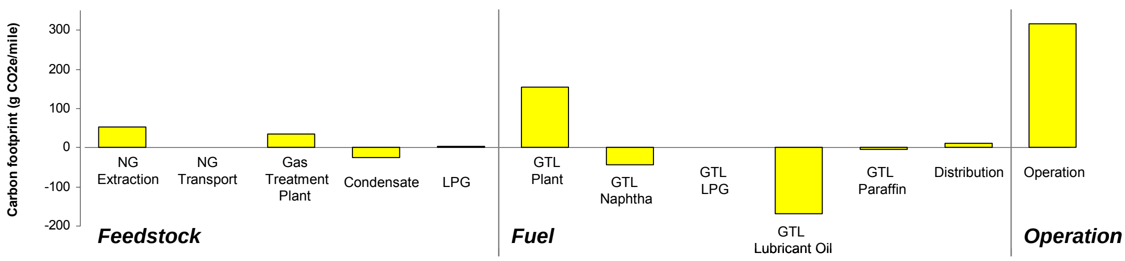

Figure 1-3: WtW treatment of GTL diesel using comprehensive co-product accounting (2010 scenario).

2 Goal and Scope of the Submission

This chapter provides information about the goal and scope of this submission.

2.1 Introduction

At the California Air Resources Board (CARB) meeting of 20 December 2007, Sasol Chevron reported that the best way to perform a life cycle analysis (LCA) for alternative fuels is to apply the substitution/system boundary expansion methodology, which is consistent with the ISO 14044 standard. This message was supported by several other meeting participants. Sasol Chevron also provided copies of past LCA work on GTL diesel, both the reports prepared by PricewaterhouseCoopers for Sasol Chevron (in 2002 and 2006) and the industry synthesis performed by Five Winds, a consultant (in 2004).

In subsequent meetings in 2008, the subject of methodology was explored further and CARB expressed interest in a better understanding of GTL co-products and their impact on the LCA analysis for GTL diesel. To support this, in November 2008, Sasol Chevron compiled this submission for CARB on the GHG impact of gas-to-liquids (GTL) to aid the impending California Low Carbon Fuel Standard (LCFS).[1]

This submission includes a discussion about the GHG benefits of GTL co-products. References to 3rd party, NGO and OEM reports are cited here-in where possible. A review of the GREET 1.8b[2] GTL data is also provided (Appendix I).

The main purpose of this submission is to;

- Demonstrate how GTL co-products carry a significant GHG benefit relative to their conventional analogues.
- Demonstrate how within the GTL context, allocation methodology fails to properly account for cases where (a) GTL co-products carry a downstream benefit (e.g. GTL lubricant oils) or (b) GTL co-products are higher quality than conventional analogues (e.g. GTL naphtha vs. oil-derived naphtha).
- Recommend that CARB take full account of GTL co-products in the LCFS GTL pathway to fully capture all the GHG benefits of GTL.
- Provide all the necessary assumptions and data and information for CARB to make a more comprehensive assessment of the GTL GHG pathway. This submission does not address the quality of the refinery diesel baseline.
- Remind CARB that GTL is very strong on two other important drivers for the state of California: 1) GTL produces less criteria pollutants relative to conventional diesel; 2) GTL is derived from natural gas which is a very strong energy alternative/complement to conventional crude oil based transportation fuels.

2.2 Context of the Submission

State of California Executive Order S-01-07, which was issued on January 18, 2007 calls for a reduction of at least 10 percent in the carbon intensity of California's transportation fuels by 2020.[3] The California Air Resources Board was asked to establish and implement the Low Carbon Fuel Standard (LCFS).[4,5]

In this context, life cycle energy use and greenhouse gases of available transportation fuel pathways (so called Well-to-Wheel or WtW) are being collected and analyzed to develop the LCFS.[6,7] It is intended that this document be used by CARB to develop the GTL pathway.

2.3 Reasons for Carrying out This Submission

The methodology to account for life-cycle emissions and in particular to account for co-products is subject to debate.[8] There are two approaches to account for co-products: the allocation rules approach and the system boundary expansion also known as the substitution approach (whereby the impacts associated with alternatives routes to produce those co-products are subtracted). Life-cycle models evaluating emissions from transportation fuels using the allocation or substitution approach can provide markedly different results.[9]

The ISO 14044 2006 standard[10] which defines requirements and guidelines to conduct Life Cycle Assessment studies strongly recommends the use of the system boundary expansion rather than the allocation approach.[11] Sasol Chevron,[12,13] Shell[14] and ConocoPhillips[15] have already published Life-Cycle Assessment (LCA) studies of GTL using the systems boundary expansion methodology as it allows accounting for all GTL products and all oil-refinery products. These studies have shown that the GHG emissions of GTL diesel are comparable to conventional diesel,[16] although the full GHG benefits of all GTL all co-products, such as lubricant oils, were not considered because of a lack of supporting information at the time of publication.

The full GHG benefits of GTL diesel are currently not fully represented using the allocation approach, since the full GHG benefits of GTL co-products, such as base oils and normal paraffin, are not accounted for adequately.

Sasol Chevron will present in this submission data that supports GHG benefits of GTL co-products relative to their conventional analogues. Sasol Chevron believes that a more comprehensive and fair accounting of GTL co-products are required.

The full GHG impacts of conventional diesel production are also not fully represented using the allocation approach, since the refinery co-products are not adequately accounted for. However, this submission does not attempt to correct the refinery baseline.

2.4 GTL Feedstock and Products

The GTL process is an umbrella term for a group of technologies that convert natural gas into high quality liquid products. The process is based on Fischer-Tropsch (FT) technology which has underpinned Sasol’s fuel production in South Africa for over fifty years. A simplified schematic of the three-step GTL process is shown in **Figure 2-1**.

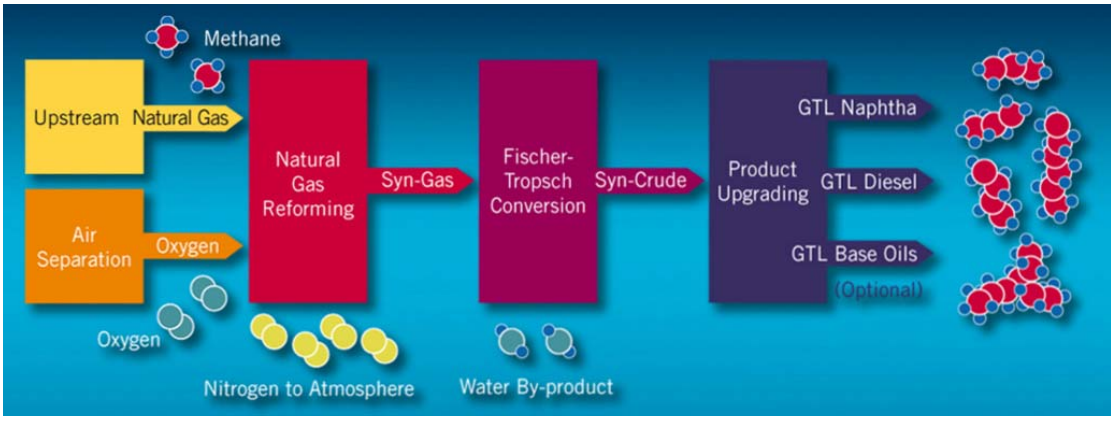

Figure 2-1: GTL process overview

Once natural gas is extracted[17] from the ground and liquids and impurities are removed from it, the GTL conversion process that follows consists of three main steps:

1. Natural gas reforming: converts lean natural gas (largely methane) mixed together with oxygen into synthesis gas, also known as syngas (a mixture of hydrogen and carbon monoxide).
2. FT conversion: converts synthesis gas into a broad-range hydrocarbon stream, also called synthetic crude. This conversion step is the heart of the GTL process.
3. Product upgrading: upgrades synthetic crude into high quality synthetic products, such as GTL diesel, naphtha, lubricant base oils and normal paraffin.

All products from the GTL process are paraffinic and have an ultra low sulfur and aromatic content, and in many cases give rise to a GHG benefit relative to their conventional refinery analogues. Details of these benefits are provided herein. For a more detailed discussion of GTL products, see Appendices A-E.

2.5 Today's GTL Industry

In 2006, with the inauguration of Oryx GTL in Qatar,[18] the GTL industry achieved a major milestone and placed itself firmly on the list of commercial gas monetization options available to countries with large natural gas reserves.

With construction of the Chevron Nigeria and Nigerian National Petroleum Corporation plant at Escravos[19] and Shell's Pearl[20] GTL project in Qatar underway, the GTL industry now includes some of the biggest energy companies on the planet with production facilities completed or under construction on two continents.

Although numerous GTL pilot/demonstration plants have recently been built,[21] the GTL industry[22] faces near-term challenges, including overloading of the construction industry which impacts project cost and schedule, and competition from pipeline gas/LNG.

As a result, in order to maximize profit and ensure project bankability, inclusion of GTL lubricant base oil, normal paraffin and jet fuel into the GTL product slate are likely to be integrated into future GTL projects where possible[23] as an economic necessity to add value to the GTL process. These realities are built into the assumptions and scenarios below.

2.6 Key Definitions, Assumptions and Scenarios

Definitions;

Definition of GTL: Within the context of this submission, we define GTL as a process which converts natural gas into longer-chain hydrocarbons *via* Low-Temperature Fischer-Tropsch[24] (LTFT) to produce GTL diesel fuel and GTL co-products destined for the California market.

Thus, within the scope of this submission, GTL that utilizes High-Temperature Fischer-Tropsch (HTFT) are not considered.[25] Non-natural gas[26] feedstock's such as coal[27,28] and biomass[29] are not considered. GTL products from pilot/test facilities are not considered. Conversion of syngas to methanol, which can be used to produce gasoline (methanol-to-gasoline, MTG process)[30] is not considered as GTL.

GTL Co-product: (Taken from CARB definition[31]): The pathway from feedstock to final fuel production and use involves several processes and operations. These processes have the potential to generate products besides the primary fuel of interest. These additional products are termed co-products.

By-product: Is a product without economic value produced along with main product.

WtW treatment of GTL: From a LCA perspective, Sasol Chevron includes the WtW treatment of GTL across the entire cradle-to-grave carbon value chain. On this basis, upstream gas extraction and processing, GTL production of diesel and co-products and tailpipe combustion of GTL diesel are all within the GTL WtW system boundary (**Figure 2-2**).

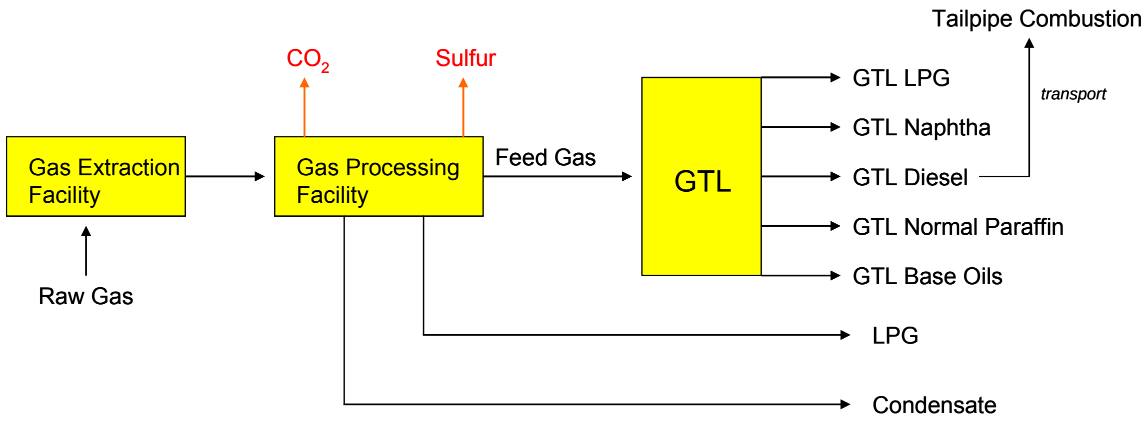

Figure 2-2: WtW treatment of GTL.[32]

Assumptions;

GTL Jet fuel is not considered in this study: Technically speaking, another potential extension of the product slate produced by a GTL plant could include a synthetically produced jet (aviation) fuel.

Currently, the only fully synthetic jet that has been fully certified for aviation use under the applicable DefStan regulations is Sasol product from South Africa.[33] This stream is based on a *high temperature* Fischer Tropsch process which by its nature will be able to meet the aromatics requirements for a fully synthetic jet fuel.

In order to include synthetic streams from (future) *low temperature* Fischer Tropsch production sites, consistency with the jet fuels normally found in the marketplace would need to be satisfied by appropriate blending with other products or components, and more work needs to be done to secure the necessary approvals for certification.

In view of the higher energy content of GTL jet fuel compared to conventional product (on weight basis), this option may be attractive from an efficiency and GHG emission reduction perspective. In addition, and as is the case with other GTL products, due to the purity and high paraffin content the use of GTL jet fuel very likely results in lower pollutant emissions during combustion compared to conventional, petroleum-derived, jet fuel. Despite this, insufficient data is available at this current time to support these assumptions.

Site specific scenarios, such as electricity and steam export are not considered in this study: In principle, if the appropriate neighbouring infrastructure exists, a GTL plant can be designed to export excess steam or electricity.[34] This scenario is likely to afford a GHG benefit relative to a GTL facility without steam or electricity export.[35] Despite this, no current GTL facility possesses this option, and future GTL plants that contain steam/electricity export are likely to be highly dependant on location and site synergies.

Scenarios;

- For this submission, we are presenting an industry view of GTL in 2010 and 2020.
- The representative GTL plants[36] are a sum of the total projected world GTL output in 2010 and 2020.
- The representative GTL plants are located in Qatar,[37] Middle East.
- GTL plant energy efficiencies[38] are 63.5 % and 65.5 % for 2010 and 2020 respectively. When upstream gas processing is included, overall GTL plant energy efficiencies are 67.6 % and 68.5 % for 2010 and 2020 respectively.
- GTL plant carbon efficiencies[39] are 79.1 % and 81.7 % 2010 and 2020, respectively. When upstream gas processing is included, overall GTL plant carbon efficiencies are 81.8 % and 83.0 % for 2010 and 2020, respectively.
- Upstream gas processing separates LPG, condensate, CO_2[40] and sulfur, while the representative GTL plants each produce LPG, naphtha, diesel, normal paraffin and lubricant base oils (**Figure 2-3** and **2-4**). GTL diesel is transported to California,[41] where it is combusted in vehicles.

Refinery Baseline: In this submission, the GHG emissions of refinery based fuels (gasoline and diesel) are not addressed, and comparisons between the GHG emissions of GTL and a refinery baseline are done so for illustrative purposes only.

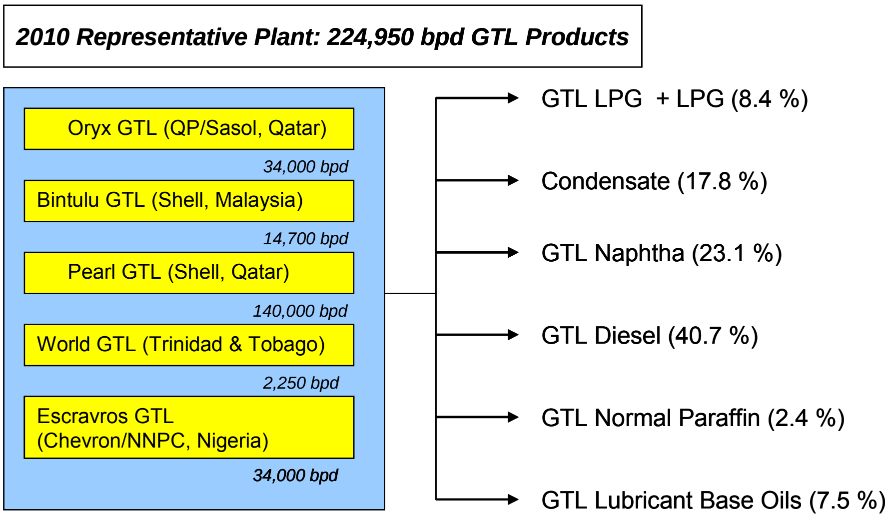

Figure 2-3: Product volumes and shares from the 2010 representative GTL plant.[42]

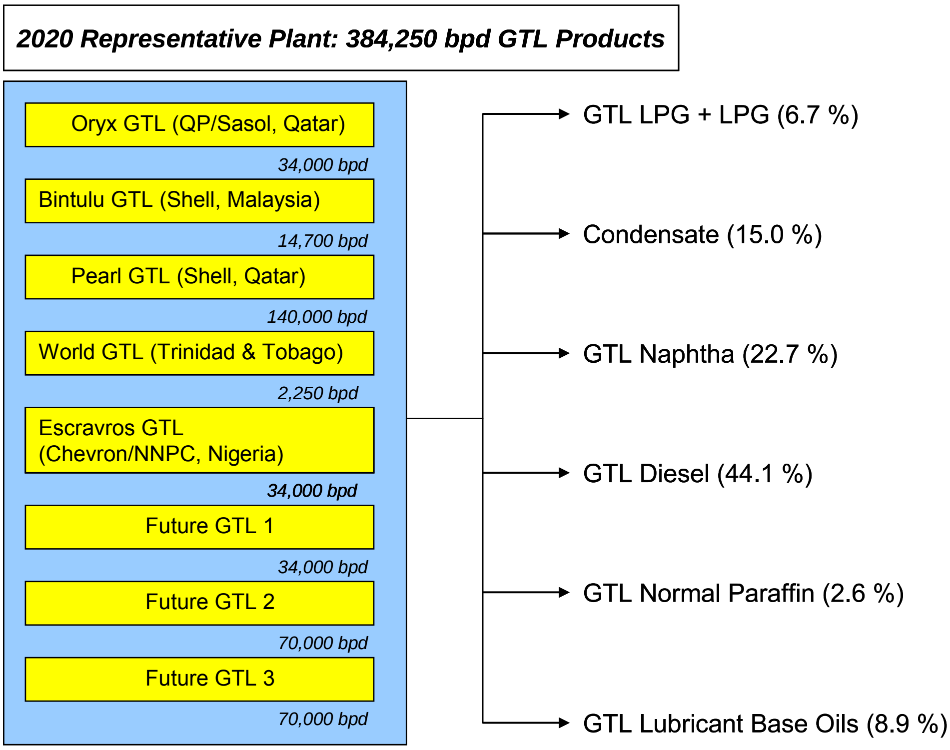

Figure 2-4: Product volumes and shares from the 2020 representative GTL plant.[43]

3 GHG Benefits of GTL Co-Products

This chapter provides information about the GHG benefits of GTL co-products.

3.1 GTL Co-products and the ISO 14040 Standard

Some processes in a fuel lifecycle, such as GTL, produce economically useful co-products in addition to the fuel. Emissions from such a process are distributed over the product and co-products in an LCA. How this allocation is performed can significantly influence the carbon footprint of the product.

The ISO 14040 Series[44,45] is an internationally recognized standard on Life Cycle Assessment, and provides guidance on how to allocate emissions;

Options Listed in ISO Order of Preference;

Option 1 – Increase granularity to avoid allocation

- Subdivide the fuel lifecycle process into sub-processes not requiring allocation

Option 2 – Use substitution to avoid allocation

- Expand the system boundary of the fuel to include co-product function

→ Use of *System boundary expansion & substitution/displacement/co-product credits*[46]

Option 3 – Allocate using physical criteria

- Allocate the inputs and outputs of the system to the product and co-product(s) in a way which reflects the underlying physical relationships between them.

Option 4 – If physical criteria not feasible then allocate using alternative criteria

- Allocate inputs and outputs to the product and co-product(s) in a way which reflect other relationships between them.

Within the GTL context, allocation methodology fails to properly account for cases where (a) GTL co-products carry a downstream benefit (e.g. GTL lubricant oils) or (b) GTL co-products are higher quality than conventional analogues (e.g. GTL naphtha *vs*. oil-derived naphtha). Sasol Chevron believes that a more comprehensive and fair accounting of GTL co-products are required. The full GHG benefits of GTL co-products are not captured using allocation methodology.

On this basis, assigning a GTL co-product credit is better at measuring the net GHG impact of GTL, and has more scientific basis than pure allocation (mass/energy).[47]

The remainder of this chapter highlights the key GHG benefits of GTL co-products.[48] The carbon balances between GTL co-products and their conventional analogues are detailed in Chapter 4.

3.2 LPG and Condensate

By definition, Well-to-Wheels analysis of GTL requires analysis of carbon products from the Gas Treatment Plant (GTP), which conditions the feed gas to meet the specifications of the downstream GTL plant (**Figure 3-1**).

Importantly, the GTP separates LPG and condensate from the methane-rich feed gas to the GTL plant at efficiencies (> 90 %) that are higher than for GTL (63 - 65 %) alone. The net effect is an increase in the overall efficiency of the entire WtW system. Further detailed information about upstream gas extraction and purification can be found in Appendix B.

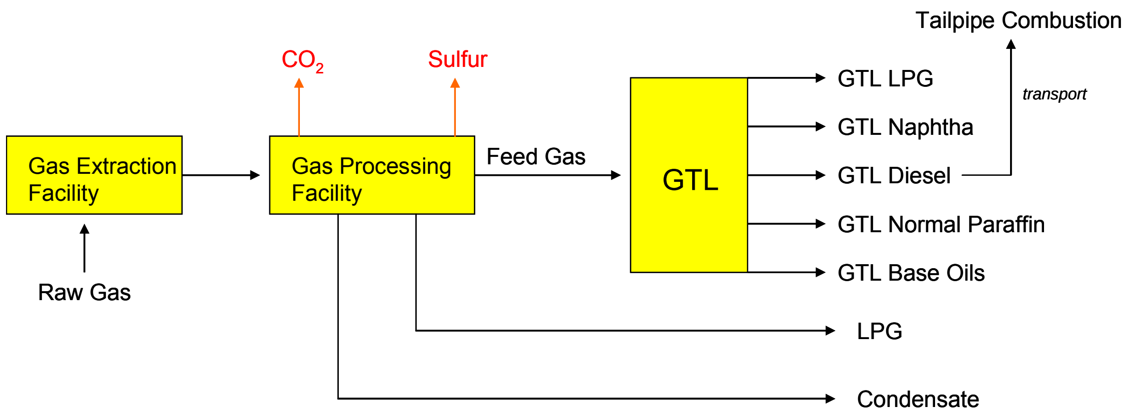

Figure 3-1: Integrated View of GTL, including gas treatment and condensate and LPG removal.

3.3 GTL Naphtha

GTL naphtha is not suitable for gasoline blending,[49] but rather is an ideal liquid feedstock for ethylene production *via* steam cracking. GTL naphtha affords the following benefits when compared to refinery naphtha:

- Cracking GTL naphtha has a higher olefin yield than cracking conventional naphtha.
- Cracking GTL naphtha is substantially more selective to the production of ethylene, propylene and butadiene.
- Because of an ultra low aromatic content, cracking of GTL naphtha results in reduced coking of furnace tubes and catalyst, thus allowing extended run duration.

Thus, from a GHG perspective, when GTL naphtha is cracked, less energy (CO_2 equivalents) is consumed to produce ethylene when compared to conventional naphtha. Further detailed information about these benefits can be found in Appendix C.

3.4 GTL Normal Paraffin

A GTL facility can be designed to separate normal paraffin which can replace conventional normal paraffin extraction from kerosene as a means for producing linear alkyl benzene (LAB) or linear alkyl benzene sulfonate (LAS) for detergent manufacture.

Normal paraffin separation from kerosene (to produce the LAB Feed) *via* the conventional separation technology[50] requires prefractionation, hydrotreating and separation and consumes a significant amount of energy. This process also produces a significant raffinate stream, which consists of *iso*-paraffins and cyclic hydrocarbons, which is typically returned to the refiner for blending into jet fuel.

In contrast, the GTL normal paraffin product stream requires minimal purification, and can be fed directly into the dehydrogenation unit, to produce olefins, the required feed stream for the alkylation[51] step with benzene (**Figure 3-2**).[52]

Thus, from a GHG perspective, production of LAB from GTL normal paraffin requires less steam, natural gas and electricity than conventional technology. Further detailed information about these benefits can be found in Appendix D.

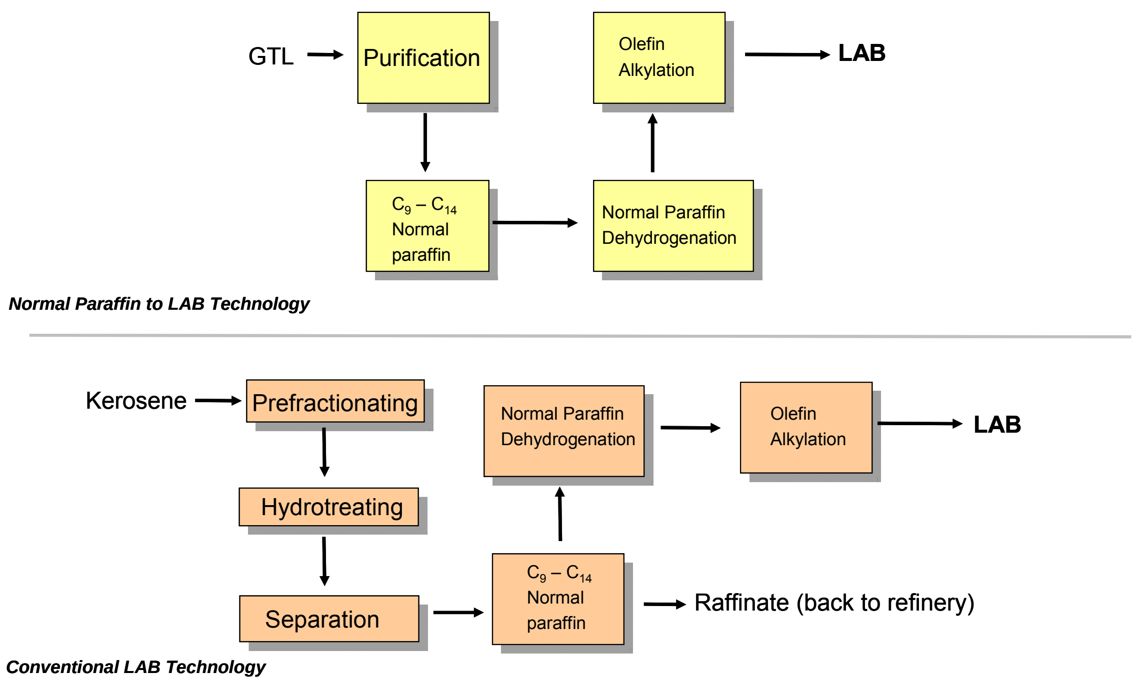

Figure 3-2: Comparison of normal paraffin production routes to produce LAB.

3.5 GTL Lubricant Base Oils

GTL lubricant base oils are produced by conventional hydroprocessing technology providing significant quality benefits, matching in many areas those of the more energy-intensive chemically-derived synthetic lubricant base oils (i.e. polyalphaolefins or PAO's). Lubricant base oils are the main component of lubricating oils, making up around 85 % by volume of the end product.

In the automotive industry there is a continued drive for improved energy efficiency, longer lubricant life, improved engine durability and higher levels of catalyst protection for emissions systems. Design changes that improve performance inherently put more stress on lubricants, requiring higher quality.

GTL lubricant base oils are high quality lubricant base oils that provide two significant benefits:

- Improved fuel efficiency for the vehicle. According to the GF-5 standard[154] to be introduced for passenger car applications, high performance fuel efficient SAE 0W and 5W oils will be required to provide fuel efficiency benefits in the region of 0.5 – 1.2 %.[53] Currently, the lack of suitable lubricant base oils is restricting widespread implementation; GTL will provide a solution for this.

- Extended oil drain intervals (up to 15000 miles or double that of Group II lubricants) for the oil, increasing the miles driven per quart of oil.

Both of these advantages provide GHG emissions reductions when compared to refinery produced lubricant base oils.[54] Further detailed information about these benefits can be found in Appendix E.

4 Carbon Footprint of GTL Diesel

This chapter presents the results and underlying assumptions of comprehensive accounting of GTL co-products.

4.1 Introduction

Sasol Chevron believes that how the life-cycle impacts of GTL co-products are accounted for has a profound impact on the carbon footprint of GTL diesel.

Sasol Chevron also believes that allocation methodology is not sufficient to capture all the GHG benefits of GTL diesel.

Thus, a study was undertaken according to the ISO 14040 and 14044 standards to determine the carbon footprint of GTL diesel. Because GTL co-products are higher quality than their conventional analogues, a different methodology other than allocation had to be used. Thus, in the current study substitution methodology was employed.

In this study, data was collected from previous peer reviewed LCA studies of GTL diesel commissioned by Sasol Chevron and from literature. In this regard, the purpose of this study was to be a modeling exercise which drew upon GTL plant projected yields and CO_2 emissions for 2010 and 2020. Published estimates of GHG emissions or energy consumption for a range of processes and the corresponding carbon conversion factors were used for all the life cycle steps of GTL diesel and its co-products.[55,56]

This section presents the estimated carbon footprint of GTL diesel using the substitution approach. The results are compared to GHG emissions values for conventional diesel and GTL diesel as available in the current model used by CARB (GREET 1.8b) which is based on an allocation method. A full summary of the key assumptions used within this study are provided in Section 2.6 and in the Appendices.

4.2 System Boundaries

Figure 4-1 provides an overview of the system boundaries considered in this study.

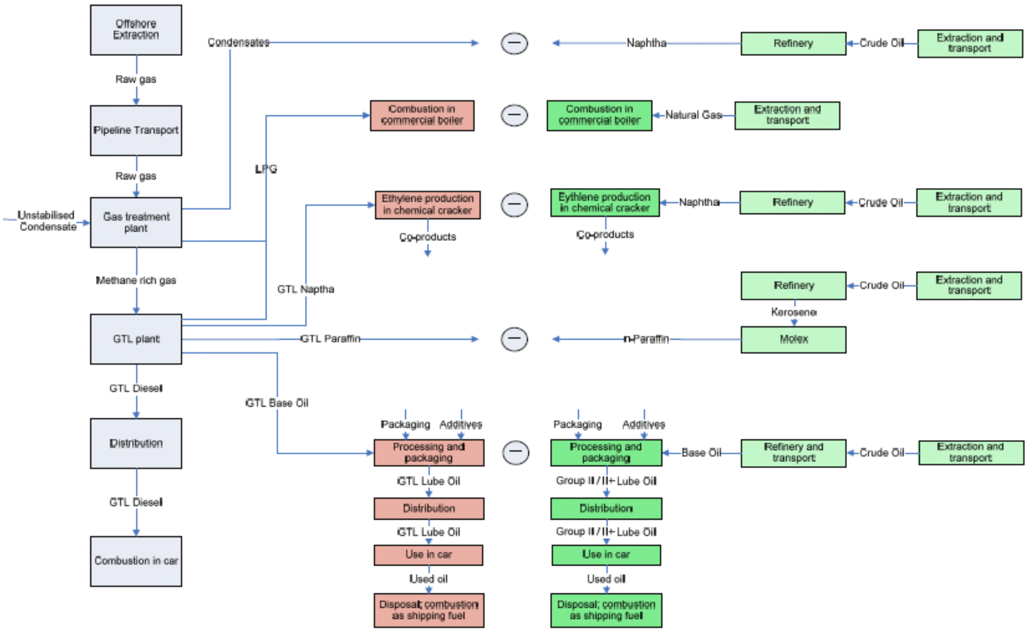

Figure 4-1: System boundaries considered in this study.

4.3 Results

1. If the full GHG benefits of GTL co-products are considered, GHG emissions of GTL are lower than conventional diesel.

Figure 4-2 shows the GHG emissions calculated in this study for the 2010 GTL scenario where GTL co-products are comprehensively accounted for (substitution methodology) compared to results obtained using allocation methodology (GREET 1.8b). These results show that GTL diesel GHG emissions are 15 % *higher* than conventional diesel using allocation, but are 15 % *lower* using more comprehensive GHG co-product accounting for GTL (current study).

The reason for the difference in these results is because allocation methodology does not capture, or give full credit to, the impacts associated with GTL co-products.

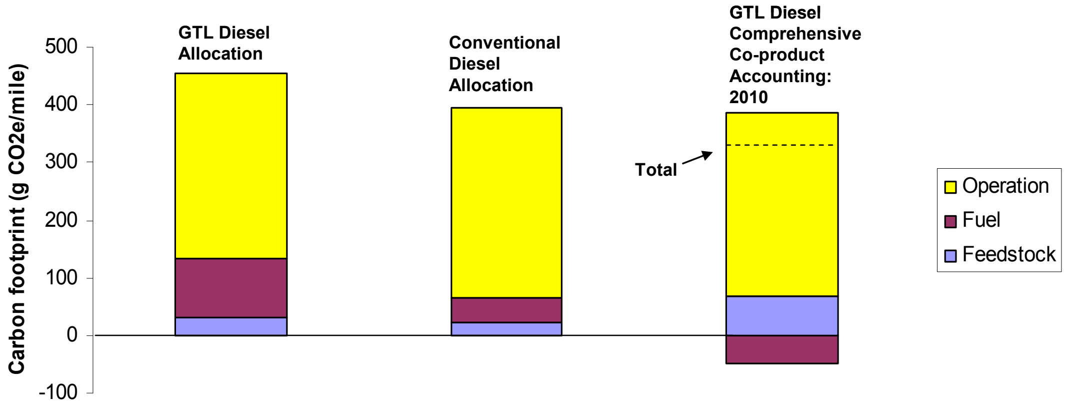

Figure 4-2: GHG emissions calculated in this study using a substitution approach for the 2010 base case GTL scenario compared to results obtained using allocation methodology.

2. GHG emissions of GTL diesel are reduced under the 2020 scenario.

Figure 4-3 shows the GHG emissions calculated in this study for the 2020 GTL scenario where GTL co-products are comprehensively accounted for compared to results obtained using allocation methodology.

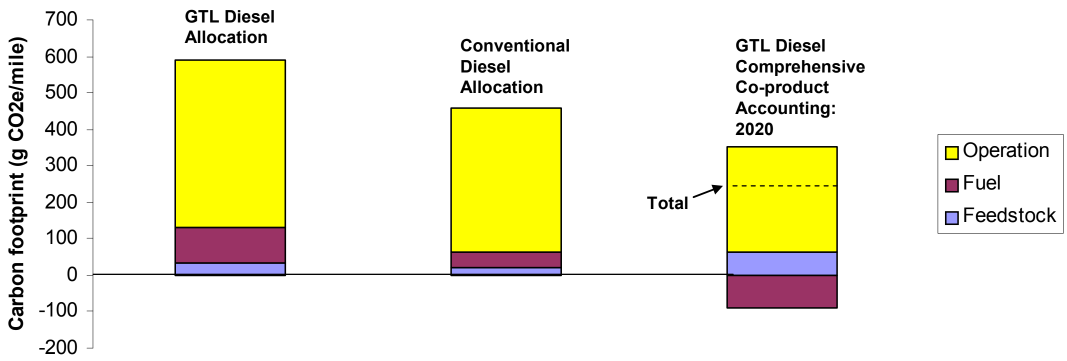

Figure 4-3: GHG emissions calculated in this study using a substitution approach for the 2020 base case GTL scenario compared to results obtained using allocation methodology.

Under the 2020 scenario, the GHG emissions of GTL diesel using comprehensive GTL co-product accounting are 26 % lower than conventional diesel (allocation method). This is due to the larger share of GTL lubricant oils produced by 2020 (5300 tonnes per day in 2020 – almost 9 % of GTL plants products against 2800 tonnes in 2010 which represents 7.5 % of GTL plants products). In addition, carbon and energy efficiencies in the GTL plant are expected to be higher in 2020 than in 2010.

3. The most significant benefits are associated with the use of GTL lubricant oils, which afford greater fuel economy than refinery lubricant oils.

Figure 4-4 shows the breakdown of the feedstock and fuel phases for the 2010 base case scenario.

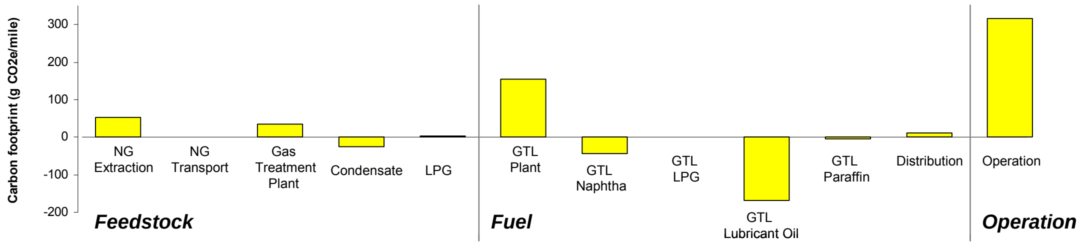

Figure 4-4: Feedstock and fuel phases for the 2010 base case scenario.

These results suggest that significant GHG savings are generated with GTL lubricant oils, assuming that GTL lubricant oils will generally replace poorer quality lubricant oils and allow greater fuel economy during the use of the lubricant oils in cars. The key assumptions considered in this submission are;

- 0.85 % fuel economy saving for GTL lubricant oils compared to Group II/II+ lubricant oils.
- 7500 mile drain interval for GTL lubricant oils compared to 5000 mile drain interval for Group II/II+ lubricant oils.

These key assumptions are supported by OEM studies (as detailed in Appendix E).

The potential for fuel efficiency gains would be even greater in developing countries where GTL lubricant oil would displace even lower-quality lubricant oils. For example, if a GTL lubricant oil were to replace a Group I lubricant base oil (currently used in significant quantity in China), then the fuel efficiency gains could be as much as 5 %.

Given the important contribution of GTL lubricant oils to the overall results, a number of sensitivity analyses were run on the following parameters:

- The percentage of fuel economy saving between GTL lubricant oils and Group II/II+ lubricant oils (FES in %).
- The drain intervals for GTL lubricant oils (GTL-DI in miles) and Group II/II+ lubricant oils (BC-DI in miles).

Figure 4-5 shows a summary of these sensitivity analyses.

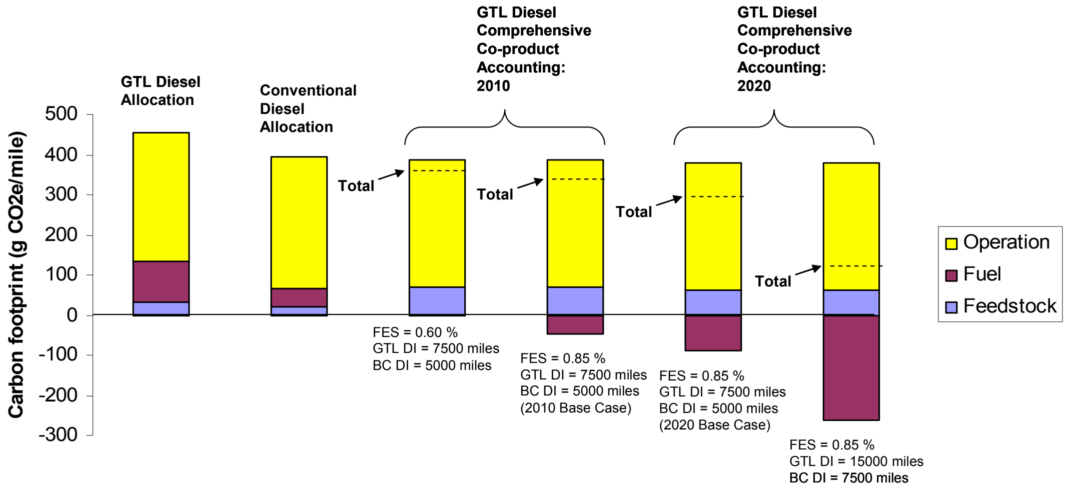

Figure 4-5: Summary of lubricant oil sensitivity analyses performed in the current study. FES = fuel economy savings, GTL DI = Gas to Liquids drain interval, BC DI = base case drain interval.

These analyses show that even with a fuel economy saving of 0.60 %, the carbon footprint of GTL diesel is lower than conventional diesel (allocation methodology) and that with a fuel economy of 0.85 %, a significant improvement is obtained should motorist change their oil replacement habits.

Interestingly, under the 2020 scenario;

- If consumers used GTL lubricant oil to its full potential and changed their GTL lubricant oil at a drainage interval of only 15,000 miles instead of 7,500 miles with ordinary lubricant oils, the carbon footprint of GTL diesel could be as little as 115 g CO_2e/mile in 2020, representing a 71 % decrease in the allocation estimations of conventional diesel.
- These results suggest that GTL lubricant oils have the capacity to help California to lower its overall carbon footprint.

Assuming a 0.85 % fuel economy saving for GTL lubricant oils compared to Group II/II+ lubricant oils and a 7500 mile drain interval for GTL lubricant oils compared to 5000 mile drain interval for Group II/II+ lubricant oils, then 1.185 tonne CO_2e can be saved per barrel of GTL lube oil used in California. If 10 million U.S. gallons of GTL lubricant oils are used in California in 2020, this would result in a saving of 282,095 tonne CO_2e per year.[57]

5 Other GHG Benefits of GTL

This chapter provides information about the benefits GTL diesel can bring for enhancing local and regional air quality and benefits for refiners for using GTL diesel as a blend stock.

5.1 Criteria Pollutants

GTL diesel is positioned as a clean, premium product or as a blend stock to enhance the quality of conventional diesels.[58] The high cetane number and very low levels of sulfur and aromatics ensure a more efficient and cleaner-burning combustion environment.[59] This leads to a substantial reduction in engine wear and exhaust emissions.[60]

GTL diesel can provide significant reductions in tailpipe emissions (particulate matter,[61] nitrogen oxides,[62] carbon monoxide[63] and hydrocarbons[64]), contributing to improvements in local air quality.[65] Whereas the application of successive emission standards applies to new vehicles only, the introduction of GTL diesel will have an immediate positive impact on the local emissions from the existing vehicle fleet,[66] particularly where older vehicles are in operation.[67] This can all be achieved without the need for expensive modifications to refuelling infrastructure and engines, making GTL diesel a cost-effective option for reducing pollutant emissions in urban areas (**Figure 5-1**).[68]

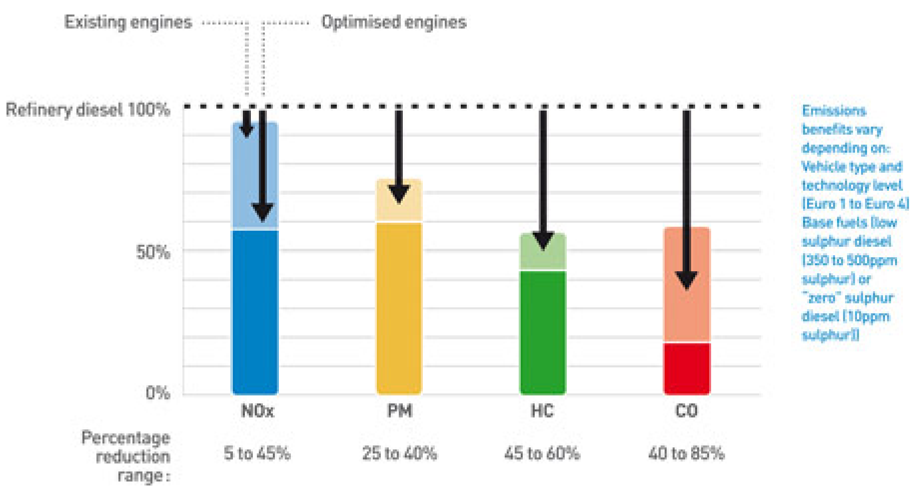

Figure 5-1: Summary of exhaust emission ranges in light duty vehicles from neat synthetic fuels (GTL diesel).[69]

Interestingly, studies to assess the emissions reduction from a diesel engine when using GTL diesel, as well as different blends of GTL diesel showed that impact of GTL blend concentration is non-linear, giving greater emissions benefits than expected at low concentrations of GTL diesel (**Figure 5-2**).[70] Tests have shown that a blend of GTL diesel provide better than linear emissions benefits for three of the key emissions [PM, HC and NO_x] associated with diesel engines.[71]

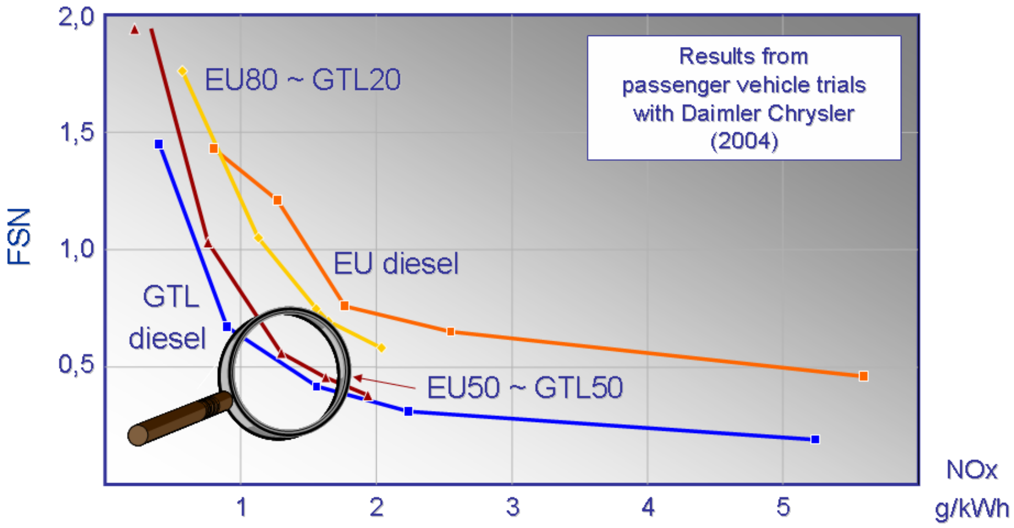

Figure 5-2: GTL emissions reduction example in a Euro-IV engine.

5.2 Reduced Nanoparticle Formation

Studies of air pollution are increasingly focused on health effects of ultrafine particles (size <100 nm).[72] Both EPA[73] and CARB[74] have conducted recent benefit assessments for $PM_{2.5}$ reduction, as well as California-specific studies that focus on the South Coast/San Joaquin[75] Valley and Los Angeles basins.[76]

These ultrafine particles (nanoparticles) have a higher deposition rate in the lungs and can lead to enhanced negative respiratory and cardiovascular health effects compared to larger visible particles (size >1 ųm). Increases in levels of asthma, genotoxicity and tumor promotion are closely related to combustion-derived nanoparticles.[77]

Combustion of GTL diesel can result in a significant reduction in nanoparticle formation relative to conventional diesel.[78]

Recently, GTL Diesel exhaust nanoparticle number concentrations and size distributions produced during steady-state tests of a US heavy-duty engine and a European passenger car engine using GTL diesel, and a US D2 on-highway diesel fuel were measured. These results showed that the use of the GTL diesel resulted in a significant reduction in total particle number emissions, *and particularly in emissions of particles smaller than 50 nm*, under idle conditions (**Figure 5-3**).[79]

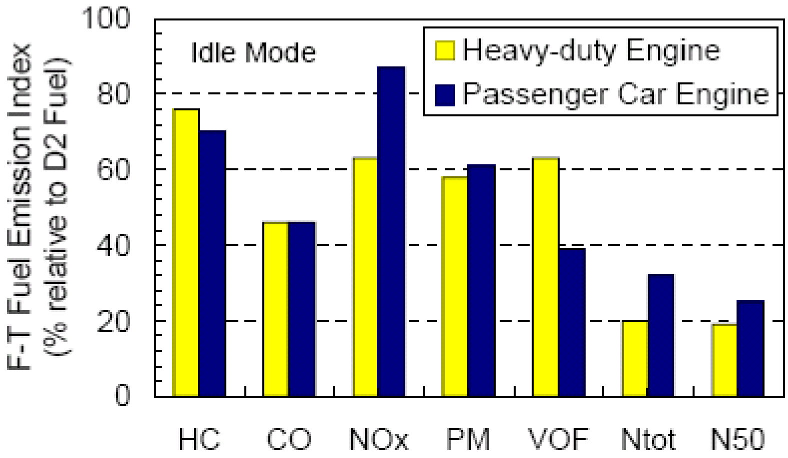

Figure 5-3: Emission Indices Relative to D2 Fuel, Idle Mode Ntot = Total Particle Number. N50 = Number of Particles < 50 nm.

5.3 GHG Benefits of Using GTL Diesel as a Blend-stock

GTL diesel can be used as a high quality diesel blending component, as a component enabling premium diesel formulations, or as a pure, neat diesel fuel.

CARB has already shown[80] that under mature cost conditions for FT diesel and EPA diesel, the use of FT diesel to produce a compliant CARB diesel can be an attractive option for reducing demand for diesel and producing consumer savings.[81]

GTL diesel can help extend a refiner's conventional diesel output,[82] and alleviate density pressure in the refinery if it exists, thus potentially increasing the GHG efficiency of the entire refinery.[83] In addition, it may enable refinery blending optimization opportunities in combination with suitable higher density, lower cetane components that might otherwise be downgraded to heating oil or to other, lower value products. Examples of suitable complementing components include hydrotreated light cycle oil,[84] coker gasoil, first generation biodiesel (FAME), or other high density (e.g. naphthenic crude derived) low sulfur middle distillates (**Figure 5-4**).

Any upgrading with GTL diesel could reduce the need for hydrotreating in the refinery, which is GHG intensive. For example, The Steam Methane Reforming (SMR) process[85] in centralized plants used to produce hydrogen for hydrotreaters emits more than twice the CO_2 than hydrogen produced.[86] A LCA of hydrogen production *via* SMR indicates that the overall global warming potential (GWP of the SMR system is 11.9 kg CO_2-equivalent/kg of hydrogen produced.[87]

The exact GHG benefits of blending GTL diesel in a refinery would depend on the volumes of GTL diesel in the refinery system,[88] and how the refiner chooses to utilize the GTL product.

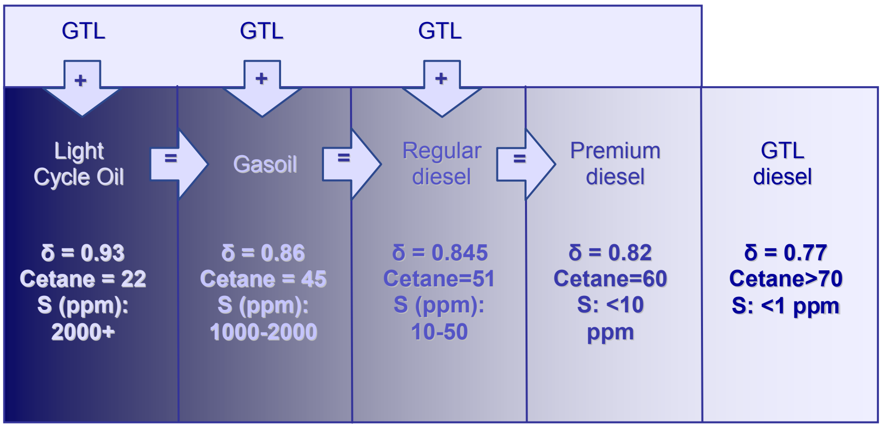

Figure 5-4: GTL diesel can enable upgrading of suitable middle distillates to higher value products.

5.4 Diversification of energy supply

GTL diesel is natural gas based and therefore offers a strategic diversification of energy supply. Natural gas is a very attractive alternative to crude oil derived fuels. Crude oil will remain the dominant energy source in the transport section for the foreseeable future; however it cannot meet increasing demand indefinitely. World energy demand is expected to grow towards 50 % by 2030[89,72] and natural gas is set to play an ever-increasing role if the energy challenge is to be met effectively.

Meeting transportation fuel demand will require a diverse range of commercially viable fuel supplies compatible with fuel distribution infrastructure and prevailing drive-train technologies. GTL is an alternative technology which provides an opportunity to use natural gas resources to produce ultra-clean, high performance liquid fuel as well as other premium products.

6 Summary

This chapter provides a summary of the GHG benefits of GTL.

All GTL products (not just GTL diesel) are highly paraffinic and have zero aromatics, affording GHG benefits relative to their conventional analogues. In some cases, such as GTL lubricant oils (which carries a downstream benefit), these GHG benefits are significant. Allocation methodology fails to properly account for GTL co-products because they can carry a downstream benefit (e.g. GTL lubricant oils) and are higher quality than conventional analogues (e.g. GTL naphtha vs. oil-derived naphtha).

Sasol Chevron has undertaken in this submission to demonstrate how comprehensive accounting of GTL co-products can lead to a dramatically different life cycle analysis result for GTL compared to allocation methodology.

These results show that, when the full GHG benefits of GTL co-products are considered using substitution methodology, a significantly lower carbon footprint for GTL diesel compared to that derived using allocation methodology is obtained.

Secondly, this study highlights the potential for Californian regulators to achieve significant reductions in CO_2 emissions at the state level by encouraging the use of higher quality lubricant oils, such as GTL lubricant oils over traditional lubricant oils.

Sasol Chevron recommends CARB develops a unique fuel pathway for GTL diesel; one that correctly accounts for, and gives full credit to, all GTL co-products in both a fair and comprehensive manner. Sasol Chevron also recommends CARB does not ignore the improved criteria pollutant profile relative to conventional diesel.

Considering the importance of this to the emerging GTL industry, Sasol Chevron would be happy to help, as may be deemed appropriate for the process.

7 Glossary

This chapter provides a glossary of terms used in this submission.

AGO	Automotive Gasoil
Allocation	Partitioning of the input or output flows of a unit process to the product system under study
API	American Petroleum Institute
API gravity	A measure of how heavy or light a petroleum liquid is compared to water
Associated Gas	Natural gas found with crude oil in an underground geological formation
ASU	Air separation unit
ATR	Auto thermal reformer
Base Oil	Base component used in lubricant manufacture
BSCFD	Billion Standard Cubic Feet per Day
BP	British Petroleum
Bpd	Barrel per day
BTL	Biomass to liquids
Btu	British Thermal Units
ºC	Degrees Celsius
CA	California
CARB	California Air Resources Board
Carbon efficiency	GTL Plant carbon efficiency is the fraction of carbon in the Methane Rich Gas stream that is present in the GTL product streams
Carbon footprint	Equivalent to “Life cycle greenhouse gas (GHG) emissions” or “GHG impact”
CBM	Coal bed methane
Cetane	(hexadecane, $C_{16}H_{34}$): A colorless, liquid, straight-chain paraffin (alkane) used to standardize the knock rating of diesel
CI	Compression ignition
CIDI	Compression-ignition direct injection engine
CO	Carbon monoxide
Cold cranking	The low temperature performance of lubricants (start-up of a cold engine)
cP	Centipoise, a measure of dynamic viscosity used to characterize the cold crank characteristic of an oil

Co-product	Any two or more products from the same unit process
cSt	Centistoke, a measure of kinematic viscosity (fluid thickness)
CTL	Coal to liquids
DI	Drain interval
DOE	Department of Energy
Energy efficiency	GTL Plant energy efficiency is the fraction of internal energy within the Methane Rich Gas stream that remains within the GTL product streams
ENI-IFP	Italy-based ENI Technologies and France-based IFP
EPA	EPA U.S. Environmental Protection Agency
Euro 3	European engine emission standard applying to 2005
FAME	Fatty acid methyl ester
FC	Fuel consumption
FES	Fuel economy saving
FT	Fischer-Tropsch
FTBO	Fischer-Tropsch lubricant base oils
FTD	Fischer-Tropsch Diesel
Functional unit	Quantified performance of a product system for use as a reference unit in an LCA study
GHG	Greenhouse gas. Release of gas into the air which contributes to the greenhouse effect. The major emission adding to the greenhouse effect is carbon dioxide (CO_2), but other emissions, such as methane and nitrous oxide or CFCs/HCFCs absorb energy more efficiently than CO_2 and thus have a higher impact per amount emitted.
GREET	The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model
GTL	Gas to Liquids
GTP	Gas treatment plant
GWP	Global warming potential
HC	Hydrocarbons
HD	Heavy duty
HDEO	Heavy duty engine oil
Heating	Provision of heat to a building, by combustion of fuel in a boiler
HHV	Higher heating value
HTFT	High-Temperature Fischer-Tropsch
Hydro-Processing	Refinery up-grading technology utilising hydrogen
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organisation for Standardisation
JOGMEC	Japan Oil, Gas and Metals National Corporation
Kg	Kilograms
kPa	Kilopascals
LAB	Linear alkyl benzene

LAS	Linear alkyl benzene sulfonate
LCA	Life cycle assessment.
LCFS	Low Carbon Fuel Standard
LCI	Life cycle inventory (analysis)
LCIA	Life cycle impact assessment
LD	Light duty
LEM	Lifecycle Emissions Model
LHV	Lower heating value
Life cycle inventory analysis	Phase of LCA involving the compilation and quantification of inputs and outputs for a given product system throughout its life cycle
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
LTFT	Low-Temperature Fischer-Tropsch
Lubricant Base Oil	Base component used in lubricant manufacture
Methane (CH_4)	A colorless, odorless gas that combusts easily and produces a pale, slightly luminous flame; it is the main constituent of natural gas and can undergo chemical reforming to produce syngas
Mogas	Motor gasoline (petrol)
Mt	Million tonnes
Naphtha	A generic term for a flammable, light distillate or hydrocarbons feedstock, or a mixture of light hydrocarbons, used for gas or petrochemicals manufacture
NG	Natural gas
NGO	Non-government organization
NNPC	Nigerian National Petroleum Organization
Noack	A measure of volatility. The NOACK Volatility Test, otherwise known as ASTM D-5800, determines the evaporation loss of lubricants in high- temperature service
NO_x	Nitrogen oxides
NREL	National Renewable Energy Laboratory
OEM	Original equipment manufacturer
Paraffin	Wax-like substance high-boiling residue obtained from GTL and certain petroleum crudes
PCMO	Passenger car motor oils
Pearl (GTL)	Pearl GTL will have a capacity to produce 140,000bpd of GTL products and 120,000bpd oil equivalent of LPG, condensate and ethane. Over its lifetime the integrated project will produce upstream resources of approximately three billion barrels of oil equivalent
Photochemical oxidant formation	LCIA characterisation method using indices developed by the WMO that quantifies the potential for creation of tropospheric ozone as a result of specific emissions. It is expressed in terms of a photochemical oxidant formation potential associated with an equivalent mass of ethylene
PM	Particulate matter
Polyalphaolefin	Long chain olefin produced from ethylene in a 2 stage process, classified as a

(PAO)	synthetic olefin
ppm	Parts per million
Psi	Pounds per square inch
QP	Qatar Petroleum
Raffinate	A waste stream remaining after a given refinery or petrochemical process
Reid vapour pressure	The absolute vapour pressure exerted by a liquid at 100 °F
SAE 0W-x & 5W-x	Grades of motor oil
SCAQMD	South Coast Air Quality Management District
Sensitivity analysis	Systematic procedure for estimating the effects on the outcome of a study of the chosen methods and data
SGP	Shell Gasification Process
SI	Spark ignition
SO_2e	Sulfur oxide equivalent
SMDS	Shell Middle Distillate Synthesis
SMR	Steam Methane Reforming
Synthesis gas (syngas)	A carbon monoxide-hydrogen mixture used as a petrochemicals feedstock for synthesis and normally derived from the partial oxidation, or catalytic reaction with steam, of methane, which can be derived through natural gas reforming or coal gasification
System boundary	Interface between a product system and the environment or other product systems
System boundary expansion	Methodology by which allocation is avoided by expanding a product system to include additional functions related to the co-products
tpd	Tonnes per day
TRUs	Transport refrigeration units
UCG	Underground coal gasification
ULS	ULS Ultra low sulfur. In a European context, we use a sulfur content of 10 ppm
VGO	Vacuum Gas Oil
Viscosity Index (VI)	Measure of the uniformity of viscosity performance over a range of temperatures (higher the better). A key characteristic of a lubricant base oil; in a car, an engine oil must flow freely enough to permit cold starting, but must be viscous enough after warm-up to provide full lubrication
Visgrade product	10W, 5W or 0W specification
VOC	Volatile organic compound
Vol	Volume
Well to wheel (WtW)	Life cycle of a transportation fuel from extraction of feedstock to combustion in the engine and drive to the wheels

8 Appendices

A GTL Diesel Supporting Information

This appendix provides information about GTL diesel and its GHG benefits relative to conventional diesel.

A.1 GTL Diesel Properties

GTL diesel is an odourless and colorless synthetic fuel that can be used in all conventional compression ignition (CI) diesel-fuelled engines (**Figure A-1**). It has an exceptionally high cetane value and contains no sulfur or aromatics. These qualities enable significant reductions in regulated[90] and non-regulated exhaust gas emissions, with considerable potential benefits to the environment.[91]

Figure A-1: Fuelling of a vehicle with ultra-clean GTL diesel.

GTL diesel is fully compatible with existing fuel distribution infrastructures and can be used with all diesel engines. Furthermore, GTL diesel enhances the lifetime performance of gas after-treatment technologies and is considered an enabler of future engine and exhaust gas after-treatment technologies.

Over the past decades, continuous improvements in engine and fuel technologies have dramatically reduced transport related pollutant emissions in most parts of the world. Sulfur and aromatics content specifications of diesel fuel across the globe continue to tighten in order to further reduce tailpipe emissions and create a cleaner environment.

GTL diesel exceeds even the most stringent quality requirements in terms of these properties, whilst offering an ultra high cetane rating, which promotes efficient combustion (**Table A-1**). In addition to reducing engine-out emissions, the clean combustion of GTL diesel helps protect the engine oil and can result in an opportunity for extended oil drain intervals.

Property	GTL diesel (typical)	Euro Diesel (specification)	Units
Density @ 15°C	770	820 - 845	kg/m^3
Sulfur content	≤ 1	≤ 50 **	ppm
Cetane	> 74	> 51	rating
95 percent volume recovered	< 360 *	< 360	°C
Cold Filter Plugging Point	0 to -20 *	5 to -44 ***	°C
Flash Point (PMCC)	≥ 62 *	> 51	°C
Aromatics	< 0.5	< 11 ****	Wt percent
Viscosity @ 40°C	1.8 – 2	2 – 4.5	mm^2/s

* These properties can be tailored and/or optimized to meet specific market requirements

** To be further reduced to 10 ppm max in January 2009. A number of EU member states have already transitioned to 10 ppm max sulfur diesel fuel specification.

*** Depends on climate rating.

**** Refers to maximum polyaromatic content.

Table A-1: Overview of key GTL diesel properties.

A.2 GTL and the Global Energy Challenge

Over the past five years, the global economy grew by 4.6 percent per year, the largest growth for any five-year period on record. The world gross domestic product of nearly US$ 55 trillion[92] is now shared, unequally, between 6.5 billion people that inhabit our planet. Today, global human population is about two billion more than only thirty years ago, and about three billion less than expected for 2050.[93]

Rapid global population growth and an increase in the purchasing power of individuals across the globe will put additional pressure on what is an already tight global energy system. History has shown that as people become richer they use more energy. Despite high energy prices and anticipated reductions in energy intensity per capita the burden on limited energy resources is expected to increase. **Figure A-2** highlights the differences in per capita oil consumption between developing and developed nations. An increase in global oil consumption is expected to come primarily from the developing world, with two countries alone – China and India - accounting for nearly 45 percent of this increase.[94]

In line with this trend, the world's energy needs are projected to be 50 percent higher in 2030 than today.[95] One of the greatest challenges the world faces today is how to satisfy this increase in energy demand sustainably, with minimal negative impact on the environment and economic growth.

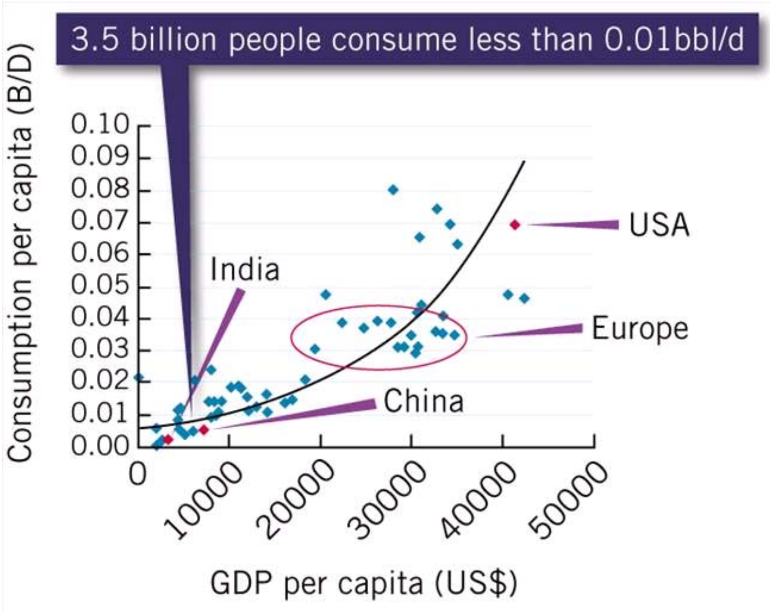

Figure A-2: Oil consumption *vs*. GDP per capita

There is no doubt that fossil fuels will remain the dominant source of primary energy for many years to come. Today, conventional hydrocarbon-based resources – coal, oil, and natural gas – make over 80 percent of the world primary energy. Oil remains the dominant energy source, accounting for approximately a third of total world energy consumption. At the moment, the transportation sector accounts for almost half of global oil consumption and by 2030 this is expected to increase to almost 60 %, resulting in a requirement for over 25 million bpd oil equivalent of additional production.

Figure A-3 illustrates the tremendous global growth in car ownership in the past dozen years.[96] Total world motor vehicle production reached 73.1 million units in 2007 - an increase of 3.8 million units compared to the previous year - and is expected to continue to grow. Today, there are 900 million vehicles around the world, and it is estimated that by 2050 there will be two billion vehicles.

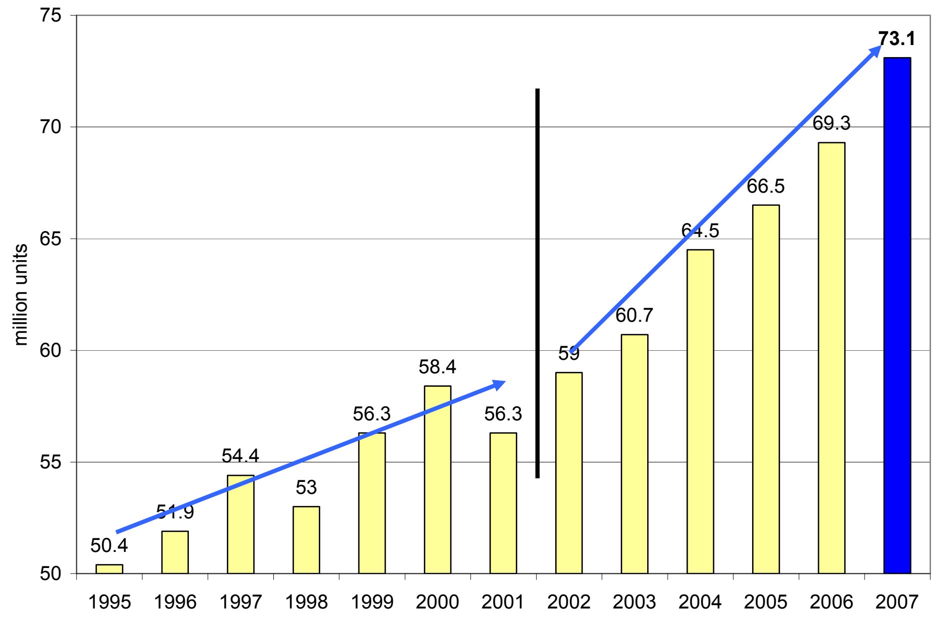

Figure A-3. World motor vehicle production (1995 – 2007)

An increase in the number of vehicles on the road globally will obviously have an impact on the world demand for transportation fuels. Reducing emissions from vehicles is a priority for cities around the world, especially for those with chronic air pollution. This means that future fuels will need to be more plentiful, but also greener, which puts technology and innovation at the forefront.

Unlike in the power and heating sectors, fuel substitution in the transport sector is difficult as most alternatives are either costly, have major technical barriers, limited supply potential, or are environmentally unacceptable. Oil by itself will be unable to fill the forecast demand growth for transportation fuels entirely.

Meeting future demand for transportation fuels will require a diverse range of commercially viable fuel supplies that are compatible with fuel distribution infrastructure and prevailing drive-train technologies. Gas to liquids, or GTL, is an alternative fuels technology that provides a unique opportunity to convert natural gas to produce low emissions, high performance liquid fuel as well as other premium products. GTL diesel is compatible with existing fuel distribution infrastructure and diesel engine technology.

World diesel demand in 2005 was approximately 14 million bpd.[97] Demand has grown close to 3 percent per year for the past two decades, making diesel the fastest growing segment of the refined products market (**Figure A-4**). Typically, diesel demand is closely correlated to economic growth since it is the primary fuel driving the global economy and is the preferred choice for road freight transportation, mining, and agriculture. In Europe, and increasingly in other parts of the world, passenger transport is now also contributing to diesel demand growth. Reasons for this aggressive dieselisation of passenger fleet include more favourable diesel fuel and vehicle taxation, significantly improved diesel technology, but also higher fuel efficiency and therefore lower greenhouse emissions compared to petrol vehicles. The latest diesel technology is both clean and quiet, offering a good alternative to less efficient petrol cars.

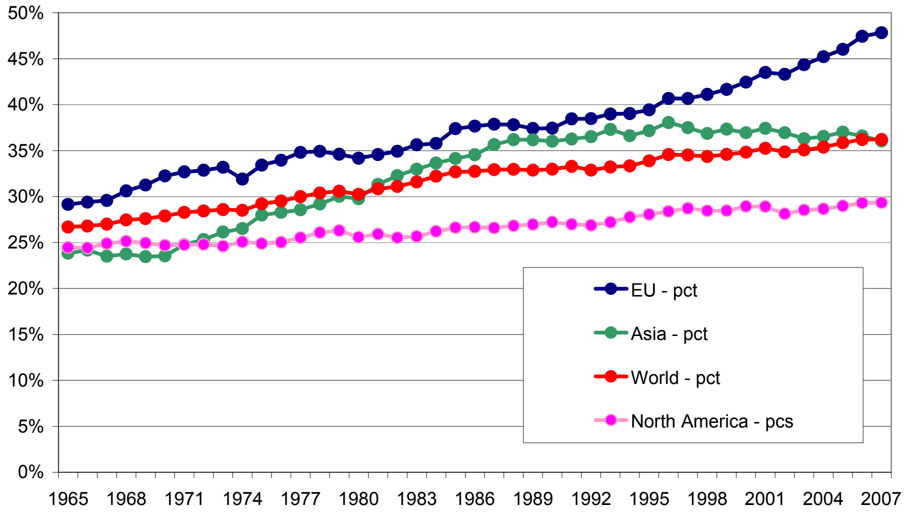

Figure A-4. Middle distillates as percentage of total oil consumption.[98]

Globally, it is widely forecast that diesel demand as a percentage of oil products will continue to grow while the percentage demand for most other refined products is more likely to flatten out and even start declining. In parallel with an increase in diesel fuel consumption, more stringent fuel quality requirements are also being introduced across the globe, and as a consequence refiners are facing significant challenges to meet diesel demand, both in terms of quantity and quality. Against this backdrop, in mid 2008 prices for low sulfur diesel fuels reached unprecedented levels, both in absolute terms and relative to crude oil. GTL producers are assured to have access to high value and growing markets for their products for the foreseeable future.

A.3 GTL Diesel Markets

The global market for transportation diesel fuel was estimated at approximately 14 million bpd in 2005,[99] of which two-thirds is concentrated in the 30 OECD countries. Within the category of transportation fuels, demand for diesel fuel has been particularly strong unlike for some other transportation fuels.

While demand for diesel fuel increased year-on-year (**Figure A-5**) and was around 15 percent higher in mid 2008 than only three and a half years ago, gasoline fuel demand remained relatively flat during this period and even declined in 2008 in response to high fuel prices.

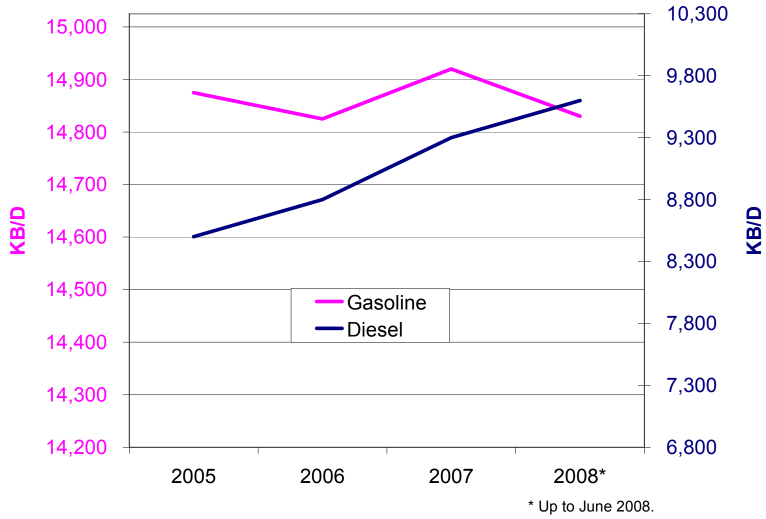

Figure A-5: OECD diesel demand is growing compared to gasoline as a transportation fuel.

A.4 GTL Diesel Demonstrations

Both Sasol Chevron[100] and Shell have partnered with various NGO's and OEM's to demonstrate that GTL diesel is a CARB alternative diesel.[101] A summary of these global studies are provided below;

Sasol Chevron, A C Transit (California)[102]

In October 2007 AC Transit and Chevron Products Company launched the Cleaner Fuels Test Program, which will study a biodiesel fuel blend and GTL (gas-to-liquids) diesel in a fleet of 22 unmodified diesel buses traveling Bay Area roadways. It's anticipated the test buses will transport more than 1.5 million passengers, travel over 400,000 miles and consume more than 100,000 gallons of alternative fuels during the study period.

Sasol Chevron, National Renewable Energy Laboratory (NREL) Study, (California)

NREL and the South Coast Air Quality Management District (SCAQMD) are conducting a controlled study to evaluate GTL fuel in transport refrigeration units (TRUs) used by a small vehicle fleet. The objectives of this study, to be conducted in the South Coast Air Basin (Los Angeles area), are to:

- Quantify emissions over a representative test cycle using ultra-low sulfur diesel (ULSD), GTL fuel, and GTL fuel with passive catalytic regenerative particle filters;
- Evaluate the use of GTL in combination with passive catalytic regenerative particle filters, in a centrally fuelled vehicle fleet operating over a twelve month period;
- Provide fleet test data to industry, agencies, and other stakeholders involved in introducing GTL fuel into the marketplace.

Sasol Chevron, Daimler GTL Vehicle Optimisation Programme (Europe)[103]

A study between Sasol Chevron Consulting Ltd and DaimlerChrysler AG, found that very low NOx emissions were achievable with GTL diesel fuel. Road trials of synthetic fuels in several European capitals demonstrated that GTL diesel provided significant local air quality improvement by reducing tailpipe emissions (particulate matter, nitrogen oxides, carbon monoxide and hydrocarbons).

Sasol Chevron, Asian Games Fleet Demonstration Programme (Qatar)

Ten of the official buses for the 15th Asian games in Doha 2006 were fuelled with ultra-clean GTL diesel. The buses for the campaign were provided by Qatari bus company Mowasalat.

Sasol Chevron, GTL Challenge (Africa)[104]

A team of twelve men and women took part in the Sasol Chevron GTL Challenge to complete an 10,157 km journey from South Africa to Qatar, through eight countries and some of the toughest conditions on the planet, to arrive in Doha for the official opening of the ground-breaking ORYX gas-to-liquid (GTL) plant.

One of the team's five vehicles, a standard Toyota Hilux Raider, dubbed African Renaissance, was fuelled from beginning to end with neat GTL diesel fuel from Sasol's plant at Sasolburg.

Sasol Chevron, Aloga Bay Fleet Test (South Africa)

In July 2005, 20 Vehicles (10 in control group (EN590), 10 in a test group (GTL)) from Aloga Bus Company (Port Elizabeth, South Africa) were used to evaluate the performance of Gas-to-Liquids (GTL) diesel produced with the Sasol Slurry Phase Distillate (SPD®) process in an on-road heavy duty fleet application. After 45,000 km of test operation, a change to GTL diesel resulted in significant decrease of test group vehicles soot loading. Regular smoke measurements were performed on trial vehicles, and the amount of measured smoke decreased when vehicles were changed over to GTL. Scanning Electron Microscope (SEM) photographs show that *the* GTL injector holes have less deposit build-up than on the EN590 injectors

Sasol Chevron, De Wildt Cheetah Tracker Programme (South Africa)[105]

Inn April 2007 Sasol Chevron sponsored a three year research programme to support cheetah conservation across South Africa. The team will have to cover many hundreds of thousands of kilometres to get the work done and, to help them do this Sasol Chevron has donated two M class Mercedes. These vehicles will run on GTL diesel donated by Sasol Chevron as part of a three year fuel test and this revolutionary clean fuel will allow De Wildt to do its work with the lowest possible vehicle emissions.

Shell, C40 Large Cities Climate Change Summit (New York)

Two Audi A8 limousines were fuelled with 100% GTL Fuel for the use of visiting mayors and their delegations at the C40 Large Cities Climate Change Summit in New York in May 2007. These included mayoral parties from London, Shanghai, Rotterdam and Tokyo and New York City officials who experienced the reduced noise and cleaner performance of a natural gas derived synthetic fuel in diesel engines.

Shell, Yosemite Waters (California)[106]

A fleet of six trucks with conventional engines operated by Yosemite Waters have been running on GTL Fuel for 12 months, delivering mineral water in southern California. The trial results, announced in October 2004, scientifically demonstrate the robust operability of the combination of fuel and exhaust systems, and a significant reduction in emissions. The results show that GTL Fuel reduced all regulated emissions, with a cut in oxides of nitrogen (NO_x) and particulate matter (PM) emissions by 16 % and 23 % respectively. The emissions were tested in “New York City Bus” drive cycle without a particulate filter (the "New York City Bus" drive cycle is a laboratory simulation of driving under standardised conditions characterised by the vehicle spending over 65 % of the time at idle and with much less continuous driving). With a catalyzed diesel particulate filter, NO_x and PM emissions were further reduced, to overall reductions of 20 % and 97 % respectively.

Shell, Ralph Groceries (California)

A trial began in August 2004 involving heavy-duty trucks operated by Ralphs Groceries stores in southern California and was completed in 2005. This trial compared GTL Fuel in two trucks with modified engines and integrated after treatment systems, with standard CARB diesel. Emissions and performance levels are currently being evaluated to demonstrate that GTL Fuel is an effective alternative fuel.

Department of Transportation (CALTRANS), California[107]

In 2002 Shell completed a fleet trial with the Department of Transportation, California (CALTRANS), with 69 trucks, pickups, tractors and construction units running on 100% Shell GTL Fuel. The results were very positive. The Business, Transportation and Housing Agency of California have officially confirmed that none of the vehicles experienced fuel-related problems, either during the trial or since converting back to ULSD (Ultra Low Sulfur Diesel).

Shell, Toyota (London)[108]

Collaboration between Toyota & Shell, launched in 2004, 10 Avensis cars equipped with Toyota D-CAT exhaust systems & powered by Shell GTL Fuel, 3 months, driven by charitable organizations. Neat GTL diesel was used in the trial. The objective was to demonstrate GTL diesel can be used in latest technology vehicles without modifications and with positive emission impacts. The results for GTL emissions compared to "zero sulfur" diesel (10 ppm S) were: 73 % reduction in hydrocarbons, 94 % reduction in CO, NOx similar for GTL and diesel but still half of the Euro IV standard as a result of D-CAT effectiveness, and 25% reduction in PM.

Shell, London Bus (London)

Collaboration between Shell, London General transport and the DaimlerChrysler subsidiary EvoBus (UK) Ltd., launched 2003, 3 months, one bus (number 507 ‘bendy bus’), Waterloo to outside Shell office in Victoria.

Shell monitored the 507 bus, which ran at peak hours, throughout the three month trial, demonstrating that it delivered the sort of emissions, fuel consumption and performance benefits that have already been seen in trials elsewhere in the world.

Shell, Volkswagen (Berlin)

In Germany, a collaborative fleet trial with Volkswagen was launched in May 2003. A fleet of 25 Volkswagen Golf cars were driven by welfare workers around Berlin for a period of five months, fuelled by Shell GTL Fuel. Former German Chancellor Gerhard Schröder launched the event and emphasized that close cooperation with Shell, Volkswagen and other automotive industry players was strongly supported by his government.

Tests showed emissions benefits for 100 % GTL Fuel in a current (Euro-3) light duty engine and compared to current European diesel of approximately 26 % lower particulates, 6 % lower nitrogen oxides, 63% lower hydrocarbons, and 91 % lower carbon monoxide.

Tests carried out by Volkswagen show that modern Golf diesel cars operating on Shell GTL Fuel will, without any modifications, comfortably meet the stringent future Euro 4 emission limits; next generation vehicles can lower emissions even further. Moreover, Shell GTL Fuel will support innovative drive systems like Volkswagen’s combined combustion system, which combines the fuel economy advantages of a diesel engine with the emission benefits of a gasoline engine.

Shell, Toyota

Shell GTL Fuel was used by vehicles owned by Toyota Transport in and around Toyota City, Aichi and between Toyota offices, from November 2007 to March 2008. This was to demonstrate that the fuel could be used in existing fleets without modification to engines or infrastructure. The road trials were completed successfully with no fuel-related problems during the trial.

Shell, JR Tokai Bus Co. (Japan)[109]

A demonstration of GTL Fuel blend in a Hino diesel hybrid bus was launched in July 2005, in co-operation with Showa Shell Sekiyu, Toyota Tsusho and JR Tokai Bus Company. The bus carried visitors to the 2005 World Exposition in Aichi, as well as commuters in Seto City and Kasugai City. The trial supported the "Nature's Wisdom" theme of the Aichi Expo by reducing the impact of public transport on the environment and developing more efficient technologies.

Shell, Co-op Truck (Japan)

In Japan, a 3-stage fleet trial and emissions testing programme was carried out in Saitama Prefecture in November 2003 and Chiba Prefecture in May 2004, involving laboratory tests, vehicle testing on a test track and a fleet test on the road. Three Co-op trucks (13 ton, 4 ton and 1.5 ton) were able to use a blend of Shell GTL Fuel and standard diesel without any engine modifications.

Shell, Shanghai Bashi (China)[110]

During 2006 and 2007, Shell, the Shanghai Clean Energy Center, Shanghai Bashi, Yuchai and the Tongji University successfully conducted 150,000 kilometers of road trials using 100% Shell GTL Fuel on six unmodified Euro II and III buses in Shanghai. The engine test results showed that Shell GTL Fuel could reduce particulate matter by 35 % to 40 % compared to conventional diesel. The road trials results indicated that the fuel economy and engine performance of engines running on Shell GTL Fuel were similar to those using conventional diesel fuel.

Shell, Shanghai VW Passat Taxi (China)

In 2006, Shell, the Tongji University, Shanghai Volkswagen, Shanghai Da Zhong Taxi Co. and the Shanghai Science & Technology Commission successfully completed a nine-month trial on eight VW Passat 1.9TDi diesel engine taxis using 100 % Shell GTL Fuel. The aim of the project was to demonstrate the feasibility of dieselisation of the light-duty fleet and increase the public awareness of diesel development, including non-petroleum derived diesel, such as synthetic GTL Fuel. Of great significance is that the 8 vehicles operated for an impressive 600,000km, which represents one of the longest vehicle trials on GTL Fuel ever undertaken. This allowed an assessment of engine durability to GTL Fuel usage at extended duration regimes. No fuel-related problems were reported.

Shell, Beijing Public Transport (China)

In 2007 Shell, the Tsinghua University, Beijing Public Transport Holdings and Cummins demonstrated the feasibility and performance of Shell GTL Fuel on four unmodified Euro III standard buses through a four-month, 72,735 kilometers road trial in Beijing. The tests demonstrated that 100 % Shell GTL Fuel could reduce particulate matter, a prime local emissions concern for the city, by up to 33 % in comparison with Euro III standard engines.

Shell, Michelin Bibendum Challenge (China) [111]

At the Michelin Bibendum Challenge events in 2004 and 2007, Shell teamed up with Audi to demonstrate the use of Shell GTL Fuel in the latest Audi diesel cars. Trials using different Audi models demonstrated that significant reductions in exhaust emissions can be achieved with 100 % Shell GTL Fuel when compared with standard diesel.

A.5 Key Assumptions for GHG Accounting of GTL Diesel

To illustrate the effect that correct co-product GHG accounting has on the life-cycle assessment of GTL, the GHG impact of GTL using the substitution methodology was assessed and compared to results using the allocation method. This section describes the key technical and economic assumptions for GTL diesel production used in this submission.

Assumptions and Comments	Source
Natural gas is extracted offshore and processed onshore in a representative plant in the Middle East. During extraction, 0.4 % of the crude gas is vented and 0.2 % is flared.	ETH data[112]
Pipeline transport from offshore gas rig to onshore gas treatment plant (47 miles).	
Raw gas, which contains unstabilised condensate is firstly treated in a Gas Treatment Plant to produce methane rich gas. Part of the raw gas is used as fuel energy to treat and compress the gas. Outputs of the upstream treatment of raw gas are methane rich gas, condensates and LPG. Inputs and outputs values have been provided by Sasol Chevron (see Appendix I). CO_2 emissions have been accounted for by subtracting the carbon content of methane rich gas and the co-products to the carbon content of the inputs.	See Appendix I
GTL diesel is shipped from Middle East to California using the GREET assumption for sea transportation (7,200 nautical miles).	GREET 1.8b[113]
GTL diesel is then transported by road to filling stations using the GREET assumption for road transportation (50 miles).	GREET 1.8b[114]
It is assumed that there is a 0.6 % evaporative loss during transport and filling.	U.S. EPA[115]
Vehicle fuel use of GTL diesel: 0.034 US gallons/mile. It is assumed the same vehicle (CIDI) is used as in GREET 1.8b with adjusted emissions factors to take into account the fuel specifications of GTL diesel.	GREET 1.8b adjusted with Sasol Chevron fuel specifications

Table A-2: GTL Diesel Key Assumptions

B LPG and Condensate Supporting Information

This appendix provides information about LPG and Condensate from upstream gas reception facilities.

B.1 Condensate and LPG

GTL projects that are based on a complete 'reservoir to products out' value-chain entity encompass both onshore, and where applicable, offshore developments to produce gas from the field, and to treat and convert it into liquid products using the GTL process.

The upstream development plan for each project is different as it depends, amongst other things, on the size, quality, and location of the reservoir, as well as on the distance to the GTL plant and feedstock requirements.

The associated upstream production process that operates to feed the GTL plant, depending on the characteristics of the gas reservoir and the amount of condensate contained in the produced gas – can produce significant volumes of gas condensate, which can add substantially to the overall liquid product output of an integrated upstream / GTL project.

Therefore, when assessing the overall WtW GHG impact of GTL, the associated gas condensate produced by the upstream portion of the facilities should be considered.

In addition, depending on the wet gas composition, total LPG production from a fully integrated upstream / downstream GTL project can be sizeable and add substantial value to the project, especially if LPG's can be used to meet specific local or regional demand. Key applications for LPG's include domestic home heating or cooking.

B.2 Upstream Gas Processing

A block flow diagram of an integrated GTL facility that includes upstream gas processing is shown in **Figure B-1**.

Gas Extraction Facility – This facility receives a multiphase feed from a pipeline into a slug catcher. The slug catcher serves to separate field condensate and glycolated water from the feed gas stream. Field condensate is stabilised and treated, if required, for atmospheric storage as final product, and glycol is recovered from the aqueous phase to be returned and the remaining water is treated.

Gas Treatment Plant – The purpose of the Gas Treatment Plant (GTP) is to condition the feed gas to meet the specifications of the downstream GTL plant. The GTP removes sulfur components, mercury, CO_2 partially if required and water in the gas to generate a sweet, methane-rich feed gas to the GTL plant as well as final product streams of propane, butane and plant condensate. Where feed gas has high sulfur content, the facility design allows pelletized sulfur to also be a product from the GTP.

Gas to Liquids Plant – The GTL plant takes the sweet, methane-rich gas from the GTP and converts it in a three step process consisting of autothermal reforming, FT synthesis and refining into GTL diesel, GTL naphtha, and mixed LPG products. The mixed LPG is recycled to the GTP for further processing into the product streams.

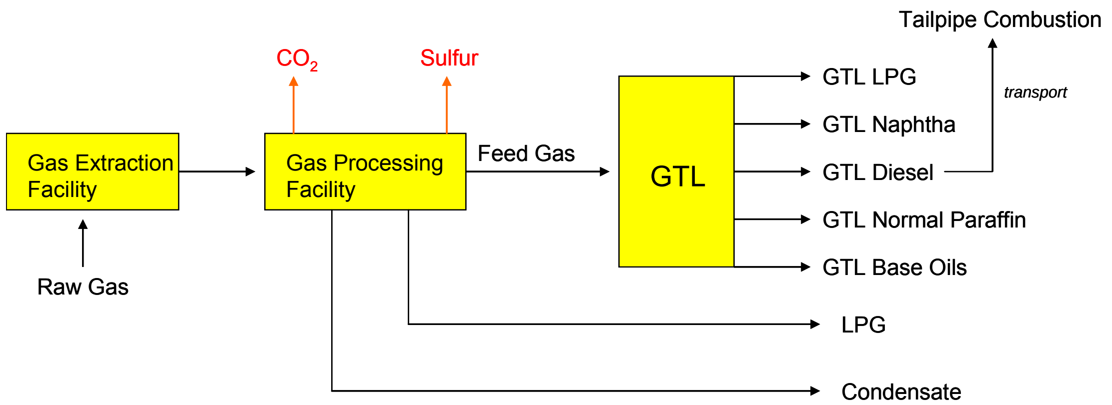

Figure B-1: Block flow diagram of a fully integrated GTL process

B.3 Key Assumptions and System Boundaries for GHG Accounting of LPG and Condensate

This section describes the key technical and economic assumptions used in this submission to compare the GHG impact of condensate and LPG within the GTL context with conventionally derived condensate and LPG.

LPG: System Boundaries

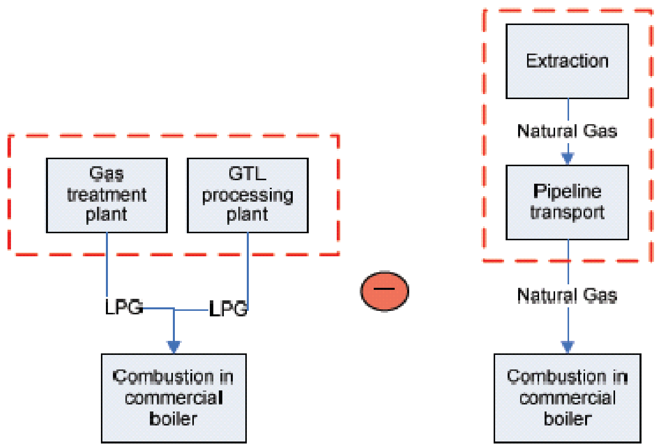

Figure B-2: System boundaries used to compare the GHG Impact of GTL LPG with the alternative boiler fuel, natural gas.

LPG: Key Assumptions

Assumptions and Comments	Source
LPG is a co-product from the gas treatment plant and GTL plant (**Figure B-2**).	
It has been assumed that LPG is burned locally in a commercial boiler. Because the LPG is used within the industrial complex, transport has not been included.	
It is assumed that emissions from the boiler correspond to a representative commercial boiler.	U.S. EPA emission factors[116]
It has been assumed that LPG used as fuel displaces natural gas, which is the major energy source in Qatar (81 % of total energy use).	Earthtrends[117]
The emissions associated with the extraction, transport and combustion of natural gas in a commercial boiler have been subtracted to the system under study according to the substitution approach (**Figure B-2**). Natural gas is assumed to be extracted off-shore, transported in a pipeline (47 miles) and burned in a commercial boiler.	Offshore extraction and pipeline transport: ETH data[118] Combustion: US EPA[119]

Table B-1: LPG Key Assumptions.

Condensate: System Boundaries

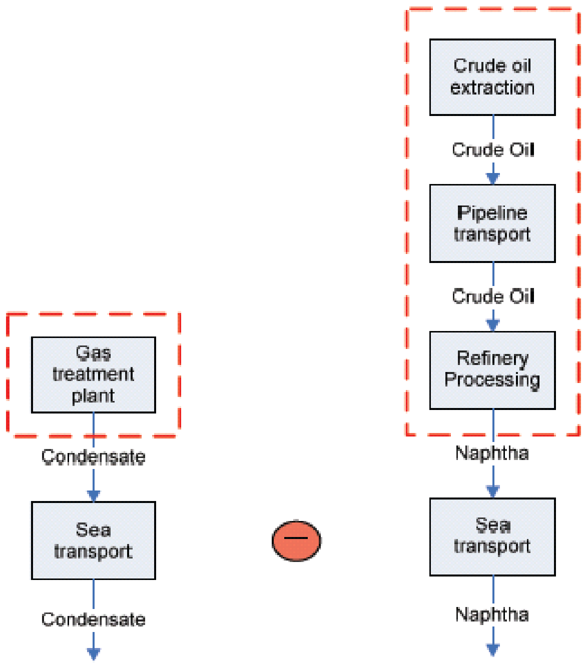

Figure B-3: System boundaries used to compare the GHG Impact of GTL condensate with conventionally derived naphtha.

Condensate: Key Assumptions

Assumptions and Comments	Source
Condensates are separated from the raw gas at the gas treatment plant (**Figure B-3**).	
It has been assumed that condensates are shipped from the Middle East to China and India. An average of 4,000 nautical miles has been considered. Emissions associated with sea transport are derived from literature data.	Portworld,[120] ETH data[121]
It is assumed that the quality of GTL condensate is equivalent to refinery naphtha, therefore it has been assumed that it directly displaces naphtha.	
The upstream emissions from extraction, transport and processing of crude oil to produce naphtha have been subtracted from the system under study according to the substitution method. Crude oil is assumed to be extracted on-shore in the Middle East, transported by pipeline (over 47 miles) to a complex refinery, processed into naphtha which is shipped to China and India (4,000 nautical miles). Emissions from the refinery are derived from a number of literature sources.	Crude oil extraction & Transport; ETH data.[122] Refinery: US EPA,[123] ETH.

Table B-2: Condensate key assumptions

B.4 GHG Accounting of LPG and Condensate Using the Substitution Method.

Table B-3 provides a breakdown of the amount of GHG emissions associated with the further processing and use of LPG and condensate after leaving the gas treatment and GTL plants and the displaced GHG emissions corresponding to the production and use of the products displaced by the co-products. All GHG emissions values are given in g CO2e/mile for the 2010 base case scenario.

Condensate	Processing	Substitution	Delta
Total	3	-28	-25
Oil extraction	-	-5	
Refinery	-	-20	
Transport	3	-3	

LPG from GT and GTL plant	Processing	Substitution	Delta
Total	64	-59	5
NG extraction	-	-3	
Combustion	64	-56	

Table B-3: The CO_2 balance between LPG and condensate and the displaced products using the substitution method. All GHG emissions values are given in g CO2e/mile for the 2010 base case scenario. “Delta” refers to net emissions using the substitution methodology.

C GTL Naphtha Supporting Information

This appendix provides information about GTL naphtha and its GHG benefits relative to conventional naphtha.

C.1 GTL Naphtha Properties

GTL naphtha has the following high quality features:

- Almost exclusively paraffinic
- High normal to *iso*-paraffin ratio
- Virtually no aromatics and sulfur
- No metallic contaminants

Typical properties of GTL naphtha produced in the Sasol Chevron GTL process are presented in **Table C-1**.

Property	Typical	Units
Density @ 15°C	680	kg/m^3
Sulfur content	≤ 1	ppm (wt)
Metallic contaminants: Mercury	< 1	µg/l
Lead, Arsenic	<5	ppb (wt)
Chlorides	<1	ppm (wt)
PONA Aromatics	<1	vol percent
Naphthenes	<1	vol percent
Olefins	<1	vol percent
Paraffins	97	vol percent
Ratio – normal to iso paraffins	1.3 : 1	
Reid Vapour Pressure @ 37.8°C	<10	psi

Table C-1: Properties of GTL naphtha.

C.2 GTL Naphtha Markets[124]

The global market for cracking naphtha for use as feedstock in steam crackers is large (currently at 170 Mt per annum or 4.2 million B/D) and growing.

The key markets consist of Asia, accounting for 45 percent of the global demand, followed by Europe at 35 percent of global demand. North America follows at a lower level, using about 10 percent of global cracker naphtha consumption, as shown in the **Figure C-1**.

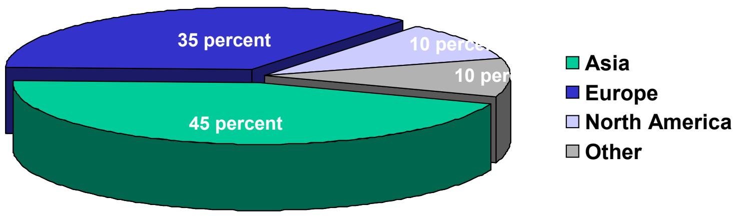

Figure C-1: Global cracking naphtha demand**.**

Overall, naphtha demand in **Asia** is on the rise, driven by expanding naphtha-based ethylene capacities in the region. Japan is by far the largest consumer and importer of petrochemical grade naphtha, followed by South Korea. By 2010, total naphtha demand in Asia is expected to rise to 182 Mt (4.5 million B/D), up 35 percent compared with 2006 levels. Two thirds of the growth is expected to occur in China, while South Korea, Taiwan, Singapore, and India are also going to see strong demand growth. For the period 2010 – 2025, naphtha demand is expected to increase at an average of 4.7 percent per annum.

The region's naphtha deficit is expected to increase sharply over this period, growing from 29 Mt in 2006 to 65 Mt by 2010 (715,000 and 1.6 million B/D respectively), and – if no additional production capacity were to be added after 2015 - further to over 150 Mt (3.7 million B/D) by 2025.

While **Europe** is the second largest market for cracker naphtha, its supply-demand balance shows an overall surplus that is expected to sharply increase by 2010 as new upgrading investments increase the naphtha yield which refiners will most likely not add to the already large (and surplus) gasoline pool.

In the Mediterranean region most naphtha is consumed in the Euro-Med zone, which currently accounts for 87 percent of the total regional demand. Whilst naphtha consumption is forecast to grow in the entire Mediterranean as economic growth boosts demand for petrochemicals, most of the growth will be in the Euro-Med, as this is where the majority of the petrochemical plants are located.

By 2025, the overall European naphtha surplus is forecast to reach almost 15 Mt per annum (370,000 B/D).

In **North America**, naphtha is a relatively minor chemical feedstock, accounting for only around 15 percent of oil product demand in the petrochemical sector. Most of the refinery produced naphtha is used in the very large (and deficit) gasoline pool.

As demand grew strongly between 1995 and 2005, naphtha's share of the sector has increased – a trend that is expected to continue. While demand is forecast to increase from 14 Mt in 2006 to almost 17 Mt in 2025 (350,000 and 420,000 B/D respectively), the rate of growth slows significantly, increasing at an average annual rate of just 0.7 percent between 2015 and 2025.

North America naphtha deficit is anticipated to be relatively flat at around 5 Mt per annum, or 120,000 B/D.

In **Brazil**, naphtha demand almost doubled between 1990 and 2000 to reach 10 Mt (250,000 B/D), thanks to rapidly expanding petrochemical sector in this country.

However, as economic growth slowed from 4.4 percent in 2000 to an average of just 1.2 percent over the next three years, feedstock demand shrank. With economic growth forecast to average 3 percent per annum over the next fifteen years and further expansion in petrochemical production planned, demand for naphtha is forecast to grow. Increasing use of natural gas feedstock limits the naphtha growth to 2 percent per annum to 2010, slowing gradually to 1.0 percent per annum from 2015 to 2025 when demand reaches over 12 Mt (300,000 B/D).

The naphtha deficit widens between 2006 and 2010, as refinery supply falls due to investment in reforming capacity. Post 2010 the deficit remains fairly constant, with refinery output growth matched by growth in demand.

C.3 GTL Naphtha Applications

GTL naphtha is an ideal liquid feedstock for ethylene production *via* steam cracking. It delivers steam cracking performance that is comparable, and in certain instances better, than the best high paraffinic content petrochemical naphtha commercially available today. It is considered a premium feedstock as a result of the comparative increase in high value product yield obtained when GTL material is cracked. Moreover, because of the ultra low aromatic content, cracking of GTL naphtha also results in reduced coking rates of furnace tubes, thus allowing extended run duration at high cracking severities

Sasol Chevron contracted Kellogg Brown Root (KBR), a reputable steam cracking technology supplier, to evaluate the performance and suitability of GTL naphtha as a steam cracking feedstock.[125]

The pilot plant test program was designed to determine the yields of GTL naphtha and a Middle East naphtha for a range of cracking severity from maximum ethylene to maximum propylene (P/E range of 0.40 to 0.70).[126]

The pilot plant was de-coked before and after each feed to provide a general indication of the coking tendency of GTL naphtha compared to the ME naphtha.

A comparison of the two types of naphtha tested in the study is given in **Table C-2**.

	GTL naphtha	Middle East light naphtha
Specific Gravity	**0.682**	**0.672**
Sulphur (ppm wt)	**<1**	**300 -500**
Composition (%)		
n-paraffins	**52.2**	**49.5**
i-paraffins	**45.7**	**41.5**
Total Paraffins	**98.2**	**91**
Olefins	**0.3**	**0.4**
Naphthenes	**1.5**	**6.5**
Aromatics	**nd**	**2.1**
Total	**100.0**	**100.0**

Table C-2: Properties of the two types of naphtha tested in the KBR study.

The test results showed that GTL Naphtha produced more olefins compared to Middle East high paraffin Naphtha (**Figure C-2**). In this regard, comparison to other petroleum naphtha's showed that cracking of GTL naphtha is substantially more selective to the production of ethylene, propylene and butadiene.

Importantly, the measured amount of coke deposited during the five-day coking run was roughly half that of typical petroleum naphtha's under similar conditions. The coking rate for the GTL Naphtha under commercial conditions is expected to be lower than that of conventional feeds, meaning the commercial steam cracking run lengths processing the GTL naphtha are expected to be longer than those expected for conventional naphtha's at similar cracking severities.

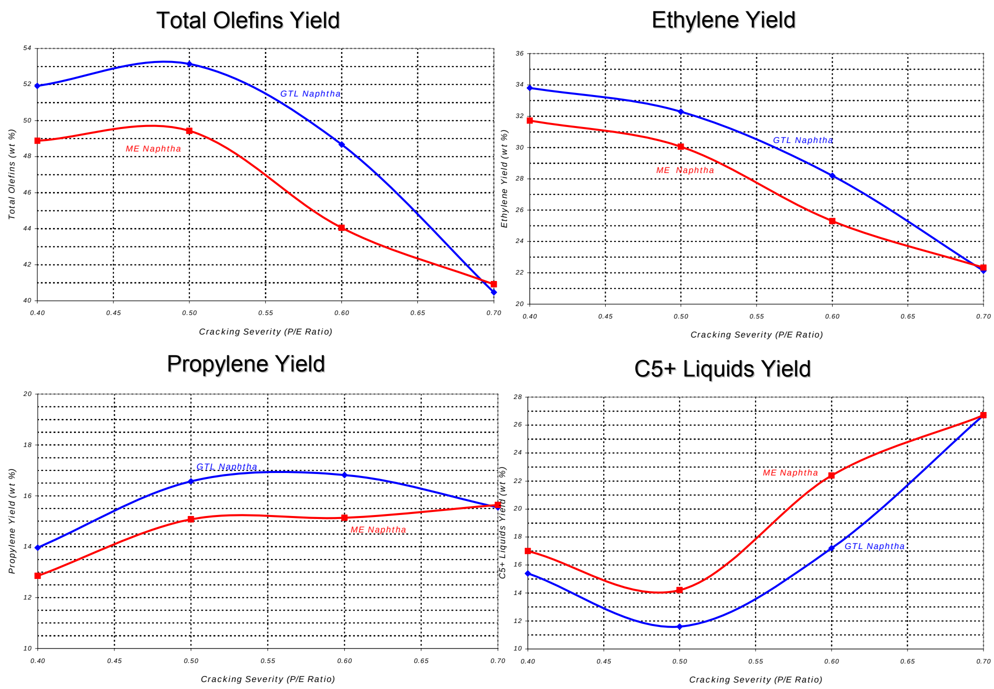

Figure C-2: Comparison of Total Olefin Yields in the KBR study.[127]

C.4 Key Assumptions and System Boundaries for GHG Accounting of GTL Naphtha

This section describes the key technical and economic assumptions used in this submission to compare the GHG impact of GTL naphtha with oil derived naphtha.

GTL Naphtha: System Boundaries

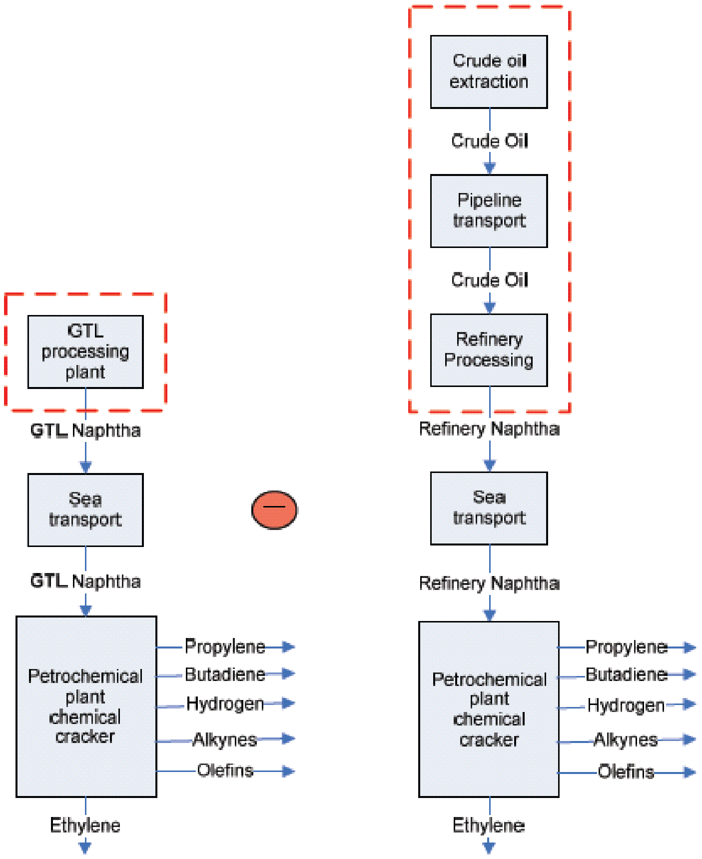

Figure C-3: System boundaries used to compare the GHG Impact of GTL Naphtha with oil derived naphtha.

GTL Naphtha: Key Assumptions

Assumptions and Comments	Source
GTL naphtha is a co-product from the GTL plant (**Figure C-3**).	
It has been assumed that GTL naphtha is shipped from the Middle East to China and India. An average of 4,000 nautical miles has been considered. Emissions associated with sea transport are derived from literature data.	Portworld,[128] ETH data.[129]
The upstream emissions from extraction, transport and processing of crude oil to produce naphtha have been subtracted from the system under study according to the substitution method. Crude oil is assumed to be extracted on-shore in the Middle East, transported by pipeline (over 47 miles) to a complex refinery, processed into naphtha which is shipped to China and India (4,000 nautical miles). Emissions from the refinery are derived from a number of literature sources.	Crude oil extraction & transport: ETH data.[130] Refinery: US EPA, ETH.[131]
It has been assumed that naphtha is used as feedstock in a petrochemical plant to produce ethylene. The chemical cracking process produces a range of co-products, including propylene, butadiene, hydrogen, alkynes and olefins. The yield and emissions from the petrochemical cracker using GTL naphtha have been modeled using a number of different literature sources and validated by a Sasol internal expert.	ETH data,[132] University of Berkeley,[133] Sasol internal expert.
The quality of ethylene produced from GTL naphtha is equivalent to ethylene produced from refinery naphtha. Therefore the upstream emissions from extraction transport and processing of crude oil to produce naphtha, and the subsequent transport and processing of naphtha to produce ethylene have been accounted for using the substitution approach. More specifically: Crude oil is assumed to be extracted on-shore in the Middle East, transported by pipeline (over 47 miles) to a complex refinery, processed into naphtha which is shipped to China and India (4,000 nautical miles). Emissions from the refinery are derived from a number of literature sources. Refinery naphtha is then processed into a petrochemical cracker. The yield and emissions from the petrochemical cracker using refinery naphtha are different from a plant using GTL naphtha. They have been modeled using a number of different literature sources and validated by a Sasol internal expert.	Crude oil extraction & transport ETH data,[134] Refinery: US EPA,[135] Ethylene production: ETH data,[136] University Of Berkeley,[137] Sasol Internal expert.
As the yield between both petrochemical crackers differs, the impacts related to the production of the other co-products have been balanced between both systems by adding to the GTL naphtha system the impacts related to the production of the other co-products (propylene, butadiene, hydrogen, alkynes and olefins) using literature data.	Plastics Europe.

Table C-3: GTL naphtha key assumptions.

C.5 GHG Accounting of GTL Naphtha Using the Substitution Method.

Table C-4 provides a breakdown of the amount of GHG emissions associated with the further processing and use of GTL Naphtha after leaving the gas treatment and GTL plants and the displaced GHG emissions corresponding to the production and use of the products displaced by the co-products. All GHG emissions values are given in g CO_2e/mile for the 2010 scenario.

Naphtha	Processing	Substitution	Delta
Total	104	-148	-44
Oil extraction	-	-8	
Refinery	-	-34	
Transport	3	-5	
Chemical cracker	51	-101	
Other co-products	49	-	

Table C-4: The CO_2 balance between GTL naphtha and the displaced products using the substitution method. All GHG emissions values are given in g CO_2e/mile for the 2010 base case scenario. "Delta" refers to net emissions using the substitution methodology.

D GTL Normal Paraffin Supporting Information

This appendix provides information about GTL normal paraffin and its GHG benefits relative to conventional normal paraffin extraction from kerosene.

D.1 GTL Normal Paraffin Properties

Compared to the traditional route of extracting normal paraffin from kerosene, the GTL route is simpler and has significant capital and operating cost advantages. In the future, GTL technology could largely replace traditional technology to meet the growth in demand for normal paraffin.[138]

Test results to date demonstrate that the performance of GTL normal paraffin, and LAB and LAS derived from it, is equal to that of kerosene derived normal paraffin. GTL normal paraffin from Shell's Bintulu plant has been successfully marketed to LAB producers in Asia since 1993.[139]

Studies show that GTL normal paraffin has no adverse effect on homogeneous and heterogeneous alkylation processes. In addition, LAS made from GTL normal paraffin is adequately biodegradable and its surfactancy and detergency performance is identical to commercially available LAS.[140]

The key benefit of GTL normal paraffin is its cost-effectiveness. Since the manufacturing cost of GTL normal paraffin is lower than normal paraffin made from conventional, kerosene-extraction plants, GTL normal paraffin provides an LAB producer with a more cost-effective feedstock, enabling market growth.

As such, GTL normal paraffin provides significant cost savings for:

• New LAB producers by removing the need to invest in a kerosene-based normal paraffin unit.

• Existing LAB producers looking to expand their capacity by eliminating the need to debottleneck their existing kerosene-based normal paraffin unit.

• Existing, non-integrated LAB producers considering backward integration by removing the need to invest in a kerosene-based normal paraffin unit

In addition to its cost-effectiveness, GTL normal paraffin provides LAB producers with additional benefits. It releases LAB producers from the requirement to build their plant next to a refinery and simplifies plant set up and operation. LAB producers can choose their optimal geographic location, e.g. close to their major customers, that no longer necessarily has to be adjacent to a refinery.

GTL normal paraffin also frees the LAB producer from the competition for kerosene between the aviation, domestic heating and petrochemical markets. LAB producers no longer have to worry about sufficient kerosene being available to run their normal paraffin plant nor about meeting the specification for the kerosene return stream.

D.2 Normal Paraffin Markets

Worldwide consumption of normal paraffin's is expected to grow at an average annual rate of 3 percent, from 2.4 million tons in 2000 to 3.2 million tons in 2010.[141] After four years of tight supplies that drove prices to levels not seen since the early 1990s, the *n*-paraffin market is coming into balance, but if all the planned new plants and expansions proceed, *n*-paraffin capacity could greatly exceed demand towards 2010.

D.3 About LAB

- Linear alkylbenzene sulfonate (LAS or LABS)[142] is a component of laundry detergents and other cleaning products that was created in the early 1960's.
- Linear alkyl benzene sulfonate (LAS) is a common non-soap anionic surfactant in cleaning compositions, and especially laundry detergent compositions, as it provides excellent soil removal benefits, and is widely available.
- Linear alkylbenzene (LAB), the material used to produce LAS, is derived exclusively from petroleum derivatives: benzene and linear normal paraffin.
- The total world LAB production capacity in 2002 was estimated at 2.5 million tons.
- LAS currently represents one-third of the active ingredients in detergents worldwide. Virtually all LAB is transformed into LAS.

D.4 Conversion of Normal Paraffin to LAB[143] *via* Kerosene Extraction

Production of LAB *via* normal paraffin extraction from kerosene is a multi-step energy intensive process. The major steps in the flow scheme of the integrated complex incorporate dehydrogenation and alkylate units. A more detailed discussion of each process step is provided below.

Normal Paraffin Extraction from Kerosene[144]

The separation of normal paraffin's from *iso*-paraffins is performed commercially for a number of reasons. In the lighter hydrocarbon range, *iso*-paraffins are often more desirable because of their higher octane values and their superior gasoline alkylation characteristics. In the heavier range, normal paraffin's are typically the desired product because of the benefits derived from their linearity in the production of plasticizers, linear alkylbenzene sulfonates, detergent alcohols, and ethoxylates.

Commercially proven methods for the liquid-phase adsorptive separation of normal paraffin's from *iso*-paraffins and cyclo-paraffin's exist. Conventional production of normal paraffin's offers an opportunity for the refiner to upgrade straight run kerosene to higher valued products.

Most normal paraffin's extracted from kerosene (about 80 %) are used in the production of LAB. The remainder serves the detergent alcohol, solvent, and lubricant markets.

High purity normal paraffin's in the kerosene can be recovered using separation technology and a long-life molecular sieve adsorbent. The raffinate stream, which consists of *iso*-paraffins and cyclic hydrocarbons, is typically returned to the refiner for jet fuel blending.

A kerosene hydrotreating unit is required to pre-treat the kerosene to a low level of sulfur, nitrogen and oxygenate contaminants. The severity of hydrotreating depends on the level of impurities in the kerosene feedstock and the desired quality of the raffinate stream.

Normal Paraffin Conversion to Linear Olefin

Once normal paraffin's have been separated, they are catalytically dehydrogenated to linear olefins of the same carbon number.[145] The linear olefins are then alkylated with benzene in a detergent alkylation unit.

In the dehydrogenation reaction mechanism, the conversion of *n*-paraffin's to mono-olefins is near equilibrium, and therefore a small but significant amount of di-olefins and aromatics are produced (**Figure D-1**).

Because the process is in near equilibrium, only a small conversion per pass (12 %) is possible, necessitating a significant recycle.

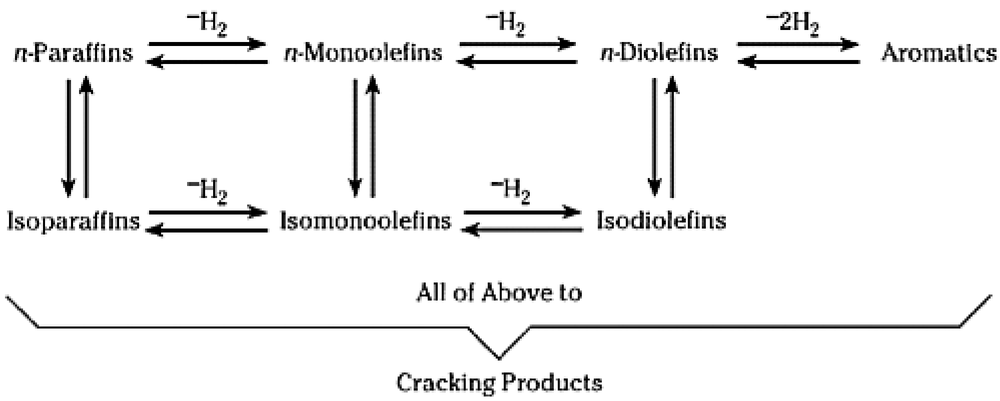

Figure D-1: Conversion of *n*-paraffin's to monoolefins in near equilibrium.

The dehydrogenation of *n*-paraffin's is an endothermic reaction with a heat of reaction of about 125 kJ/g · mol (30 kcal/g · mol; 54,000 Btu/lb · mol). The equilibrium conversion for the dehydrogenation reaction is determined by temperature, pressure, and hydrogen partial pressure. As expected, the equilibrium conversion increases with temperature and decreases with pressure and with increasing hydrogen-to-hydrocarbon ratio. Kinetically, the overall conversion depends on space velocity (feed-to-catalyst ratio): excessively high space velocities do not allow for sufficient conversions, and space velocities that are too low lead to lower selectivities because of the onset of side and competitive reactions.

Selective Hydrogenation of Di-Olefins

Di-olefins produced in the dehydrogenation step can be selectively hydrogenated back to mono-olefins.

Selective Aromatics Removal

Aromatics can be separated prior to the alkylation step. Two streams are created in this step, and these are separated in a column, producing an olefin/paraffin product along with benzene (which is used in the downstream alkylation step).

Alkylation

The alkylation step can utilize a solid catalyst[146] or traditional liquid acid catalyst (HF or $AlCl_3$).

Typically, the alkylation reaction is carried out at a temperature of greater than 100 °C and a pressure of about 300 kPa (abs).[147] The olefins from the paraffin dehydrogenation feed react with the benzene in the alkylation reactor to provide a C_{11}-C_{14} linear alkyl benzene product, unreacted paraffin's, unreacted benzene, and a heavies stream. The unreacted benzene is recycled to the alkylation reactor. The unreacted normal paraffin may be recovered as a product or it may be recycled to the dehydrogenation reactor.

D.5 Production of LAB from Separation and Purification of GTL Normal Paraffin

The Gas to Liquids (GTL) C_9-C_{14} normal paraffin stream is an ideal LAB feedstock because it is linear, has zero sulfur and is free of aromatics. The design of the Shell process[148] means that the C_9-C_{14} broad cut that comes from the Fischer-Tropsch stream is absent of olefin, so is feed first into the dehydrogenation unit.

In the context of the current submission, it is assumed that normal paraffin originating from the Shell process is used. The design of the Shell process means that the C_9-C_{14} broad cut that comes from the Fischer-Tropsch stream is absent of olefin, so it must be fed into the dehydrogenation unit (**Figure D-2**). It needs to be noted here that because of the design of the Sasol process,[149] the C_9-C_{14} broad cut that originates from the Fischer-Tropsch unit would already contain around 25 % olefin,[150] thus reducing or totally eliminating the need for the energy intensive dehydrogenation step.

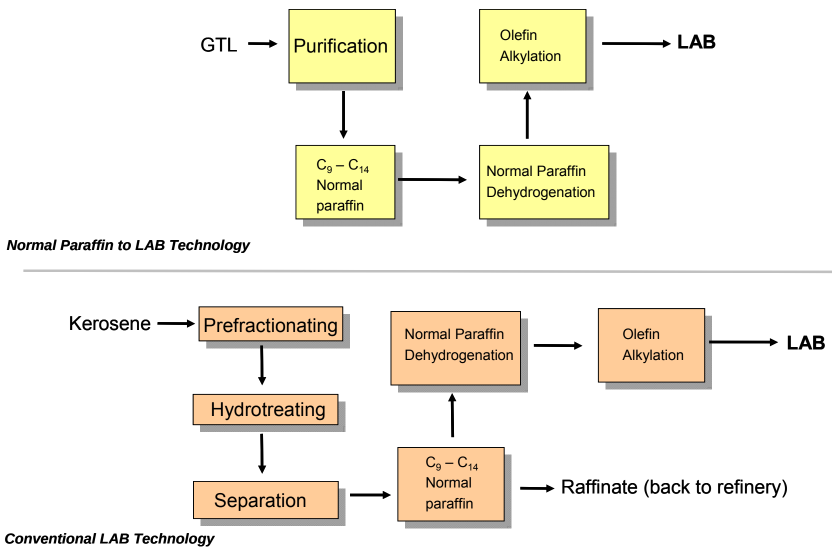

Figure D-2: Comparison of normal paraffin production routes to produce LAB.

D.6 Key Assumptions and System Boundaries for GHG Accounting of GTL Normal Paraffin

This section describes the key technical and economic assumptions used in this submission to compare the GHG impact of GTL normal paraffin with oil derived normal paraffin.

GTL Normal Paraffin: System Boundaries

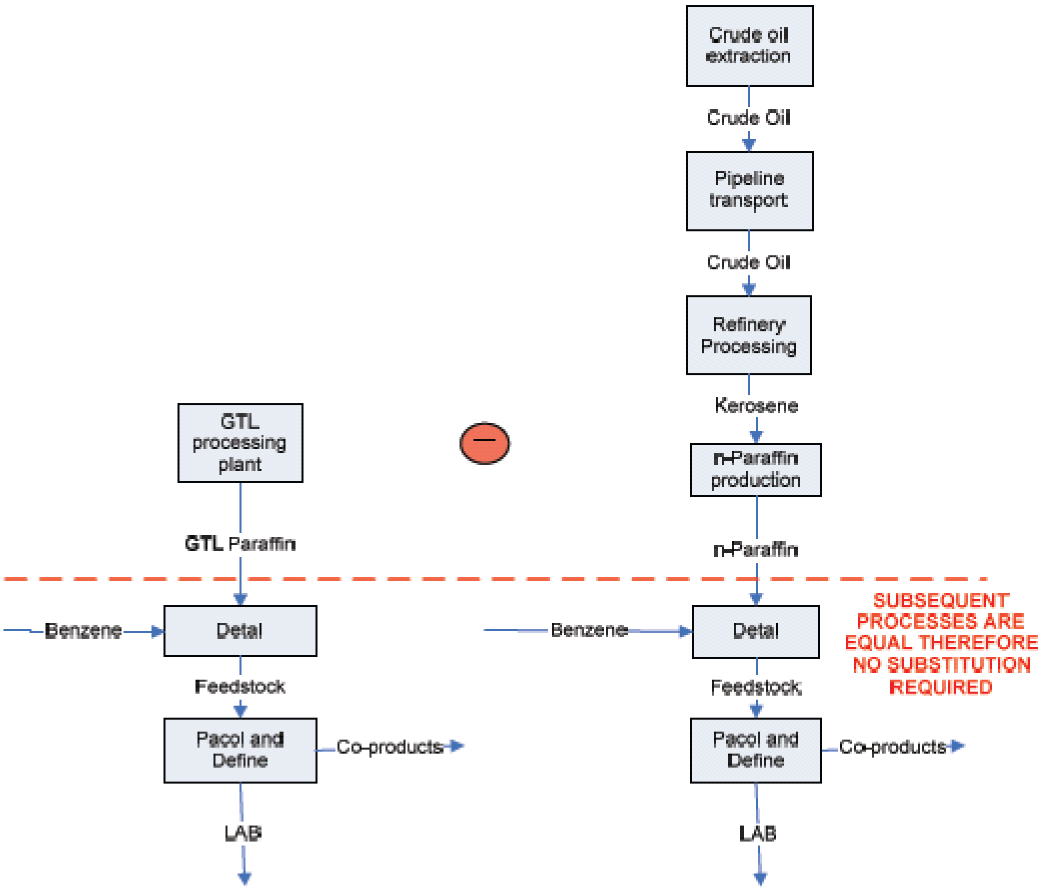

Figure D-3: System boundaries used to compare the GHG Impact of GTL normal paraffin and subsequent LAB production to oil derived normal paraffin and subsequent LAB production.

GTL Normal Paraffin: Key Assumptions

Assumptions and Comments	Source
GTL normal paraffin is produced as a co-product from the GTL plant.	
GTL normal paraffin is used to produce linear alkylbenzene (LAB) for use in detergents (**Figure D-5**). The production process includes dehydrogenation and alkylation (requiring	

benzene as an input). Traditional LAB production requires prefractionation, hydrotreating and separation step of oil derived Kerosene to produce normal paraffin. It is assumed that GTL normal paraffin and conventionally derived normal paraffin are of equal quality therefore the downstream normal paraffin is identical. For this reason, there is no need to account for processes downstream of normal paraffin production.	
It is assumed that GTL normal paraffin production displaces refinery normal paraffin production. The upstream emissions generated from the extraction, transport and processing of crude oil to produce kerosene and then subsequently normal paraffin have been accounted for using the substitution approach.	Tenside, Surfactants, Detergents.[151]

Table D-1: GTL normal paraffin: key assumptions

D.7 GHG Accounting of GTL Normal Paraffin Using the Substitution Method.

Table D-2 provides a breakdown of the amount of GHG emissions associated with the further processing and use of GTL normal paraffin after leaving the gas treatment and GTL plants and the displaced GHG emissions corresponding to the production and use of the products displaced by the co-products. All GHG emissions values are given in g CO_2e/mile for the 2010 scenario.

Paraffins	Processing	Substitution	Delta
Molex	-	-5	-5

Table D-2: The CO_2 balance between GTL normal paraffin and the displaced products using the substitution method. All GHG emissions values are given in g CO_2e/mile for the 2010 base case scenario. “Delta” refers to net emissions using the substitution methodology.

E GTL Lubricant Base Oils Supporting Information

This appendix provides information about GTL lubricant base oils and its GHG benefits relative to conventional lubricant base oils.

E.1 GTL lubricant base oil properties

GTL lubricant base oils have the following high quality features:

- High viscosity index
- Virtually sulfur free
- High oxidation stability
- High saturates

These features contribute to the high performance nature of the lubricants produced from these lubricant base oils. Properties which include compatibility with emission control systems, extended drain periods and improved fuel efficiency for the vehicle.

Typical properties of GTL lubricant base oils produced in the Sasol Chevron GTL process are presented in **Table E1**.

	3 cSt GTL	4 cSt GTL	7 cSt GTL
API Gravity*	43.5	41.5	40
Density, kg/L*	0.809	0.818	0.825
Kinematic Viscosity, cSt at 100ºC	2.7 – 3.1	4.0 - 4.4	6.7-7.3
Viscosity Index*	>120	>135	>145
Pour Point, ºC (D-5950)	<-30	-25 max	-20 max
Noack, wt% (D-5800)	35 max.	12 max	3 max.
Cold Cranking Simulator, cP*		1600 @-35°C	4000 @-30°C

Table E-1: Properties of the core GTL lubricant base oils products.

E.2. GTL Lubricant Base Oils Markets

The global lubricant base oils market is in the region of 740,000 B/D, of which around 56 percent is supplied into the automotive industry for applications such as formulations of engine oils, transmission fluids and gear oils. Industrial lubricants are another significant consumer of lubricant base oils for heavy machinery.

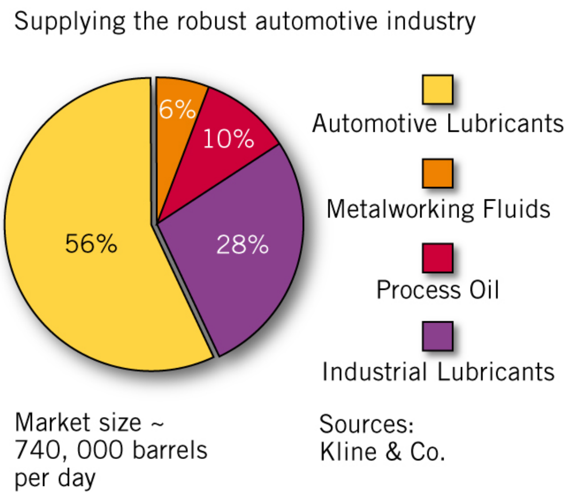

Figure E-1: GTL lubricant base oils supplying the robust automotive industry demand, Kline & Co.

In the automotive industry there is a continued drive for improved energy efficiency, longer lubricant life, improved engine durability and higher levels of catalyst protection for emissions systems. Design changes that improve performance inherently put more stress on lubricants, requiring higher quality.

The automotive lubricant industry bodies classifies a lubricant base oil by its physical and chemical characteristics into four main groupings, as shown in **Table E-2** below.

API & ATIEL Lubricant Base Oil Classification System	
Group I	Lowest quality, least expensive, most readily available. Used in industrial lubricants, and engine oils, which do not require high performance. Better quality Group I may be improved with the addition of Group II or Group III oils to meet some of today's lubricant requirements
Group II	Better quality, most popular lubricant base oil for motor oils in North America (majority of Group II refining capacity) because it's easy to blend with and requires lower treat rate from additives.
Group III	GTL lubricant base oils superior performance properties, but must be blended with Group II/III to make higher performance heavier grades level for new car factory-fill for both engine oils and automatic transmission fluids
Group IV	PAO – Synthetic base stock. Very high performance, but limited availability and expensive. Used in specialty applications requiring excellent thermal stability and cold flow properties

Table E-2: API & ATIEL Lubricant base oil Classification System, API Document 1509.

Although the lubricant base oils market as whole is only growing in the region of 1-2 percent per annum, there is a drive to higher quality products, and in some markets demand for premium lubricant base oils is expected to quadruple by 2015.

GTL lubricant base oils are considered as Group III+ due to their exceptionally high performance which offers lubricant formulators a performance beyond that of current Group III products. This enables them to formulate higher performance oils such as 0W engine oils (normally only produced from Synthetic oils such as PAO's).

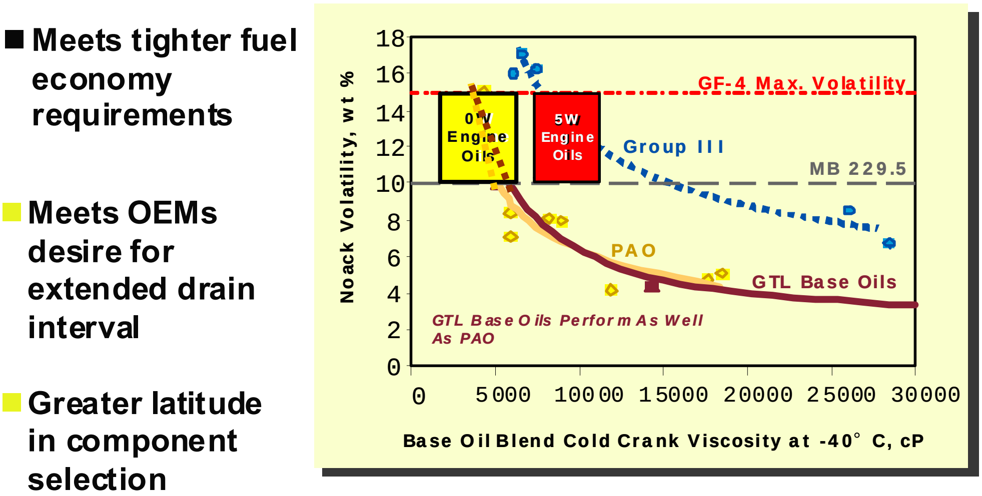

Figure E-2: Performance of GTL lubricant base oils, Chevron Global Lubricants.

Kline & Company's view for passenger car motor oils (PCMO) viscosity grade usage in North America, (representative of the Californian market) shows the improvement in oil quality. Currently 5W-XX engine oil usage is growing at around 5 % per year, eating into the 10W-XX and heavier sales. 0W-XX is showing a small penetration accounting for 1 % in 2007 driven by the supply constrains. Should GTL lubricant base oils be more readily available then OEMs will begin to factory fill and tie warranty coverage to 0W-20 usage. Toyota made a recent announcement about expanding its use of 0W-20 at the expense of 5W-20 in some of its vehicles but has not indicated what % of its fleet will use the lighter visgrade product.

Kline & Company's most recent outlook North America estimated the Californian PCMO market at around 80 million US gallons per annum where 0W-20 is expected to grow by about 3 to 4 % per year to 2016 (**Figure E-3**).

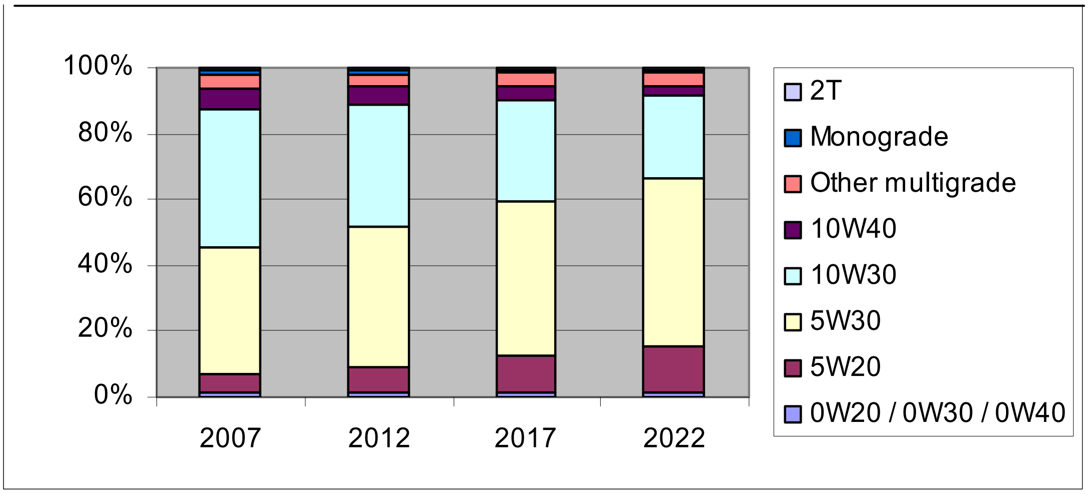

Figure E-3: United States PCMO Market, Chevron & Kline & Co.

E.3 GTL Lubricant Base Oil Applications

Typically a GTL lubricant base oils facility will produce a range of products, some of which are ideally suited to being used in automotive lubricants.

Grade	Typical Applications
3 cSt GTL	Diluent oils for lubricant additives, automatic transmission fluid blends, process oils, metal working fluids
4 & 7 cSt GTL	Top tier fuel efficient SAE 0W-X, 5W-X passenger car motor oils, 10W-X passenger car and heavy duty motor oils, automatic transmission fluids, automotive gear oils, specialist industrial lubricants

Table E-3: GTL lubricant base oils product grades.

E.4 GHG Benefits of GTL Lubricant Base Oil

Vehicle Fuel Efficiency

GTL lubricant base oils provide the opportunity to produce 0W-20 and 5W-20 motor oil grades currently being produced by synthetic material (a chemical derivative). These motor oils have a significant fuel efficiency advantage as can be seen in the claim by ExxonMobil for their synthetic based Mobil 1 product[152]. The fuel efficiency benefit is gained from to high viscosity index of these oils, enabling the oils to provide good lubrication (i.e. low viscosity) to the engine over a broad range of operating temperatures.

In fact in the United States, the new GF-5[153] standard for lubricants will require 0W-20 to provide 0.5 % fuel economy benefit over 5W-20, a 1 % improvement over 5W-30, and 1.7 %

improvement over 10W-30. Over time and as the technology develops for GTL lubricant base oil blending, there is potential for further fuel efficiency gains.[154]

Extended Drain Intervals

In addition to providing fuel economy savings, Fischer-Tropsch-derived lubricant base oils (FTBO's) are extremely stable and enable greatly extended drain intervals. Typical drain intervals in North America are in the region of 5000-6000 miles. A reasonable drain interval for 0W and 5W oils compounds such as those produced by GTL lubricant base oils in normal service with certain manufacturers vehicles could be in excess of 15,000 miles (in fact Renault have released a new specification for Europe, RN 0720, if the oil meets performance and oxidation tests which GTL should be able to, the drain interval will be doubled to 30000 km or 18600 mile). Manufacturers such as Mercedes and VW also offer extended drain periods if specific high performance lubricants are used. Despite the longer drain intervals being supported by OEM warranties, it may take time to change the habits of the consumer thus extended drain intervals to between 7500-10000 miles are expected in the medium term.

E.5 Key Assumptions and System Boundaries for GHG Accounting of GTL Lubricant Base Oils

This section describes the key technical and economic assumptions used in this submission to compare the GHG impact of GTL lubricant base oils with oil derived lubricant base oils.

GTL Lubricant Base Oils: System Boundaries

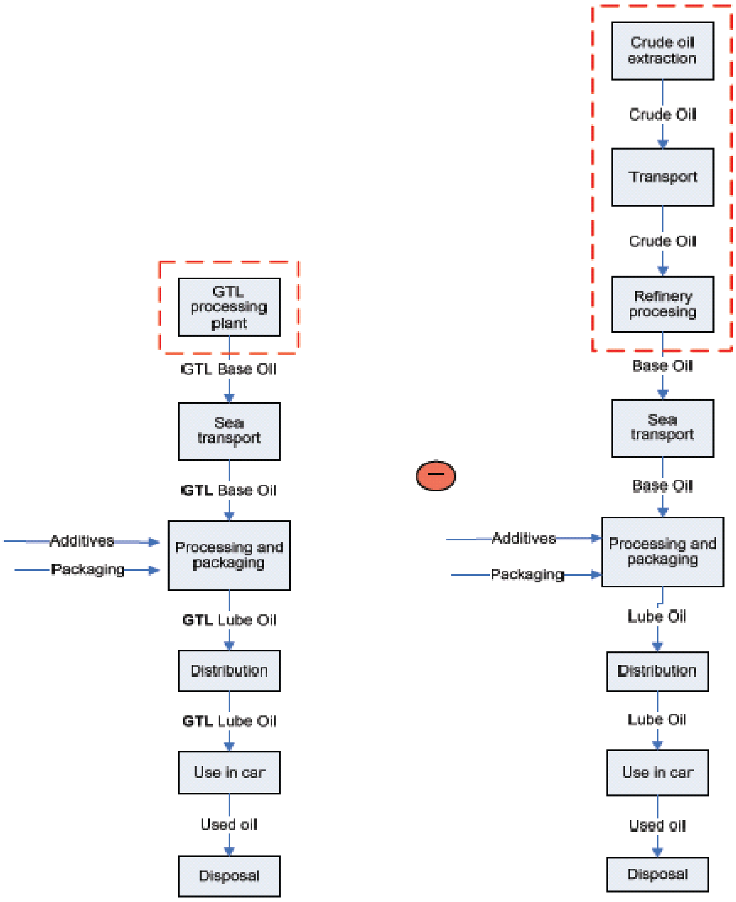

Figure E-4: System boundaries used to compare the GHG Impact of GTL lubricant base oils with oil derived lubricant base oils.

GTL Lubricant Base Oils: Key Assumptions

Assumptions and Comments	Source
GTL lubricant base oil is a co-product from the GTL plant (**Figure E-4**). It is used to produce GTL lubricant oil. GTL lubricant oil is equivalent to Group III+ lubricant oils.	Sasol Chevron data[155]
The quality of GTL lubricant oil is not the same as conventional lubricant oils used in California. Based on lubricant oil market projections (Chevron), it has been assumed that the introduction of GTL lubricant oils will accelerate the replacement of 5W lubricant oils by 0W lubricant oils and 10W lubricant oils by 5W lubricant oils,	Sasol Chevron assumption based on Kline and NPRA information (See section E-2)

respectively, in the Californian market. Therefore it is assumed that GTL lubricant oils will displace Group II lubricant oils.	
The difference in quality between GTL and refinery derived lubricant oils means that GTL lubricant oils allows a greater fuel economy than Group II lubricant oils during the use phase of the lubricant oils as well as greater drain intervals. As a result, the emissions associated with the production, use and disposal of GTL lubricant oils have been modeled and the emissions associated with the life cycle of Group II lubricant oils from the extraction of crude oil to the disposal phase subtracted.	
The upstream emissions from the extraction, transport and processing of crude oil to produce refinery group II/group II+ lubricant base oil have been subtracted from the system under study according to the substitution method. Crude oil is assumed to be extracted on-shore in the Middle East, transported by sea (over 47 miles) to a complex refinery.	Crude oil extraction & Transport: ETH data.[156]
Emissions associated with the refinery of crude oil were provided by Baker O'Brien for the Chevron refinery in Richmond, CA. Refinery lubricant base oil constitutes 6 % of the output of a conventional refinery. As such, an allocation of 6 % of refinery inputs has been used to account for refinery lubricant base oil production.	Baker O'Brien[157]
GTL lubricant base oil shipped 7,200 nautical miles from Middle East to California. Emissions associated with sea transport are derived from literature.	Portworld,[158] ETH data.[159]
It is assumed that Group II+ refinery lubricant base oils used in California comes from two locations: - 50 % in California and is co-located with the lubricant base oil processing plant. - 50 % on the Gulf Coast which requires 2175 miles of road transport to a Californian lubricant base oil processing plant. It is assumed that a Group II lubricant base oil is produced in California (100 %) and is co-located with the processing plant.	ETH data.[160]
The lubricant base oil processing plant is located in California.	
California electricity has a carbon factor of 700lb/MWh.	U.S. EPA161
Additives (15 %) are added to the lubricant base oil in the production of lubricant oil.	
Lubricant oil used in car engines at a quantity of 1.3 US gallons per oil change.	
Oil change interval is 7500 miles (GTL lubricant oil) and 5000 miles (refinery lubricant oil) GTL lubricant oils allow intervals of up to 15000 miles. Despite this, consumer behavior is slow to change and many do not extend their drain interval when using GTL oils. A drainage interval of 7500 miles reflects the use of the full 15000 mile drainage interval by 25% of consumers in 2010. As an indication of the full impacts of GTL lubricant oils if consumers were to use them to their full potential, an oil change interval has also been tested.	Sasol Chevron assumption.
No top up of lubricant oil between oil change intervals.	Kline.[162]
GTL lubricant oils generate average fuel efficiency savings of 0.85 % Derived from assumption that:	Sasol Chevron data.[163]

- GTL lubricant oils are 50 % 0W and 50 % 5W - GTL 0W replaces 5W at efficiency gain of 0.5 %[156] - GTL 5W replaces 10W at efficiency gain of 1.2 %[156]	
Waste lubricant oil is collected and combusted as shipping fuel, displacing the combustion of heavy fuel oil.	Sasol Chevron assumption, US EPA.[164]
No waste oil is re-refined. This is considered an appropriate assumption for two reasons. Firstly, the proportion of waste lubricant oil that is collected and re-refined in the USA is currently very low and considered to be insignificant. Secondly, of that which is re-refined, there are no collection schemes which separation GTL from refinery lubricant oil therefore information regarding the collection volumes and re-refinement of each is unavailable.	U.S. EPA.[165]

Table E-4: GTL Lubricant Base Oils key assumptions

E.6 GHG Accounting of GTL Lubricant Base Oils Using the Substitution Method.

Table E-5 provides a breakdown of the amount of GHG emissions associated with the further processing and use of GTL lubricant oil after leaving the gas treatment and GTL plants and the displaced GHG emissions corresponding to the production and use of the products displaced by the co-products. All GHG emissions values are given in g CO_2e/mile for the 2010 scenario.

Base oil	Processing	Substitution	Total
Total	18944	-19111	-168
Oil extraction	-	-7	
Refinery	-	-1	
Transport/processing	9	-13	
Distribution	1	-2	
Use	18955	-19118	
Disposal	-21	28	

Table E-5: The CO_2 balance between GTL lubricant oil and the displaced products using the substitution method. All GHG emissions values are given in g CO_2e/mile for the 2010 base case scenario. “Delta” refers to net emissions using the substitution methodology.

F The GTL Industry

This appendix provides information on the drivers for GTL and a history of the GTL industry.

F.1 GTL Drivers

A country will often have unique set of drivers for developing a new gas monetisation industry, such as abundant natural gas reserves (**Figure F-1**), limited domestic demand, competitiveness of gas monetization options, etc. Typically, however, each country with large and remote gas would encounter one or more unique aspects that could further add to attractiveness of GTL as gas monetisation option and contribute to the development of a sustainable GTL industry for the benefit of stakeholders.

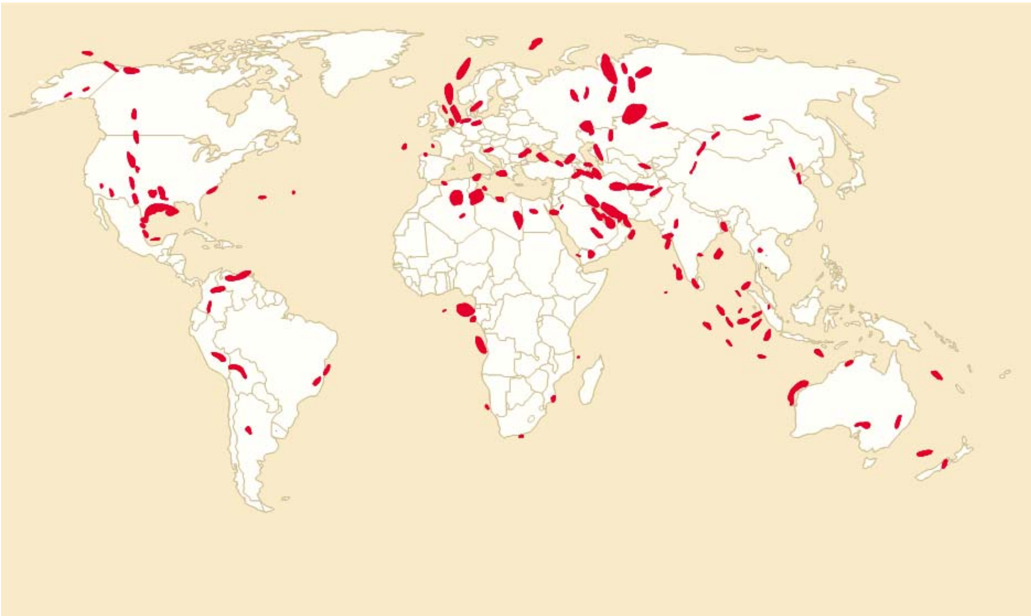

Figure F-1: Distribution of world's natural gas reserves.

- *Security of energy supply*: since GTL diesel is made from natural gas, it contributes to the diversity of transport fuels supply and reduces dependence on petroleum products. This is especially the case where domestic gas can be used to produce GTL products and substitute imports, and where there are domestic gas supply obligations.
- GTL brings *market diversification* for natural gas resource owners and governments alike – often, gas producers will be connected to one or more gas markets *via* pipelines and LNG exports, but making liquid products brings somewhat different market cycles to bear.

- GTL can provide a *potentially greater financial upside to investors*, in the case where natural gas prices are not fully linked to crude oil price.

- GTL brings *significant direct investments* into a country as well as *incremental revenues to the government* (e.g. through profit taxation).

- The GTL process *creates value-added products*, helping get away from exportation of raw materials.

- GTL has *substantial indirect economic benefits*. Greater employment and payroll mean a greater infusion into the local commercial economy.

- GTL creates clean products that *contribute positively to local environments*. GTL diesel has a large number of benefits for both regulators and fleet operators. As mentioned earlier, GTL diesel can be used in conventional diesel engines, and provide significantly lower emissions of local pollutants, such as particulates, carbon monoxide, hydrocarbons and nitrogen oxides, even when compared to so-called 'sulfur-free' diesel. GTL lubricant base oil lubricants can help improve fuel efficiency in the local transport fleet and reduce hydrocarbon use.

- Unlike crude oil refining the GTL process does not produce less desirable by-products such as heavy fuel oil but *targets primarily large market for middle distillates*, which is the fastest-growing part of the petroleum barrel.

- GTL can also create a *blending advantage to local refineries*, which can play to diesel volume creation, avoided capital investment, and adjustment of crude oil slate.

- GTL technology promises to *revolutionize the lubricant base oils market*, and can contribute to a country's position of becoming a leader in lubricants blending and marketing.

- GTL can also *enhance development of petrochemical industry in a country* – although GTL naphtha volume from a typical GTL plant is not sufficient on its own to justify investment into ethylene complex, it can serve one train or so and contribute to creation of a critical mass of feedstock for making ethylene production a reality.

- GTL can have *synergies with other industries*, for example by sharing the cost of building new infrastructure, providing power, heat or water to industrial users in locations nearby GTL plant, etc.

- GTL technology provides a platform for development of Biomass to Liquids (BTL) and Coal to Liquids (CTL) products with identical chemical composition, allowing for a *co-ordinated long-term strategy toward alternative fuels* in the transportation sector.

F.2 GTL History

GTL technologies are well proven and have been in development for nearly a century. In 1922, the F-T process was developed by two German scientists who went on to win the Nobel Prize, Franz Fischer and Hans Tropsch. It was used in Germany during the Second World War to produce approximately 600,000 bbl per year of liquid transportation fuels from coal. Carthage Hydrocol conducted further development in Brownsville, Texas, from 1948 to 1953 to convert natural gas rather than coal. The plant they constructed had a production of 365,000 bbl per year but was shut down and dismantled when there was a dramatic rise in natural gas prices. South Africa began using the F-T process in 1955 using coal as feedstock. A summary of modern GTL development is shown in **Figure F-2**.

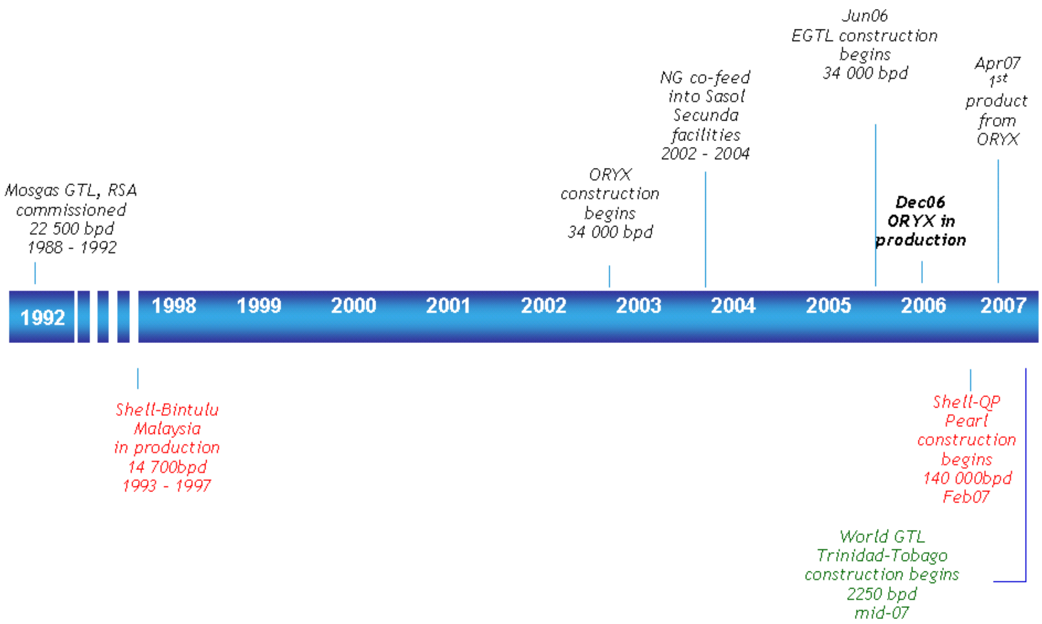

Figure F-2: A summary of modern GTL development.

G About Sasol Chevron

This appendix provides profiles of Sasol Chevron, Sasol, and Chevron Corporation.

Sasol Chevron was established in October 2000 as a 50/50 joint venture between Sasol and Chevron in order to actively pursue the commercial application of GTL technology. Through its parent companies, Sasol Chevron is able to combine the knowledge of the most experienced synthetic fuel producer in the world with the commercial reach and scale of a leading global energy company.

The parent companies are:

Chevron is one of the world's largest integrated energy companies. Headquartered in San Ramon, California, Chevron conducts business in more than 100 countries. The company is engaged in every aspect of the oil and natural gas industry, including exploration and production, manufacturing, marketing and transportation, chemicals manufacturing and sales, geothermal, and power generation, and is also investing in renewables and advanced technologies.

Chevron’s diverse and highly skilled global workforce consists of more than 59,000 employees and about 5,800 service station employees. In 2007, Chevron produced 2.62 million barrels of oil-equivalent per day. About 70 percent of that volume occurred outside the United States and in more than 20 different countries. Chevron had a global refining capacity of more than 2 million barrels of oil per day at the end of 2007, and its marketing network supports more than 25,000 retail outlets on six continents.

Sasol, established in 1950, is a world-leader in the commercial production of liquid fuels and chemicals from coal and natural gas *via* Fischer-Tropsch (FT) process. Headquartered in Johannesburg, South Africa, Sasol is listed on the Johannesburg Securities Exchange and the New York Stock Exchange. The company produces more than 200 fuel and chemical products in plants in Sasolburg and Secunda in South Africa, as well as at several other plants abroad. One of those is Oryx GTL, the largest and technically most advanced GTL facility in the world which is operated in the joint venture with Qatar Petroleum in Ras Laffan, Qatar. These core operations are complemented by oil refining, fuel retailing and coal-mining operations and oil and gas exploration and production.

With a workforce of over 32,000 worldwide and total assets of 17 U.S. $ billion as of mid 2007, Sasol is a leading energy and chemical company comprised of diverse businesses with almost 50 entities located in The Americas, Australasia, Europe and Africa.

Chevron’s international upstream and downstream technologies, experience and resources, combined with Sasol’s FT technologies and experience, creates many synergies between the two companies. For example, Sasol’s leading low-temperature FT technology and Chevron’s renowned ISOCRACKING™ technology offer a unique combination of world class technologies that make part of Sasol Chevron GTL offering. Cooperation between the technology groups of Chevron and Sasol ensure that Sasol Chevron GTL activities remain state-of-the-art and world class.

Sasol Chevron is actively pursuing application of GTL technology for selected Chevron and Sasol reserves of natural gas, for third-party gas reserves and on behalf of host countries seeking to monetise their gas reserves. In addition, it is fostering the development of a GTL industry and global markets for GTL products.

Sasol Chevron's aim is to build, own, operate and manage number of GTL plants around the world and where possible, increase production capacity *via* a series of expansions. This approach is expected to increase the efficiency of operations through the capture of site-specific learning's and deliver economies of scale. This strategy is also supported by a continuous programme of technological development in order to drive down costs of building and operating GTL facility, improve plant performance and increase overall returns.

A unique feature of Sasol Chevron's GTL proposition lies in its ability to leverage knowledge gained from the construction and operation of the Oryx and the Nigeria GTL plants. This has already enabled Sasol Chevron to identify process optimisation and cost-saving opportunities for future GTL facilities, placing it in an advantageous position with respect to other GTL proponents.

The completion, operation and successful marketing of GTL products from the 34,000 bpd Oryx GTL facility stands as proof of the capabilities that Sasol Chevron and its parent companies. In addition, the Nigeria GTL project, which is using the same technology platform as the Oryx GTL project, is in the process of construction. Sasol Chevron provides management, operating and technical services for this project, and will market the GTL products once the plant becomes operational early next decade. It is pertinent to note that the Nigerian and Oryx projects are two of only three new-generation commercial scale GTL projects in the world that have advanced through EPC stage in recent years.

In summary, Sasol Chevron is building a large, sustainable, global GTL business. It is developing and improving its technology in such a way as to ensure robust project economics. The company is fostering the development of a GTL industry and global markets for GTL products, setting new global standards for premium, high quality products. Sasol Chevron's heritage allows it to deploy a combination of operating experience, technology know-how, project management skills and market reach that is unparalleled in the GTL industry. The combination of experience and expertise of Sasol Chevron, its parent companies, and strategic alliances involved in Sasol Chevron's integrated GTL offering gives the company the opportunity to set, together with partners, the worldwide industry benchmark for efficiency and overall returns.

H Overview of Main GTL Technologies

This appendix provides an overview of the main GTL technologies discussed in this submission.

There has been considerable effort over the last 20 to 30 years to commercialise GTL technology. The principles of synthesis gas generation and FT synthesis are common to all, but variations exist in the development of the technology to maximize efficiency and reduce the capital and operating costs.

The most prominent technology developers discussed in this submission are:

a) Sasol

b) Shell

c) GTL.F1 (Statoil / PetroSA/Lurgi)

d) ExxonMobil

e) ConocoPhillips

f) BP

g) Syntroleum

h) Rentech

i) JOGMEC

j) ENI-IFP

k) World GTL

Many of these technology suppliers have allied with specific suppliers of synthesis gas technology and/or product upgrading technology to allow fuller process and utility integration and optimise overall plant performance to improve project economics.

Key features of the major technology developers are described below.

Sasol SPD™

Sasol has operated the FT process at commercial scale since the 1950's. The process has undergone considerable evolution in this time. The initial process, the Arge Process, involved low temperatures (200-250°C), medium pressures (20-30 bar), and tubular fixed bed reactors with an iron based catalyst. The Arge process primarily produced linear paraffin waxes, which were further processed into petrochemical feedstock and transport fuels. The process was suited to synthesis gas produced from coal gasification, had a low efficiency and capacity per train, and required frequent catalyst replacement.

The Arge process was the only process available until the 1960s when the Sasol Synthol Process was developed. This process involved high temperatures (300-360°C) and medium pressures (20-30 barg) and used circulating fluidised bed reactors to produce light olefins for chemicals production and gasoline components. This process has recently been updated to make use of Sasol Advanced Synthol reactors.

The latest development of Sasol Fischer-Tropsch reactor technology is the Sasol Slurry Phase reactor, which is an integral part of Sasol's Slurry Phase Distillate™ (Sasol SPD™) process, and carries out the synthesis reaction at low temperatures (200-250°C) and low pressures (20-30 barg).

Sasol SPD™ technology has undergone several developments primarily concerned with catalyst formulations (**Figure H-1**). Initial development used an iron based catalyst, but recent designs have used a cobalt based catalyst, giving greater conversion and better selectivity towards high value products.

The Sasol SPD™ process employs ATR technology, licensed by Haldor Topsoe, for synthesis gas production. The combination of a single train Haldor Topsoe ATR and Sasol SPD™ FT reactor yields approximately 17,000 bpsd of GTL products. The reactor system is efficient and requires low recycle of carbon dioxide and unconverted synthesis gas.

The product upgrader uses Chevron's hydroprocessing technologies, consisting of Isocracking™ and Isodewaxing™ processes, to produce the diesel, naphtha, lubricant base oils and LPG products.

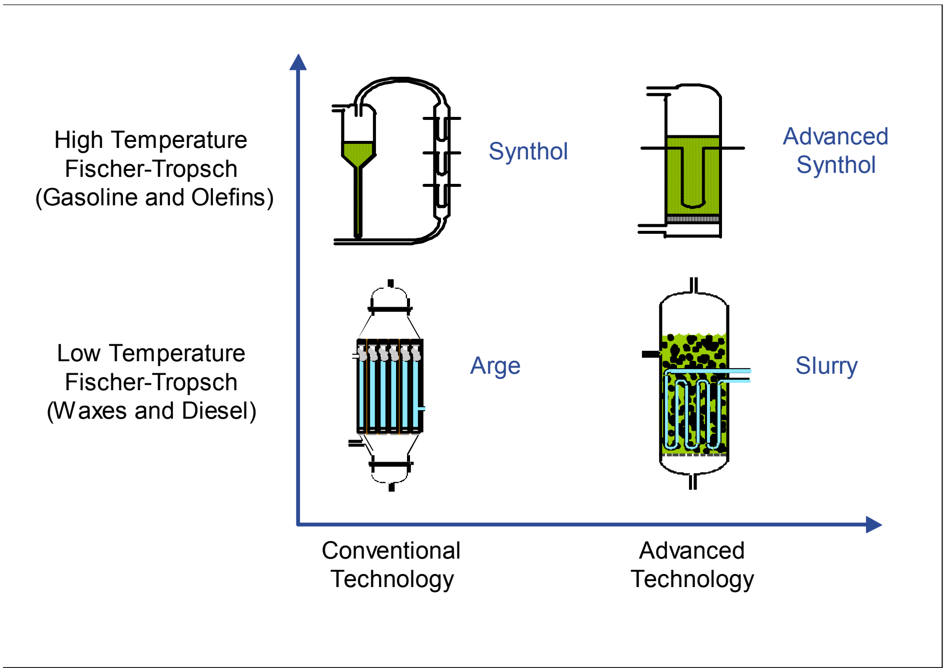

Figure H-1: Sasol's FT Technology Portfolio

Shell Middle Distillate Process

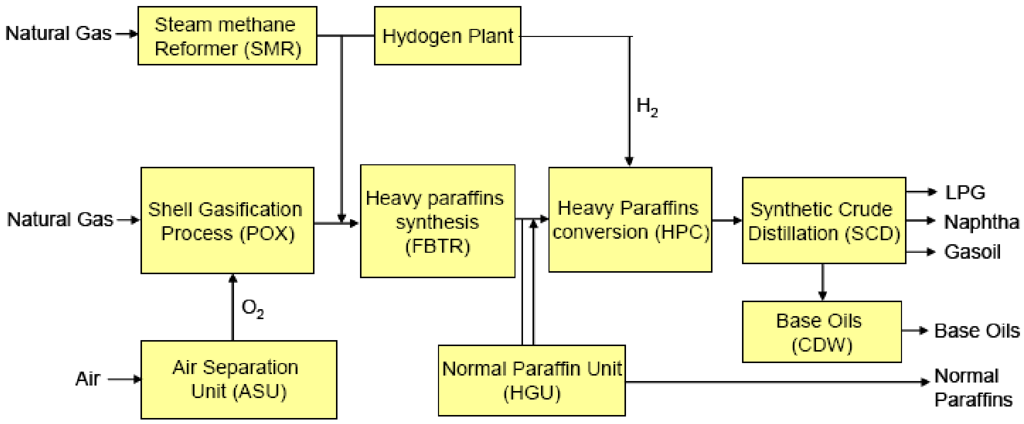

Figure H-2: Shell Middle Distillates Process

Shell has developed a low-temperature FT process known as the Shell Middle Distillate Synthesis (SMDS). Shell GTL technology is based on full integration of three proprietary core technologies (**Figure H-2**). The Synthesis gas technology is based on Shell's extensive experience with partial oxidation technology for coal and oil gasification. It is a proven non-catalytic and highly efficient partial oxidation process and is termed the Shell Gasification Process (SGP). The process was first developed in the 1960's for oil gasification and was adapted for natural gas gasification in the mid 1980's. The SGP technology is supplemented by 'open art' steam methane reforming of tail gas and/or natural gas to achieve the desired H_2:CO ratio adjustment required for FT synthesis. These processes have been proven on a modified commercial scale first generation (SMDS-1) facility built in 1993 at Bintulu in Malaysia.

The FT reactor system is referred to as the heavy paraffin synthesis unit (HPS). The main FT reactor is a tubular fixed bed reactor with a cobalt based catalyst.

The liquid products upgrading section utilises a hydro-conversion process. It includes hydrocracking technology based on Shell's extensive experience in designing and operating hydrocrackers in oil refineries. For the GTL process it has a specially designed catalyst for the benign conditions of F-T wax processing, producing fuels of excellent cold flow properties with high yields of heavy lubricant oil base stock.

Shell is currently constructing the Pearl GTL plant in Qatar. The scale-up from Bintulu to Pearl is almost a 10 fold increase, resulting in a world scale capacity plant. The plant is not simply a scale-up or multi train version of the Bintulu design. Significant developments have been made in terms of scale and /or efficiency whist maintaining the key elements of the technology. One of the key elements of the design is energy management. The gas plant will process about 1.6 BSCFD of North field gas to produce approx. 120,000 BPD of condensate, liquefied petroleum gas and ethane. The dry gas from the gas plant will be used in the new GTL plant to manufacture an additional 140,000 barrels per day of liquid hydrocarbon products.

Shell claim the Pearl GTL will result in:

- World's largest capacity to produce premium quality lubricant base oils;
- World's largest producer of GTL based normal paraffin and at the lowest cost;

- Will include the world's largest single train Hydrocracker in Shell and the worlds largest hydrocracking capacity in one location;
- Will include the world's largest ASU in terms of purity of Oxygen and production capacity in one location;
- World's largest ever catalyst supply contract;
- World's largest system for full recovery of industrial process water, achieving zero-liquid discharge;
- World's largest steam generation capacity of any hydrocarbon processing plant.

GTL-F1 (JV between StatoilHydro, PetroSA and Lurgi)

GTL-F1 is a joint venture between StatoilHydro, PetroSA and Lurgi. Statoil- Hydro and PetroSA established the joint venture in 2002 and Lurgi joined in 2004.

StatoilHydro began development of their GTL technology in 1986 based on use of an active cobalt based catalyst in a slurry bed reactor.

PetroSA own the GTL plant at Mossel Bay which is based on the Sasol Synthol Circulating Fluidized bed reactor technology using iron catalyst at high temperature. The plant had a capacity of 22,500 b/d when started up in 1992.

Lurgi supplied synthesis gas technology to Sasol in South Africa, Shell in Bintulu and PetroSA in Mossel Bay, South Africa. This technology has been further developed and is now licensed as MegaSyn.

The joint venture will license MegaSyn technology in its GTL applications. The joint venture has built and started up a semi-commercial GTL demonstration plant at PetroSA's GTL establishment in South Africa using natural gas from the Mossel field. The demonstration plant uses synthesis gas produced by the existing GTL plant and the products produced are integrated into the existing product refinery. The output from this demonstration unit is up to 1000 bpd of liquids and waxes.

The demonstration reactor is a slurry bed design. Construction was completed in March 2004 and the unit went into production in May 2004. There were initial teething problems in obtaining separation between the catalyst and the wax product which required extensive plant modifications to solve. The test program was delayed until July 2005 when a significant breakthrough in catalyst-wax separation was made. Various trial programs were conducted and in July 2006 the criteria for proof of concept were achieved. Further plant modifications were made from October 2006 to July 2007. The plant is now successfully operating in Phase 2 which is concerned with optimisation of the catalyst-wax separation and proving catalyst performance (activity, attrition etc) over an extended period under commercial operating conditions.

Statoil-Hydro-PetroSA is continuing to improve the process, especially the catalyst and specific reactor internals. A new experimental pilot plant was started up in the Statoil-Hydro's research laboratory to complement work at the demonstration plant and test new catalysts and operational procedures. Its nominal capacity is 0.1 bpd.

ExxonMobil AGC-21 Process

Exxon Research and Engineering began developing process technology to convert natural gas to high quality refinery feedstock in the early 1980's. This resulted in the proprietary Exxon technology: Advanced Gas Conversion for the 21st Century (AGC-21) which was proved in its pilot plant at Baton Rouge, LA.

Exxon's synthesis gas generation process evolved from the company's proprietary fluid catalytic cracking process, Flexicoking, and other large high temperature fluid-bed processes. The current AGC-21 offers synthesis gas generation through simultaneous catalytic partial oxidation and steam reforming in a novel fluid-catalytic bed reactor.

The FT synthesis takes place in an advanced slurry bed reactor system using a proprietary FT catalyst to produce liquid hydrocarbons.

Product upgrade is achieved using conventional fixed-bed Hydroprocessing reactors with proprietary Exxon catalysts to produce diesel, jet fuel, naphtha and heavy hydrocarbons.

In Dec 2004 ExxonMobil and Syntroleum announced an agreement to provide Syntroleum with a worldwide license under Exxon Mobil's GTL patents to produce and sell fuels from natural gas or other carbonaceous substance such as coal. The scope of the agreement included the fields of synthesis gas production, Fischer Tropsch (F-T) synthesis, product upgrading to make fuels and various related processes. It included all existing Exxon Mobil patents in these areas and future improvement patents in this area over the next few years.

A planned GTL Project in Qatar was cancelled due to huge escalation in capital costs.

ConocoPhilips

ConocoPhillips accelerated research and development of their GTL technology in 1997 and claim to have tested more than 5000 catalysts for synthesis gas generation and FT synthesis.

The ConocoPhillips synthesis gas technology is based on partial oxidation in the presence of a catalyst. The technology, termed CoPOXTM, is likely to be the most efficient synthesis gas producer when it is commercialised. The main reason for this efficiency is that it is a flameless reactor where the mixture of natural gas and oxygen are sufficiently hot to react in the presence of a special catalyst. The formation of CO_2 is considerably suppressed allowing maximum conversion of carbon molecules to CO.

A proprietary FT reactor containing catalyst is being tested by ConocoPhillips for conversion of synthesis gas into longer chain molecules: 'syncrude'. The concepts and the design of the reactor remain confidential.

The product upgrading is understood to be typical of the technology employed for FT products and process selection depends on the product slate. The syncrude can be converted into a range of products including diesel, naphtha, wax and/or other liquid petroleum products.

ConocoPhillips has recently commissioned a demonstration facility at Ponca City, Oklahoma and it is anticipated that a commercial unit may become a reality by the end of the decade. However, considerable development work still remains to be performed with the selected catalysts before a commercial unit is designed and put into operation.

BP

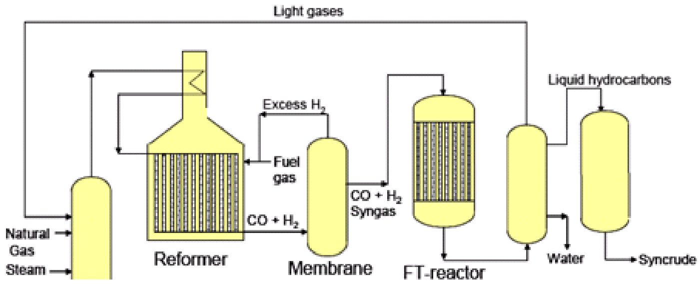

Figure H-3: BP Process

BP has been aggressively pursuing GTL technology and developing their FT synthesis process since the 1970's. The company has partnered with Davy Process Technologies (DPT) to perform pilot scale and demonstration plant activities (**Figure H-3**).

BP has carried out considerable R&D in synthesis gas production and has developed with Davy the "Compact Reformer Technology" that is based on the Steam Methane Reforming process. A typical 10,000 b/d plant would require 24 compact reformers each occupying ~ 25 m². This compact size allows the reformers to be shop fabricated and makes them suitable for application at locations which may have limited site area. The technology also offers the potential for Floating Production, Storage and Offloading (FPSO) application.

Another unique feature of the BP process is the use of a membrane separator to remove the stoichiometric excess of hydrogen which can either be used as fuel for the reformer or as feed to a PSA unit to feed the Hydrocracker and gas treatment unit.

The FT synthesis process uses a fixed bed reactor with cobalt-based FT catalyst. BP claim to have a wealth of technologies available with proprietary cobalt-based catalysts depending on the required product slate.

BP has recently commissioned a 300 bpd demonstration facility located in Nikiski, Alaska.

- Advantages claimed for this technology are:
- High gas utilisation and carbon conversion efficiency;
- High thermal efficiency and low energy usage;
- Simple water balance and low waste water emissions;
- Flexibility for varying gas feed conditions;
- Small footprint suitable for remote site installation;
- Integrated flow sheet including offsite and utility systems;
- Modular construction with short project schedule;
- Lower capital cost and fast payback.

Disadvantages

- Not proven at large scale

A further development is being undertaken at a pilot plant in Hull to improve the economic benefits of the FT process by use of Advanced Jet Technology (AJT). The perceived benefits over fixed tubular bed and slurry bed technologies are:

- More uniform and stable temperature through the reactor and its ancillaries;
- A uniform controlled hydrogen to carbon monoxide ratio throughout the reactor.

These features lead to the following:

- Higher yield of useful products
- Higher rate of production per unit volume and unit weight of reactor than a fixed tubular bed
- Efficient mass transfer from the gas through to the catalyst suspended in the products, to transfer reactants to the catalyst and remove water and lighter products

Syntroleum

Syntroleum's GTL development dates back to the late 1970's. The main distinguishing factor of their technology is in the synthesis gas production step. Synthesis gas is produced by reacting methane-rich natural gas with compressed air (rather than high-purity oxygen) and steam in an exothermic autothermal reformer using a combination of partial oxidation and steam methane reforming. This air-based synthesis gas production allegedly reduces the capital and operating cost as there is no requirement for an ASU. However, as oxygen forms only 20 % of the air the synthesis gas produced contains 50 % nitrogen which leads to larger piping and equipment sizes with increased cost. The presence of a high percentage of nitrogen also presents problems in recycling the gas and for the recovery of light components from the gas stream. This results in lower yields, which requires an increase in the number of reactors. The diluted fuel gas produced is of poor quality and of low heating value which leads to inefficiencies in combustion and heat recovery.

The FT synthesis step uses a Syntroleum pioneered cobalt based catalyst in a slurry bed reactor to produce a syncrude.

Hydrocracking and associated technologies are used to upgrade and fractionate the syncrude into a range of products such as diesel, jet fuel, naphtha, middle distillates and also synthetic gasoline.

In 1999 Arco (now BP) built and operated a 70 bpd GTL demonstration facility at Cherry Point (CA) based on Syntroleum technology. The facility was operated for one year and was dismantled in 2001 and moved to Tulsa, Oklahoma. Syntroleum has rebuilt this facility under a cooperative agreement between DoE, Syntroleum Corp., Marathon Oil Co., and integrated Concept Research Corp. The facility will produce approximately 100 bpd which will be tested in bus fleets.

Syntroleum have now entered into an agreement with Exxon Mobil.

Rentech

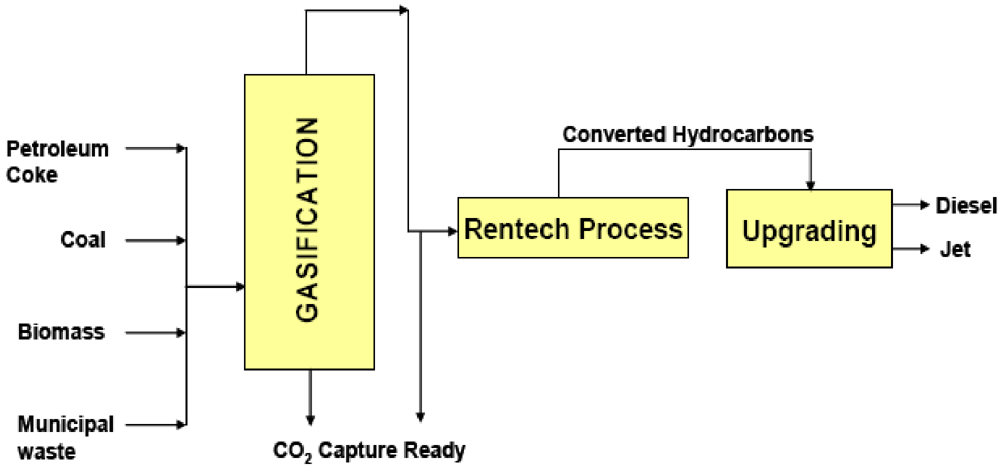

Figure H-4: Rentech Process

Rentech have been developing their GTL conversion capabilities since the early 1980's. Rentech's GTL process can be used with any of the third party synthesis gas technologies available coupled with the Rentech FT process (**Figure H-4**).

Rentech's FT synthesis process uses an Iron based catalyst in a slurry reactor. Rentech has designed, built and operated FT reactors ranging in size from 1½" diameter to a commercial scale reactor 6 feet in diameter and 55 feet tall.

In June 2004 Rentech and Headwaters announced a 50:50 joint venture between the 2 companies to combine their respective iron based Fischer Tropsch gas to liquids technologies. The joint venture will be named "FT Solutions LLC" (FTS). FTS claims to offer a solution that can utilize other low-cost carbon bearing feedstock's such as coal, orimulsion, biomass, low BTU (CO_2 rich) natural gas etc.

Technology advantages claimed for the Rentech process are:

- Flexibility: can use any commercially available front and back end
- Wide range of potential feedstock's
- Use of slurry reactor
  - high on-line time and throughput
  - low pressure drop and excellent temperature control
  - ease of scale up
- Iron-based catalyst
  - Higher diesel production
  - Significantly lower risk of sulfur poisoning
  - Lower cost with simple disposal

Rentech have recently started design work on an upgrade of a Nitrogen Fertiliser Facility which uses natural gas as a feed material to produce 830 tons/day of Fertiliser. The facility is to be converted to produce 1000 tons/day of ammonia and 2000 barrels/day of clean fuels and chemicals. The upgrade is being phased with the first phase to expand the manufacturing of fertiliser to 1000 tons/day, and the next phase adds Rentech's proprietary technology to manufacture the synthetic fuels.

JOGMEC

JOGMEC was formed from a collaboration of five Japanese private sector companies in order to conduct research and development of GTL technology. The Yufutsu Pilot Plant Project was built and operated to demonstrate the practicality of this technology between 2001 and 2004. The project conducted several thousand hours of practical operation converting a natural gas feedstock with 20 mol% carbon dioxide into GTL liquid products at 7.3 barrels per day.

JOGMEC has begun joint research with Nippon GTL Technology research, which itself is a joint venture of 6 Japanese companies established in October 2006, in order to begin a GTL demonstration plant project to convert natural gas to liquid with a potential for international development. The GTL demonstration plant project is scheduled from 2006 to 2010. The aim is to test GTL technology in a 500 barrels per day demonstration plant to further develop GTL technology and gather the data necessary to design and optimise a technically and economically competitive commercial scale process.

The unique feature claimed for JOGMEC technology is that it is capable of utilizing higher proportions of carbon dioxide in the feedstock (20 to 40 %) than other technology providers. The JOGMEC process uses innovative catalyst technology in both the synthesis gas reformer and in the FT reactor. Other developments in heat recovery have improved overall energy management at the conversion plant. The process also does not require oxygen for the synthesis gas reaction.

ENI-IFP

EniTecnologie and the Institut Francais du Petrole (IFP) are collaborating to develop gas to liquids technology. Their process includes proprietary FT and upgrading processes using proprietary catalysts and a novel reactor design.

The process yields naphtha, gas oil, and kerosene cuts, bases for lubricants, waxes, and other specialty products. A pilot plant with a capacity of 20 bpd has been built at the Eni refinery in Sannazzaro de Burgondi in 2001.

World GTL

A niche player in the industry, World GTL identifies remote, shut-in natural gas deposits that are promising development candidates for applying GTL technology, yet is too small for the majors. Around the world, World GTL seeks to employ its patent technology to efficiently unlock the value of underutilized resources and bring them to market.

World GTL's strategy is to reduce capital expenditure by using otherwise unwanted methanol reactors, allowing it to pursue small stranded gas fields.

I GTL Data for This Submission

This appendix provides the GTL Data (with Comments) that are used in this submission.

I.1 Natural Gas Recovery Efficiency

In the GTL context, natural gas recovery efficiency is defined as the fraction of mass or carbon in the natural gas stream that is present in the exported product streams. The natural gas energy efficiency excludes CO_2 extracted and separated from the gas field. This figure includes all carbon present in stabilized field condensate and CO_2 in the feed gas stream, and is represented by **Equation I-1**.;

$$\text{GTL Natural Gas Recovery} = \frac{\sum \text{(Methane Rich Gas, LPG, Condensate, } CO_2\text{)}}{\sum \text{(Raw Gas, Unstabilized Condensate)}}$$

Equation I-1. Calculation of GTL Natural Gas Recovery Efficiencies.

The natural gas recovery efficiencies for the 2010 and 2020 reference plants are shown in **Table I.1**. Both sets of values are similar for both reference years.[166]

	Gas Extraction Carbon Efficiency	Gas Extraction Energy Efficiency
2010 Reference Plant	98.00%	96.20%
2020 Reference Plant	97.80%	96.70%

Table I-1. Natural gas recovery efficiency values.

I.2 GTL Plant Process and Carbon Efficiency

GTL Plant carbon efficiency is defined as the fraction of carbon in the Methane Rich Gas stream that is present in the GTL product streams, and is represented by **Equation I-2.**

$$\text{GTL Plant Carbon Efficiency} = \frac{\sum \text{(LPG, Naphtha, Diesel, Paraffin, Base Oil)}}{\sum \text{(Methane Rich Gas)}}$$

Equation I-2. Calculation of GTL plant carbon efficiency.

GTL *Total carbon efficiency* is defined as the fraction of carbon in the Raw Gas and unstabilized condensate stream that is present in the carbon product streams. This figure includes all carbon present in stabilized field condensate and CO_2 in the feed gas stream, and is represented by **Equation I-3.**

$$\text{GTL Total Carbon Efficiency} = \frac{\sum (\text{LPG, Naphtha, Diesel, Paraffin, Base Oil, Condensate, } CO_2)}{\sum (\text{Raw Gas, Unstabilized Condensate})}$$

Equation I-3. Calculation of total carbon efficiency

GTL Plant energy efficiency is the fraction of internal energy within the Methane Rich Gas stream that remains within the GTL product streams. Efficiency calculations include total facility utility consumption, and are represented by **Equation I-2.**, on an energy basis.

GTL *Total energy efficiency* is defined as the fraction of internal energy in the Raw Gas and unstabilized condensate stream that is present in the carbon product streams. This figure includes all carbon present in stabilized field condensate and CO_2 in the feed gas stream, and is represented by **Equation I-3.**, on an energy basis.

Since a WtW assessment of GTL is being made, the overall carbon and energy efficiency, which includes condensate and CO_2 extraction, needs to be considered.

The GTL and overall carbon and energy efficiencies for the 2010 and 2020 reference plants are shown in **Table I.2**. In both reference years the overall carbon and energy efficiency is slightly higher than the GTL plant carbon and energy efficiency. This reflects the higher relative efficiency of condensate separation, offset by upstream CO_2 separation.

	2010 Reference Plant	2020 Reference Plant
GTL Carbon Efficiency	79.10%	81.70%
Overall Carbon Efficiency	81.80%	83.00%
GTL Energy Efficiency	63.50%	65.50%
Overall Energy Efficiency	67.60%	68.50%

Table I-2. Carbon and energy efficiency values

It needs to be noted that the GTL plant carbon and energy efficiency values correspond relatively closely with data in GREET 1.8b. It is Sasol Chevron's understanding that the efficiency inputs originate from a 3rd party report on the status of GTL technology, based on discussions with Shell and Sasol Chevron, and is intended as input to the JEC Well-to-Wheels Study.[167] The rationale for these assumptions is highlighted below, and is an except from the JEC submission;

The current version of the JEC Study specifies an overall energy efficiency for the GTL plant within the range 61%-65%, with a best estimate of 63%. The best estimate is based on input from Shell, and is representative of the design of the Bintulu plant in Malaysia, which has been in operation since the early 1990s. A number of larger scale plants are currently in *construction and planning, and will be able to match or exceed the level of efficiency achieved in Bintulu, so some adjustment to the figures in the JEC Study is appropriate. The overall efficiency is dependent on a close integration of all elements in the GTL process, so close attention to these aspects during the initial design of the plant is important. Enhancements to existing plants are possible, but more difficult. Many of the technology options available may be cost-effective, however measures within the market and regulatory framework that enhance the value of GHG reductions will provide further encouragement for their adoption.*

GTL plants depend for their success on an abundant and economical source of natural gas, and in some cases are a means of exploiting remote gas sources that would otherwise be difficult to bring to market. Plants are therefore usually designed to be self-sufficient, with all the energy needed derived from the feed gas. For syngas production, the feed gases need to be heated, and energy is also needed for the Air Separation Unit which produces oxygen for the syn-gas reactor. The F-T synthesis itself is a low temperature process using a cobalt based catalyst to produce the predominantly paraffinic products. A finishing unit is needed to crack larger waxy molecules, and to saturate any olefins formed in the process.

Good heat integration is a key factor in maximising plant efficiency. Excess heat is present in the syn-gas, and steam is generated in the F-T synthesis reactors. These energy streams can be used to drive the ASU and also to achieve heat-integration in the syn-gas reactor. The degree of heat-integration in the syngas reactor is limited by the temperature capabilities of the heat exchanger materials, so not all the available heat can be used, and some NG must be combusted inside the reactor to bring the gases to the required temperature. Even with this limitation, future new plants will be able to achieve improvements of around 2% over the current baseline. Materials with improved temperature resistance could allow further efficiency gains towards the end of the review period.

Even with the best heat integration, there is an excess of waste heat from the plant, which provides an opportunity if it can be harnessed. Energy and utilities from the GTL plant can be used in the upstream for the extraction of ethane, LPG and condensates, providing a credit compared with a stand-alone NG production facility. Waste heat at high temperature may additionally be used for co-generation of electricity, but electricity export may not be possible from remote locations. Waste heat from the F-T synthesis or other process steps, at much lower temperatures, could potentially be used for water desalination or district heating depending on local needs. Opportunities for integration with activities outside the plant will be greater in industrialised areas like Qatar than in more remote locations e.g. Russia. Use of waste heat in this way therefore depends greatly on the individual plant situation, and is in any case subject to economic constraints. The various options are covered by the uncertainty range included in the JEC Study.

The quality of the feed gas is an important consideration, since CO_2 *and* N_2 *in the natural gas supply will act as inert diluents in the reaction process, reducing the efficiency. For this reason, GTL plants will only be built where the gas quality is appropriate and contains a suitably low level of diluents. GTL producers base their calculations on the actual available gas composition, and it is this information that has been used in preparing this report. Variations in efficiency due to feed gas composition are adequately covered by the range included in the JEC Study.*

The F-T process is exothermic and improvements are constrained by the theoretical limits that dictate that at least 22% of the input energy is rejected as heat. Current catalysts are effective, but with increasing understanding of catalyst chemistry and the availability of rapid screening techniques, incremental improvements can be expected in the future. However, catalyst development is a lengthy process, and is unlikely to further contribute significantly to improvement of process efficiencies until near the end of the review period. A further aspect of the F-T process is the need to preserve as much as possible of the product in the more valuable liquid products. Current plants may recycle gaseous products or use them for fuel gas.This aspect is considered to be already optimised in state-of-the-art designs.

In view of the above considerations, it is recommended that the GTL efficiency in the JEC Study be revised to a range of 63% to 67%, with a best estimate of 65%. These figures are considered realistic and representative

I.3 GTL Representative Plant Product Distributions

GTL Representative GTL plant product distributions for 2010 and 2020 are depicted in **Table I.3**. GTL co-products, including condensate, make up 59.3 % and 55.9 % of the total carbon product distribution respectively.

	2010 (Carbon)	%	2020 (Carbon)	%
LPG+ GTL LPG	2612.8	8.4	3365.4	6.6
Condensate	5555.9	17.8	7554.6	15
GTL Naphtha	7214.1	23.1	11472.6	22.7
GTL Diesel	12694.7	40.7	22297.0	44.1
GTL Paraffin	758.3	2.4	1304.2	2.5
GTL Lube Oils	2346.2	7.5	4516.3	8.9
Total	31182.1		50510.1	

Table I-3. GTL representative plant product distributions for 2010 and 2020, respectively. Values are in tonnes per day of carbon content.

I.4 GTL Diesel Fuel Spec Data

Updated GTL diesel fuel spec data[168] is provided in **Table I.4**.

		GREET 1.8b FTD Value	Sasol Value
Density	grams/gallon	3,017	2,915
Carbon Content	%	85.3	85
HHV	Btu/gal	130,030	129,845
LHV	Btu/gal	123,670	121,052

Table I.4: GTL diesel fuel specification (compared to GREET 1.8b inputs).

9 Notes and References

[1] California Air Resources Board, "*The California Low Carbon Fuel Standard Regulation*", Draft, October 2008.
http://www.arb.ca.gov/fuels/lcfs/101008lcfsreg_draft.pdf

[2] GREET 1.8b was developed by the Argonne National Laboratory
http://www.transportation.anl.gov/modeling_simulation/GREET/greet_1-8b_beta.html

[3] California transport statistics (CARB);

- 5th largest economy in the world
- 5th largest economy in the world
- 5th largest consumer of energy in the world
- 2nd largest consumer of gasoline and diesel in the world
- Approximately 26 million registered motor vehicles
- $150 million for gasoline and diesel spent daily

[4] The Californian Air Resources Board identified the LCFS as an early action item with a regulation to be adopted and implemented by 2010.

[5] Simeroth, D (California Air Resources Board), "*California's Low Carbon Fuel s Low Carbon Fuel Standard*", Hart's World Refining & Fuels Conference s World Refining & Fuels Conference, May 2007.

[6] CARB is using a model called GREET (GREET 1.8b) to calculate these emissions.

[7] "*A Low-Carbon Fuel Standard for California*", Institute of Transportation Studies, University of California, Davis.
http://steps.its.ucdavis.edu/publications/2007pubs/stepspubs_its/FarrellSperlingLCFS1.pdf

[8] For examples, see:
(a) Börjesson, P. "*Life cycle assessment of biofuels; - how should we calculate?*", Agricultural biofuels and the media World Bioenergy 2008 27-29 May, Jönköping, Sweden
http://www.jti.se/uploads/Borjesson2.pdf
(b) Searchinger, T., R.; Heimlich, R.A.; Houghton, F.; Dong, A.; Elobeid, J.; Fabiosa, S.; Tokgoz, D.; Hayes, Yu, T.H., "*Use of U.S. Croplands for Biofuels Increases Greenhouse Gases through Emissions from Land Use Change*," Science, *319 (5867)*, **2008**, 1238 – 1240.
(c) Lundie, S.; Ciroth, A.; Huppes G. "*Inventory methods in LCA: towards consistency and improvement*", (Inventory methods in LCA: towards consistency and improvement), June 2007.
(d) Wang, M. (Argonne National Laboratory) "Life-Cycle Analysis of Biofuels: Issues and Results", (Presentation to the Special Committee on Domestic Biofuels), State of Wisconsin Joint Legislative Council, Madison, WI, October 14, 2008.
http://www.legis.state.wi.us/lc/committees/study/2008/BIO/oct14wang.ppt#256,1,Life-Cycle Analysis of Biofuels: Issues and Results

[9] For example, comparing estimated global warming pollution from two full-lifecycle models, GREET and LEM (LEM is the Lifecycle Emissions Model, which includes detailed estimates of emissions from land use changes ("*A lifecycle emissions model (LEM): Lifecycle emissions from transportation fuels, motor vehicles, transportation modes, electricity use, heating and cooking fuels, and materials*." Institute of Transportation Studies. University of California at Davis. http://www.its.ucdavis.edu/publications/2003/UCD-ITS-RR-03-17-MAIN.pdf) provides significantly different results for CA reformulated gasoline, ethanol and biodiesel from soybeans.

[10] The ISO 14040 series of standards contain the international standards for Life Cycle Assessment. The series was developed with international experts on LCA from more than fifty countries over a period of more than 10 years.

[11] http://www.arb.ca.gov/fuels/lcfs/111607shell.pdf

[12] "*Use of a Life Cycle Approach to Compare the Environmental Implications of Sasol's Slurry Phase Distillate Technology with Complex Refinery"*, November 2002.

[13] (a) "*Well to Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context*", March 2007, CONCAWE, EUCAR, JRC.
http://ies.jrc.ec.europa.eu/uploads/media/WTW_Report_010307.pdf
(b) "*An Assesment of Health and Environmental Impacts of GTL Diesel*", August 2005, Institute for Energy and Environmental Research (IFEU).
(c) "*Use of a Life Cycle Approach to Compare the Environmental Implications of Sasol Chevron's Slurry Phase Distillate Technology with Alternative Processes producing Transportation Fuels - European case update"*, March 2006.

[14] "*Shell Middle Distillate Synthesis (SMDS) Update of a Life Cycle Approach to Assess the Environmental Inputs and Outputs, and Associated Environmental Impacts, of Production and Use of Distillates from a Complex Refinery and SMDS Route*", May 2003.
http://www.senternovem.nl/mmfiles/150137_tcm24-280087.pdf

[15] "*Gas to Liquids Life Cycle Assessment Synthesis Report*", August 2004, Prepared for: ConocoPhillips, Sasol Chevron and Shell International Gas (Prepared by: Five Winds International)
http://www.shell.com/static/shellgasandpower-en/downloads/products_and_services/what_is_gtl/benefits_of_gtl/gtl_lca_synthesis_report.pdf

[16] Various other LCA studies of GTL have been performed, and show variable results, often because of variant allocation and substitute approaches. Selected examples;
(a) Greene, D. L.(Oak Ridge National Laboratory), "*An Assessment of Energy and Environmental Issues Related to the Use of Gas-to-Liquids Fuels in Transportation*", Center for Transportation Analysis, November 1999.
http://cta.ornl.gov/cta/Publications/Reports/ORNL_TM_1999_258.pdf
(b) Bagajewicz, M.; Sujo, D.; Martinez, D.; Savelski, M. "*Driving Without Petroleum? – A Comparative Guide to Biofuels, Gas-to-Liquids and Coal-to-Liquids as Fuels for Transportation*", May 2007.
http://www.agric.wa.gov.au/content/SUST/BIOFUEL/050607_drivingwithoutpetroleum.pdf
(c) Johnson, E. (SRI Consulting) "Carbon Footprints of Biofuels & Petrofuels", October 2007.
(d) Jaramillo, P.; Griffin, M.; Matthews, S. "*Comparative Analysis of the Production Costs and Life-Cycle GHG Emissions of FT Liquid Fuels from Coal and Natural Gas*", Env. Sci. Tech., *42(20)*, **2008**, 7559 – 7565.
(e) Oak Ridge National Laboratory for US DOE, *"An assessment of Energy and Environmental Issues Related to the Use of Gas-To-Liquid Fuels in Transportation"*, 1999.
(f) Kavalov, B. (JRC) "*Techno-economic analysis of Natural Gas application as an energy source for road transport in the EU*", January 2004.
http://www.edis.sk/ekes/eur21013en.pdf
(g) Edwards R., et al, *Well-to-wheels analysis of future automotive fuels and powertrains in the European context*, Concawe, Eucar, European Commissions, well-to-wheels report, version 2a, December 2005.
(h) Beer,T.; Grant, T.; Morgan G.; Lapszewicz, J.; Anyon, P.; Edwards, P.; Nelson, P.; Watson, H.; Williams D. (Australian Greenhouse Office, CSIRO) "Comparison of Transport Fuels -Life-cycle Emissions Analysis of Alternative Fuels for Heavy Vehicles"
http://www.cmar.csiro.au/e-print/open/beer_2001a.pdf
(i) Marano, J. J.; Ciferno, J. P. (DOE) "*Life-Cycle Greenhouse-Gas Emissions Inventory For Fischer-Tropsch Fuels*", June 2001.
http://www.futurecoalfuels.org/documents/061107_GHGfinal.pdf
(j) General Motors "*Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems – North American Analysis*" – June 2001
http://www.fischer-tropsch.org/DOE/DOE_reports/10556/ANL-ES-RP-10556,%2008-23-01.pdf
(k) Wang, M.; Wu, M.; Huo H. (Center for Transportation Research, Argonne National Laboratory) "Life-Cycle Energy and Greenhouse Gas Results of Fischer-Tropsch Diesel Produced from Natural Gas, Coal, and Biomass", May 2007.

http://www.clf.org/uploadedFiles/CLF/Programs/Clean_Energy_&_Climate_Change/Climate_Protection/Regional_Greenhouse_Gas_Initiative/Exhibit%20A.pdf
(l) Brandt, A. R; Farrell, A. E. "*Scraping the bottom of the barrel: greenhouse gas emission consequences of a transition to low-quality and synthetic petroleum resources*" Climatic Change, *84*, **2007**, 241–263

[17] The Gas Reception Facility receives a multiphase feed from a pipeline into a slug catcher. The slug catcher serves to separate field condensate and glycolated water from the feed gas stream. Field condensate is stabilised and treated, if required, for atmospheric storage as final product, and glycol is recovered from the aqueous phase to be returned and the remaining water is treated. The Gas Treatment Plant (GTP) then conditions the feed gas to meet the specifications of the downstream GTL plant. The GTP removes sulfur components, mercury, CO_2 (if required) and water in the gas to the NGL recovery section, which achieves deep recovery of NGLs to generate a sweet, methane-rich feed gas to the GTL plant as well as final product streams of propane, butane and plant condensate. Where feed gas has high sulfur content, the facility design allows pelletised sulfur to also be a product from the GTP.

[18] http://www.oryxgtl.com.qa/English/index.html

[19] http://www.chevron.com/Investors/FinancialInformation/AnnualReports/2005/human_ultraclean.asp

[20] http://www.shell.com/home/content/qatar/news_and_library/press_releases/2006/integrated_pearl_gtl_project.html

[21] Publically announced pilot/demonstration plants include:

- NCI (Italy) 10 bpd
- Rentech (USA) 10 bpd
- Conoco (USA) 400 bpd
- Exxon (USA) 250 bpd
- Syntroleum (USA) 70 bpd
- Syntroleum/Sinopec 100 bpd
- BP (Alaska) 300 bpd
- JOMEC (Japan) 500 bpd
- PetroSA (South Africa) 1000 bpd
- Sasol (South Africa) 1000 bpd
- CompactGTL (UK) <1bpd

[22] For an overview of main GTL technologies, see Appendix H.

[23] Inclusion of GTL base oils, paraffin and jet fuel into the plant product slate can add value to the GTL project, but this depends on incremental capital and logistic costs and access to markets.

[24] Espinoza R. L.; Steynberg A. P.; Jager B.; Vosloo A. C. " *Low temperature Fischer-Tropsch synthesis from a Sasol perspective*" App. Cat. A., *186(1-2)*, **1999**, 13-26.

[25] On this basis, the PetroSA HTFT GTL process in South Africa is not considered in this submission. http://www.petrosa.co.za/unsecure/attachments/documents/ProductionProcess.pdf

[26] In principle, natural gas is also available from coal-bed methane (CBM) sources.

[27] Sasol uses high-temperature Fischer-Tropsch technology to convert synthesis gas (derived from coal) into automotive and other fuels, as well as a wide range of light olefins. A fluidised, iron-based catalyst is added. This yields a significantly broader product spectrum than for LTFT. For example, using HTFT, The C_2 rich stream is split into ethylene and ethane. Ethane is cracked in a high-temperature furnace, yielding ethylene which is then purified. Propylene from the light hydrocarbon gases is purified and used in the production of polypropylene. Large quantities of olefins in the C_5 - C_{11} range also exist within this range. Alpha olefins pentene (C_5), hexene (C_6) and octene (C_8) are recovered, while the longer-chain olefins (C_7 - C_{11}) are introduced into the fuel pool. Oxygenates in the aqueous stream from the process are separated and purified in the chemical work-up plant to produce alcohols, acetic acid and ketones including acetone, methyl ethyl ketone (MEK) and methyl iso butyl ketone (MIBK).

[28] In principle, coal can be gasified underground via underground coal gasification (UCG) to produce syngas, which is then fed into the FT unit. For an example, see;
http://www.lincenergy.com.au/ucg.php

[29] For an example of BTL, see;
http://www.choren.com/en/choren_industries/

[30] Liederman, D.; Yurchak, S.; Kuo, J. C. W.; Lee, W. "*Mobil methanol-to-gasoline process*" in Energy to the 21st century; Proceedings of the Fifteenth Intersociety Energy Conversion Engineering Conference, Seattle, Wash., August, 1980. Volume 2. (A80-48165 21-44) p. 1573-1578.

[31]http://www.arb.ca.gov/fuels/lcfs/111607copro1.pdf

[32] For the purposes of this submission, we assume that sulfur produced in upstream gas plant option is recovered as elemental sulfur. Whether such sulfur will be used (for example, as a pesticide or feedstock for sulfuric acid production) depends on logistics and local markets. The subsequent use of sulfur therefore is not included in this submission.

[33]http://www.sasol.com/sasol_internet/frontend/navigation.jsp?articleTypeID=2&articleId=21200009&navid=4&rootid=4

[34] Adegoke, A. A. "*Utilizing the Heat Content of Gas to Liquids By-Product Streams for Commercial Power Generation*"
http://txspace.tamu.edu/bitstream/handle/1969.1/4217/etd-tamu-2006B-PETE-Adegoke.pdf?sequence=1

[35] Wangs estimate of emissions from GTL's includes credits for co–produced electricity;
"*Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems*", Wang, M., T. Weber, *et al*., 2001. North American Analysis: Volume I, Executive Summary. Argonne, Il, Argonne National Laboratory**:** 47.

[36] For all options, we do not include land-use, construction and decommissioning of existing or future infrastructure. The GTL plant can in principle also export water, although for the purposes of this study we assume that process water from the representative plant is emitted to a sea outfall.

[37] By 2010, two of the largest GTL facilities in the world will be located in Ras Laffan, Qatar. Qatar holds almost 15% of the world's gas resources.

[38] See glossary for definition.

[39] See glossary for definition.

[40] CO_2 is only present in a fraction of natural gas fields relevant for GTL.

[41] 7200 Nautical miles.

[42] Sasol Chevron Consulting Limited accept no responsibility for the accuracy of assumptions in this submission that are other than their own.

[43] Sasol Chevron Consulting Limited accept no responsibility for the accuracy of assumptions in this submission that are other than their own.

[44] ISO Standards can be obtained through the following link:
http://www.iso.ch/iso/en/CatalogueListPage.CatalogueList?ICS1=13&ICS2=020&ICS3=10

[45] http://www.iso.org/iso/iso_catalogue/management_standards.htm (This site provides background information on ISO 14000, pdf brochures, and ordering information for ISO publications and standards.)

[46] For a discussion of allocation and systems boundary expansion in the refinery context, see; Worhach, P. (Nexant); Abbott, R. E. (ConocoPhillips) "*Co-Product Function Expansion – A Methodology for Incrementally Considering the Effects of Co-Products in Multi-Product Systems*", in LCA/LCM September, 2005.
http://lcacenter.org/InLCA-LCM03/Worhach-presentation.ppt#548,28,CFE

[47] Bailey, S. (Sasol Chevron), "*Life Cycle Assessment of Transportation Fuel Technologies*"**,** CARB LCA Workshop, Dec 20, 2007.
http://www.arb.ca.gov/fuels/lcfs/122007sasolchevron.pdf

[48] Further detailed information about these benefits can be found in Appendices A-E.

[49] Low Octane (~25).

[50] http://www.uop.com/objects/Molex.pdf

[51] http://www.uop.com/objects/18%20LAB.pdf

[52] In the context of the current submission, it is assumed that normal paraffin originating from the Shell process is used. The design of the Shell process means that the C_9-C_{14} broad cut that comes from the Fischer-Tropsch stream is absent of olefin, so it must be fed into the dehydrogenation unit. It needs to be noted here that because of the design of the Sasol process, the C_9-C_{14} broad cut that originates from the Fischer-Tropsch unit would already contain 25% olefin, thus reducing or totally eliminating the need for the energy intensive Pacol dehydrogenation step.

[53] For an example of the effect of 0W-20 low viscosity engine oil on fuel economy, see: Tanaka, H.; Nagashima, T.; Sato, T.; Kawauchi, S. (Honda R&D Co., Ltd.) "*The Effect of 0W-20 Low Viscosity Engine Oil on Fuel Economy*", SAE Technical Paper Series, 1999-01-3468.

[54] Because the motor vehicle utilizes the higher quality lubricant base oil for thousands of miles, the GHG savings can be significant.

[55] Where there was a choice of published figures available for or where there was any doubt over the activities undertaken, a conservation or 'worst case' scenario was assumed.

[56] The functional unit used to determine the carbon footprint of GTL diesel using the substitution method is the travel of 1 mile in a passenger car in California using GTL diesel.

[57] The Californian market for lubricant oils will be about 80 mil US gallon of in 2010 and 82 mil US gallon in 2020 (Source: Kline).

[58] GTL diesel can be used in all modern diesel engines.

[59] Alleman T. L.;, McCormick R. L.; Vertin, K. (NREL) "*Assessment of Criteria Pollutant Emissions from Liquid Fuels Derived From Natural Gas*", April 2002.
http://www1.eere.energy.gov/vehiclesandfuels/epact/pdfs/ftd_docket/epact_assessment.pdf

[60] Larsson, M. "*An Experimental Study of Fischer-Tropsch Fuels in a Diesel Engine*", Göteborg, Sweden, 2007.
http://www.pff.nu/upload/EMFO/resultat/Delprogram_6_7/lic_Fischer%20Tropsch%20Monica_larsson.pdf

[61] The low aromatic contents of Fischer-Tropsch fuels contribute to low soot emissions.

[62] The lower smoke and soot emissions with GTL Diesel facilitate NO_x reductions by offering a more favorable NO_x - FSN - trade-off. NO_x reduction is facilitated by the higher EGR tolerance of GTL Diesel.

[63] The F-T fuels are less dense than conventional Diesel fuel, hence there are less spray-wall interactions when they are used, and consequently lower CO emissions.

[64] The high cetane number of F-T fuels shorten the ignition delay and reduce over-leaning, which results in lower HC emissions.

[65] (a) Larsson, M.; Denbratt, I. *'An Experimental Investigation of Fischer-Tropsch Fuels in a Light-Duty Diesel Engine'*
http://www.vv.se/fud-resultat/Publikationer_000201_000300/Publikation_000238/lic_Fischer%20Tropsch%20Monica_larsson.pdf
(b) Tsujimura, T.; Goto, S.; Matsubara, H. "*A Study on PM Emission Characteristics of Diesel Vehicle Fueled with GTL*" *Proceedings. JSAE Annual Congress* 54(06), **2006**, 1-6.

[66] Seyfried, D.; Steiger, W.; Heinrich, H. "*Renewable Fuels for Advanced Powertrains – Volkswagon's View on Future Fuels*"
http://www.eri.ucr.edu/ISAFXVCD/ISAFXVAF/EnFSR.pdf

[67] Studies have shown that use of Fischer-Tropsch diesel in place of California diesel in the test trucks led to lower levels of all four regulated emissions measured. Oxides of nitrogen were reduced by an average of 12%, particulate matter was reduced by an average of 24%, carbon monoxide was reduced by an average of 18%, and total hydrocarbon emissions were reduced by an average of 40% for diesel-powered test trucks.
Norton, P.; Vertin K.; Bailey, B. (National Renewable Energy Lab, NREL), Clark, N. N.; Lyons, D. W. (Wed Virginia Univ., WVU), Goguen, S.; Eberhardt, J. (US Department of Energy, DOE). "*Emissions from Trucks using Fischer-Tropsch Diesel Fuel*" International Fall Fuels and Lubricants Meeting and Exposition San Francisco, California, October 19-22,1998 (SAE Technical Paper Series 982526).
http://www.osti.gov/energycitations/servlets/purl/771105-bEzEOU/native/771105.PDF

[68] See "Cost-Effectiveness of Transportation Fuel Options for Reducing Europe's Petroleum Dependence", J. Thijssen, March 2006.

[69] "*ASFE Position Paper Emissions from Synthetic Fuels*", January 2007.
http://www.synthetic-fuels.org/documents/20070221124435_ASFE%20Position%20Paper%20on%20Emissions.pdf

[70] Maly, R. (DaimlerChrysler) *"Effect of GTL Diesel Fuels on Emissions and Engine Performance"* (10th Diesel Engine Emissions Reduction Conference August 29 - September 2, 2004 Coronado, California).
http://www1.eere.energy.gov/vehiclesandfuels/pdfs/deer_2004/session2/2004_deer_maly.pdf

[71] To date, most GTL diesel testing has been on compression ignition engines representative of the current reality and therefore designed and tuned to run on conventional diesel fuel. It is clear that the characteristics of GTL diesel have not been fully exploited by current technology, and to do this would require engine redesign. Sasol Chevron, both internally and in partnership with engine manufacturers, has started long-term programmes exploring the development of a GTL engine for the future. The initial results indicate that when engines are optimised to run on GTL diesel, or any other synthetic fuel for that matter, further reductions of nitrogen oxides emissions and improvements in fuel efficiency can be obtained.

[72] These particles are invisible while suspended in air and yet they may be present in a high quantity even during a beautiful clear day.

[73] (a) EPA. (2003) "*Benefits and Costs of the Clean Air Act 1990-2020: Revised Analytical Plan for EPA's Second Prospective Analysis*", May, Washington D.C.
(b) EPA. (2004) "*Final Regulatory Analysis: Control of Emissions from Nonroad Diesel Engines*", May, Washington D.C.
(c) EPA. (2005) "*Clean Air Interstate Rule: Regulatory Impact Analysis*", March, Washington D.C.

[74] (a) California Air Resources Board (CARB). (2006) "*Quantification of the Health Impacts and Economic Valuation of Air Pollution from Ports and Goods Movement in California*", Staff Report, Sacramento, CA.

(b) California Air Resource Board (CARB). (2008) "*Methodology for Estimating Premature Deaths Associated with Long-term Exposures to Fine Airborne Particulate Matter in California"*, Draft Staff Report, May, Sacramento, CA.
(c) California Air Resources Board (CARB). (2005) "*Emission Reduction Plan for Ports and International Goods Movement in California"*, California Environmental Protection Agency, Sacramento,CA.

[75] Hall, J. V.; Brajer, V.; Lurmann, F. W. "*The Benefits of Meeting Federal Clean Air Standards in the South Coast and San Joaquin Valley Air Basins",* Petaluma, CA, November 2008.
http://business.fullerton.edu/centers/iees/reports/Benefits%20of%20Meeting%20Clean%20Air%20Standards.pdf

[76] Jerrett M.; Burnett, R.T.; Ma, R.; Pope, C.A.; Krewski, D.; Newbold, K.B.; Thurston, G.; Shi, Y.; Finkelstein, N.; Calle E.E.; Thun. "*Spatial analysis of air pollution and mortality in Los Angeles*" Epidemiology *16(6)*, **2005**, 727-736.

[77] (a) Alessandrini, F., Schulz, S., Takenaka, S., Lentner, B., Karg, E., Behrendt, H., Jakob, T., Journal of Allergy and Clinical Immunology *117*, **2006**, 824–830.
(b) Dick, C.A., Brown, D.N., Donaldson, K., Stone, V. "*The role of free radicals in the toxic and inflammatory effects of four different ultrafine particle types*" Inhalation Toxicology *15*, **2003**, 39–52.
(c) Li, N., Kim, S., Wang, M., Froines, J., Sioutas, C., Nel, A., 2002. "*Use of a stratified oxidative stress model to study the biological effects of concentrated and diesel exhaust particulate matter*." Inhalation Toxicology *14 (5)*, **2002**, 459–486.
(d) Li, N., Sioutas, C., Cho, A., Smitz, D., Misra, C., Sempf, J. "*Ultrafine particulate pollutants induce oxidative stress and mitochondrial damage*." Environmental Health Perspectives *111*, **2003**, 455–460.
(e) Brown, D.N., Wilson, M.R., MacNee, W., Stone, V., Donaldson, K., "*Size dependent pro inflammatory effects of ultrafine polystyrene particles: a role for surface area and oxidative stress in the enhanced activity of ultrafines*." Toxicology and Applied Pharmacology *175*, **2001**, 191–199.
(f) Oberdörster, G. "*Toxicology of ultrafine particles: in vivo Studies*" Philosophical Transaction of Royal Society of London, Series A *358 (1775)*, **2000**, 2719–2739.
(g) Oberdörster, G. "*Pulmonary effects of inhaled ultrafine particles*." International Archives of Occupational Environmental Health *79*, **2001**, 4–8.
(h) Oberdörster, G., Gelein, R.M., Ferin, J., Weiss, B. "*Association of particulate matter air pollution and acute mortality: involvement of ultrafine particles*?" Inhalation Toxicology 7, **1995**, 111–124.
(i) Pope C. A. et al. "*Particulate air pollution as predictor of mortality in a prospective study of U.S. adults*" American Journal of Respiratory Critical Care Medicine, **1995**, 151.
(j) Pope C. A. et al. "*Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution*" J. Am. Med. Assoc. *287*, **2002**, 1132-1141.

[78] It is thought that the observed reductions are primarily due to the negligible sulfur content of the GTL diesel, which dramatically reduces the amount of sulfates available for nucleation in the exhaust gas. In addition, sulfur is capable of stabilizing carbon nanoparticles, thus reducing their ability to agglomerate into large particles.

[79] Scharberg, P. W.; Zarling, D. D.; Waytulonis, R. W.; Kittelson, D. B. "*Exhaust Particle Number and Size Distributions with Conventional and Fischer-Tropsch Diesel Fuels*" SAE Powertrain & Fluid Systems Conference & Exhibition, October 2002, San Diego, CA, USA, Session: Diesel Performance & Additives (Part A&B), 2002-01-2727.

[80] In the study, CARB staff considered the use of Fischer-Tropsch diesel (FT diesel) as a fuel extender in California diesel. FT diesel would be blended with EPA diesel to produce a diesel fuel meeting the same emission performance as the current California diesel specified by the California Air Resources Board (CARB). The blend of FT diesel and EPA diesel could then be sold as a CARB diesel fuel.

[81] "*Reducing California's Petroleum Dependence*", California Energy Agency, California Air Resources Board Joint Agency Report, August 2003, P600-03-005F.

[82] North American refinery utilization was 87 % in 2006 (Source: BP Statistical Review of World Energy 2006). Wide use of GTL blending could further optimize refinery utilization.

[83] In order to meet future fuel specifications, existing refineries will most likely need to invest in further technology, principally hydrodesulfurisation and hydrogenation units. This additional processing will increase energy requirements and therefore reduce the thermal efficiency of the refinery.

[84] For example, Light-Cycle Oil (LCO, Cetane = 30) could be upgraded with GTL diesel (Cetane = 70) to end up in the diesel pool (assume 45:55 LCO/GTL blend to produce product with cetane of 52).

[85] This process is highly endothermic and equilibrium limited. To achieve a high conversion of methane, it has to be carried out at high temperature in conventional reactors, leading to high energy consumption.

[86] "*Hydrogen Fact Sheet Hydrogen Production – Steam Methane Reforming (SMR*)", New York State Energy Research and Development Authority.
http://www.getenergysmart.org/Files/HydrogenEducation/6HydrogenProductionSteamMethaneReforming.pdf

[87] Spath P. L.; Mann, M. R. "*Life Cycle Assessment of Hydrogen Production via Natural Gas Steam Reforming"*, National Renewable Energy Laboratory, February 2001.
http://www.nrel.gov/docs/fy01osti/27637.pdf

[88] Refinery technology can vary from 'simple' to 'complex'. Both types of refinery take a crude oil input and produce a suite of outputs which may include LPG, mogas, naphtha, kerosene, diesel, light fuel oil, heavy fuel oil, petroleum coke and bitumens/waxes. Complex refineries employ technology that increases the make of the higher value parts of the barrel (such as mogas and diesel) compared to their simple refinery equivalents. It is for this reason that any future refineries are likely to be complex rather than simple. However complex refineries (and simple refineries) manufacture co-products, such as fuel oil, that are carbon 'heavy' on combustion in comparison with market alternatives such as natural gas.

[89] "*International Energy Outlook 2008*", (Energy Information Agency), June 2008.
http://www.eia.doe.gov/oiaf/ieo/world.html
http://www.iea.org/Textbase/speech/2008/Birol_WEO2008_PressConf.pdf

[90] In the USA tighter fuel specifications are being set, particularly with respect to the sulfur and aromatic content of diesel fuels. The Environmental Protection Agency (EPA) has set a sulfur content limit for diesel of 15 ppm by 2007. Such diesel is referred to as ultra low sulfur (ULS) diesel.

[91] Although diesel fuel has compelling benefits in terms of fuel consumption and thus carbon dioxide (CO_2) emissions, it has been the focus of environmental regulations due to its high nitrogen oxides (NO_x), particulates and sulfur oxides (SO_x) emissions. These pollutants can contribute to photochemical oxidant formation ('smog creation'), air acidification and human health issues, particularly in urban environments. Limiting the emissions of pollutants such as nitrogen oxides and particulates can be achieved through the treatment of exhaust gases (using catalytic converters in the vehicle exhaust system). However the presence of sulfur in the exhaust gases is damaging for catalytic converters.

[92] World Economic Outlook (WEO), International Monetary Fund (IMF)
http://www.imf.org/external/pubs/ft/weo/2008/02/index.htm

[93] World Population Prospects: The 2006 Revision Population Database.
http://esa.un.org/unpp/

[94] Energy Information Agency, "*International Energy Outlook 2008*", June 2008.
http://www.eia.doe.gov/oiaf/ieo/highlights.html

[95] World Energy Outlook 2007, Key Assumptions.
http://www.iea.org/weo/key_graphs_08/WEO_2008_Key_Graphs.pdf

[96] Comité des Constructeurs Français d'Automobiles, 2008

http://www.ccfa.fr/

[97] Skinner, R. (Oxford Institute for Energy Studies) "*World Energy Trends: Recent Developments and their Implications for Arab Countries*" May 2006.
http://www.oxfordenergy.org/pdfs/SP19.pdf

[98] BP statistical review of world energy, 2008.
http://www.bp.com/productlanding.do?categoryId=6929&contentId=7044622

[99] Obtained from the Pira Energy Group.
http://www.pira.com/default.htm

[100] http://www.worldenergy.org/documents/1.11.07_beawkshop_wells.pdf

[101] Cherrillo, R. A.; Dahlstrom, M. A.; Coleman, A. T.; Clark R. H. (Shell) "*Verification of Shell GTL Fuel as CARB Alternative Diesel*", 2007.
http://www1.eere.energy.gov/vehiclesandfuels/pdfs/deer_2007/session7/deer07_dahlstrom.pdf

[102] http://www.exploringcleanerfuels.com/
http://www.chevron.com/news/press/Release/?id=2007-10-23

[103]http://www.volkswagenag.com/vwag/vwcorp/info_center/en/publications/2006/03/asfe_brochure_driving_towards_sustainable_mobility.-bin.acq/qual-BinaryStorageItem.Single.File/Brochure-ASFE-2006.pdf

[104] http://www.sasolchevron.com/GTLChallenge/

[105] http://www.dewildt.org.za/Tracker.htm

[106] http://www.nrel.gov/vehiclesandfuels/npbf/pdfs/38195.pdf

[107] http://www1.eere.energy.gov/vehiclesandfuels/epact/pdfs/ftd_docket/gtl_fuel_test_memo.pdf

[108]http://www.shell.com/home/Framework?siteId=shellgasandpower-en&FC2=/shellgasandpower-en/html/iwgen/leftnavs/zzz_lhn3_3_0.html&FC3=/shellgasandpower-en/html/iwgen/products_and_services/what_is_gtl/global_gtl_trials/toyota_trial_0701_1617.html

[109]http://www.shell.com/home/content/media/news_and_library/press_releases/2005/gtl_release_27072005.html

[110]http://www.shell.com/home/content/china-en/news_and_library/press_releases/2007/gtl_bibendum_20071114_en.html

[111]http://www.shell.com/home/content/media/news_and_library/press_releases/2007/sustainable_mobility_bibendum_15112007.html

[112] Eidgenössische Technische Hochschule Zürich (Swiss Federal Institute of Technology Zürich) data (2002).

[113] http://www.transportation.anl.gov/modeling_simulation/GREET/greet_1-8b_beta.html

[114] http://www.transportation.anl.gov/modeling_simulation/GREET/greet_1-8b_beta.html

[115] US Environment Protection Agency (EPA) AP 42, Section 5.2

[116] US Environment Protection Agency (EPA), AP 42, Section 5.2

[117] Earthtrends Country Profiles: Qatar.
http://earthtrends.wri.org/pdf_library/country_profiles/ene_cou_634.pdf

[118] Eidgenössische Technische Hochschule Zürich (Swiss Federal Institute of Technology Zürich) data (2002).

[119] US Environment Protection Agency (EPA), AP 42, Section 5.2

[120] Location information provided by Sasol Chevron, transport distance calculated using www.portworld.com

[121] Eidgenössische Technische Hochschule Zürich (Swiss Federal Institute of Technology Zürich) data (2002).

[122] Eidgenössische Technische Hochschule Zürich (Swiss Federal Institute of Technology Zürich) data (2002).

[123] US Environment Protection Agency (EPA), AP 42, Section 5.2

[124] Information obtained from Wood Mackenzie Research and Consulting. http://www.woodmacresearch.com/home/index.html

[125] Dancuart, L.; Mayer, J.; Tallman, M. J.; Adams, J. "*Performance of the Sasol SPD Naphtha as Steam Cracking Feedstock*", Petroleum Chemistry Division Preprints **2003**, *48(2),* 132.

[126] KBR's pilot plant is capable of operating over a wide range of residence times (20 to 600 milliseconds) which covers the range of essentially all modern pyrolysis furnaces.

[127] Cracking Severity was measured by calculating the propylene/ethylene (P/E) mass ratio.

[128] Location information provided by Sasol Chevron, transport distance calculated using www.portworld.com

[129] Eidgenössische Technische Hochschule Zürich (Swiss Federal Institute of Technology Zürich) data (2002)

[130] Eidgenössische Technische Hochschule Zürich (Swiss Federal Institute of Technology Zürich) data (2002)

[131] Eidgenössische Technische Hochschule Zürich (Swiss Federal Institute of Technology Zürich) data (2002).

[132] Eidgenössische Technische Hochschule Zürich (Swiss Federal Institute of Technology Zürich) data (2002).

[133] Energy Use and Energy Intensity of the U.S. Chemical Industry, Ernst Worrell, Dian Phylipsen, Dan Einstein, and Nathan Martin, April 2000

[134] Eidgenössische Technische Hochschule Zürich (Swiss Federal Institute of Technology Zürich) data (2002).

[135] Eidgenössische Technische Hochschule Zürich (Swiss Federal Institute of Technology Zürich) data (2002).

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[138] Jory, R. "*GTL fuel: driving the growth of the GTL market*", 23rd World Gas Conference, Amsterdam 2006.
http://www.igu.org/html/wgc2006/pdf/paper/add10849.pdf

[139] Maase, B.; Dirkzwager, H. "*Shell GTL Normal Paraffin - The future LAB feedstock of choice"* 6th World Detergents Conference, 2006.
http://www.shell.com/static/shellgasandpower-en/downloads/products_and_services/what_is_gtl/benefits_of_gtl/montreux_future_feedstock_handout.pdf

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[141] "*Normal Paraffins – World Markets 2000-2010*", Colin A. Houston & Associates, Inc (CAHA).
http://www.colin-houston.com/files/Normal_Paraffins.PDF

[142] http://www.scienceinthebox.com/en_UK/pdf/LAS.pdf

[143] http://www.uop.com/objects/Detal%20DA114.pdf

[144] http://www.uop.com/objects/Molex.pdf

[145] In the late 1940s and through the 1950s, the pioneering work done at UOP by Vladimir Haensel on platinum catalysis for the catalytic reforming of naphthas for the production of high-octane gasolines and high-purity aromatics showed that platinum catalysts have interesting dehydrogenation functions. This research area was later pursued by Herman Bloch and others also within UOP. In 1963-64, UOP started development work on heterogeneous platinum catalysts supported on an alumina base for the dehydrogenation of heavy *n*-paraffins. The resulting successful process, known as the Pacol process (for paraffin conversion to olefins), was first commercialized in 1968. The advent of the UOP Pacol process marked a substantial transformation in the detergent industry and contributed to the widespread use of linear alkylbenzene sulfonate (LAS or LABS) on an economical, cost-effective basis. As of mid-2003, more than 40 Pacol units have been built, or are under design or construction; practically all new linear alkylbenzene (LAB) capacity built on a worldwide basis over the last two decades makes use of UOP's Pacol catalytic dehydrogenation process.

[146] http://www.uop.com/objects/Detal%20DA114.pdf

[147] Smith R. (1991) "*Linear alkylbenzene by heterogeneous catalysis*" PEP Review No. 90-2-4, SRI International.

[148] The Shell process utilizes a relatively high H_2/CO ratio in a fixed bed reactor, resulting in hydrogenated products

[149] The Sasol process uses a slurry bed reactor, utilizing a lower H_2/CO ratio: resulting in more olefin (25%) in the crude wax.

[150] For the Sasol process, the olefins in the low temperature Fischer-Tropsch hydrocarbon condensate (liquid fraction) product have a very high degree of linearity of greater than 95% and, even though they only make up 25%, by weight of the hydrocarbon condensate product, it is an excellent feed for the production of linear alkyl benzene and provides an economically viable manner for the production of highly linear alkyl benzene.

[151] Franke, M.; Schwalbach; Berna, J. L.; Cavalli, L.; Renta, C.; Stalmans, M.; Strombeek-Bever, M.; Thomas, H. "*A Life Cycle Inventory for the production of petrochemical intermediates in Europe: Paraffins, Olefins, Benzene, Ethylene and Ethylene Oxide*", Tenside, Surfactants, Detergents, *32*, **1995**, 384

[152] Reference ExxonMobil's data for Mobile 1, claiming 2 % fuel economy improvement (based on a comparison versus those grades most commonly used) http://www.mobiloil.com/USA-English/MotorOil/Oils/Mobil_1_Advanced_Fuel_Economy.aspx

[153] ILSAC GF-5 standard for passenger car engine oils, currently in draft form and expect to be introduced for Model year 2011 cars http://www.gf-5.com/uploads/textWidget/471.00002/documents/ILSAC_GF-5_draft_Jan_23_08_update.pdf

[154] Fuel economy lubricants for HDEO are just starting to take shape, but early results put the advantage at about 1 % for 10W-30 versus 15W-40, and of course, more versus heavy mono-grades.

[155] Sasol Chevron assumption, November 2008.

[156] Eidgenössische Technische Hochschule Zürich (Swiss Federal Institute of Technology Zürich) data (2002)

[157] Baker O'Brien, PRISM modeling, 2007

[158] Location information provided by Sasol Chevron, transport distance calculated using www.portworld.com

[159] Eidgenössische Technische Hochschule Zürich (Swiss Federal Institute of Technology Zürich) data (2002)

[160] Eidgenössische Technische Hochschule Zürich (Swiss Federal Institute of Technology Zürich) data (2002)

[161] US Environmental Protection Agency (EPA) eGrid Version 2.1 (April 2007) Year 2004 Summary Tables: State Emissions. http://www.epa.gov/cleanenergy/energy-resources/egrid/faq.html

[162] Email correspondence between Kline and Sasol Chevron, 23/10/08

[163] Sasol Chevron confirmed by email, 14/11/08

[164] US Environment Protection Agency (EPA), AP 42, Section 5.2

[165] http://www.epa.gov/waste/conserve/materials/usedoil/index.htm

[166] This assumption reflects additional GTL projects in 2020 utilizing low- or zero-CO_2 containing natural gas fields.

[167] The JEC (Joint Research Centre of the European Commission, EUCAR and CONCAWE) study is the most authoritative and comprehensive review of energy and Greenhouse Gas balances for transport fuel pathways in the European context. The study can be found at http://ies.jrc.ec.europa.eu/WTW , and the next update is currently in progress.

[168] Schaberg, P. "*Application of Synthetic Diesel Fuels - Future Fuels: Issues and Opportunities*", 11thDiesel Engine Emissions Reduction Conference, August, 2005. http://www1.eere.energy.gov/vehiclesandfuels/pdfs/deer_2005/panel1/2005_deer_schaberg.pdf