Author(s):   Martin Garrood and Tony Clemens

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Reviewed by: _____

Name & Designation: **Andrew Campbell** Manager- SET Group

Approved by: _____

Name & Designation: **Dr Trevor Matheson**

General Manager - Operations

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1   Executive Summary

Virtually every economy worldwide relies on crude oil to provide fuels for transportation. Concerns about security of supply because of political instability in some important oil producing regions and an ever increasing demand for oil, and the associated potential for large increases in price mean that many nations are considering other fuel options. These options include hydrogen, electricity, biodiesel/bioethanol and Fischer-Tropsch diesel/petrol. Sources for these fuels include biomass and coal.

In this study, the techno-economics of coal-to-liquid (CTL) fuel production using the Fischer-Tropsch (FT) process has been considered in detail. CTL is particularly relevant to New Zealand because there is a large lignite reserve available as a feedstock, the technology is mature and commercially proven with over 50 years of operational experience, and the FT diesel and petrol fuels produced can be used with existing delivery infrastructure and vehicle engines.

This report consists of five main sections. Section 2 briefly reviews: potential alternative fuels; the history and current state of CTL production; the reasons for considering CTL and barriers to its uptake for New Zealand. Section 3 compares the properties of FT fuels with those of petrodiesel, showing FT fuels to be a suitable direct substitute for crude oil derived fuels, with several benefits as far as emissions of noise, particulates, NOx, SOx and CO at the point of use are concerned. Section 4 gives more detail of generic FT production processes. Section 5 give details of a techno-economic analysis for CTL plant producing FT diesel including several options for plants based in Southland utilising New Zealand lignite, including local environmental impacts. All the plant options included carbon capture and storage (CCS) to minimise the high carbon dioxide output of CTL processing. Finally, Section 6 considers the likely advances in CTL technology and their effect on costs as well as the sensitivity of FT production costs to various economic parameters used in the modelling.

Base economic analysis was carried out for five different plant sizes and configurations. In Cases 1, 3 and 5 any un-reacted syngas was recycled to the reactor. In cases 2 and 4 the un-reacted gas was used to generate power for the plant with any excess being exported to the grid. The results of these analyses are reproduced from the main text in the following Table:

	Case 1	Case 2	Case 3	Case 4	Case 5
Plant production scale bbl/day	10,000	10,000	30,000	30,000	60,000
Recycling un-reacted FT output?	yes	no	yes	no	yes
FT fuel cost, NZ cents/l	62.9	67.6	51.3	52.4	47.0
FT fuel cost, NZ\$/GJ	17.2	18.5	14.1	14.4	12.9
Lignite use, kg/l FT fuel	5.97	7.84[1]	5.93	7.19	5.57
Carbon dioxide emitted during production (after carbon capture) gCO$_2$/l FT fuel	446	1638	514	1129	256
Overall thermal efficiency [1]	43.9%	40.8%	45.5%	43.5%	46.7%

In summary, for plant capacity of 10,000 to 60,000 barrels per day of FT fuel output, the production costs range from 47 to 68 NZ cents per litre (12.9 to 17.2NZ\$/GJ). For production of FT without co-production of electricity, lignite use would be 5.5 to 6.0kg lignite per litre of fuel produced, with annual plant consumptions ranging from 3.5 to 19.4Mt lignite. The increase in carbon dioxide

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[1] NB for cases 2 and 4 lignite use, carbon dioxide emission and efficiency figures are not directly comparable to those for the other cases because they include the effects of the significant amount of electricity exported from the plant to the national grid. No allowance is made for this, so the overall result is reduced FT output and a decrease in overall efficiency.

emissions from processing over the life-cycle of the fuel compared to crude oil based fuels would range from 10 to 20%, depending on the capacity of plant producing the fuel.

The results from the sensitivity analysis are reproduced from the main text in the following Table:

	Case 1	Case 2	Case 3	Case 4	Case 5
Plant production scale bbl/day	10,000	10,000	30,000	30,000	60,000
Recycling of un-reacted FT output?	yes	no	yes	no	yes
Base case (FT cost in NZ cents/litre)	62.9	67.6	51.3	52.4	47.0
Capital costs increased by 10%	66.2 (+5.3%)	71.9 (+6.3%)	54.1 (+5.4%)	55.7 (+6.2%)	49.4 (+5.1%)
Operational costs increased by 10% (excluding lignite cost and electricity sales)	64.9 (+3.2%)	70.1 (+3.6%)	52.9 (+3.1%)	54.3 (+3.6%)	48.4 (+3.0%)
Low lignite price – lower range limit 0.6 NZ$/GJ	58.4 (-7.1%)	61.8 (-8.7%)	46.9 (-8.7%)	47.0 (-10.3%)	42.8 (-8.9%)
High lignite price – upper range limit 1.6 NZ$/GJ	67.4 (+7.1%)	73.5 (+8.7%)	55.8 (+8.7%)	57.8 (+10.3%)	51.2 (+8.9%)
Electricity wholesale price increased from 50 to 75 NZ$/MWh	62.7 (-0.4%)	61.5 (-9.1%)	50.3 (-2.1%)	47.0 (-10.4%)	46.9 (-0.1%)
Exchange rate change from base case of 0.70 US$/NZ$ to 0.60 US$/NZ$	67.0 (+6.6%)	72.9 (+7.7%)	54.7 (+6.6%)	56.4 (+7.6%)	49.9 (+6.3%)

The sensitivity analysis showed some sensitivity to capital and operational costs, but more sensitivity to lignite feedstock price and exchange rate variations as well as to electricity wholesale costs for the plant exporting electricity to the grid (Cases 2 and 4).

Contents

2   Introduction

Internationally, the demand for crude oil is increasing, at a time when many experts are predicting that the peak in oil production will occur sometime over the next 20 years. This combined with concerns about the security of oil supply, particularly with the current political instability in several oil producing regions, means that the price of oil has the potential to rise to unprecedented levels over the next two decades. New Zealand depends on imported oil for 99% [MED 2006] of its transportation fuels. If the cost of crude oil rises as predicted and the possibility of serious supply interruptions becomes more pressing, then alternatives need to be sought now to avoid serious transportation fuel shortages in the future.

There are several alternative transport fuel options which could alleviate these problems to some extent including bioethanol, biodiesel, hydrogen, electricity as well as coal-to-liquid (CTL) fuels. Some, like biodiesel and bioethanol, can already be incorporated into the current transport system by blending with traditional petrol and diesel. The amount that can be incorporated depends on the vehicle to be fuelled; some modern vehicles are able to accept 100%; older vehicles might be limited to just 5% biofuel. As biofuels are produced from crops or wastes, only a small percentage of transport fuels can be produced from secure NZ sources. Hydrogen and electrical powered vehicles are an option which may play a significant role in future transport for NZ. The resources to provide them (renewable electricity for both electricity and hydrogen production, and coal for hydrogen production) are abundant in NZ. However, the technology to produce and utilise electricity and hydrogen as fuels requires further development and significant infrastructural changes would be necessary before they can be widely adopted, perhaps pushing the timeline out for mainstream use of these options by up to 20 years. The option considered in detail for this study is that of making liquid transport fuels from coal, using well established technology.

CTL processes were first developed in the early 1900s with the Bergius direct coal liquefaction process ("direct" because there is no intermediate gaseous stage in the processing). The Bergius process was investigated using demonstration and pilot plant projects constructed in the 1970s and 1980s. Recently, renewed interest in direct coal liquefaction has seen several feasibility studies carried out. China's Shenhua Energy Company Ltd announced in 2006 that they intend to build the world's first full-scale plant with a production capacity of 20,000 barrels of CTL fuels per day.

The alternative CTL process of indirect coal liquefaction utilising the Fischer-Tropsch (FT) process was established in the 1920s ("indirect" because there is an intermediate gas stage in the processing). During the Second World War Germany used both Bergius and FT technologies to provide transport fuels for its armed forces.

After the War, FT production technology was developed commercially by the South African oil company, Sasol, to meet South Africa's petroleum product demand. South Africa had large coal reserves but always relied on imports for its crude oil. Sasol built three CTL production plants from 1955 to 1983 which produced up to 40% of South Africa's petroleum products (the figure has fallen to 28% as demand has risen). The remainder was supplied by refining imported crude oil which was available despite international trade restrictions from the 1970s to the 1990s. These three South African plants are capable of producing a combined total of 150,000 barrels per day of crude oil equivalent from coal and remain the only commercial integrated CTL plants built worldwide (although the first of the three Sasol plants to be built has recently been converted to use natural gas piped from Mozambique as its feedstock [SSEB 2006]).

Several feasibility studies have been undertaken for indirect coal liquefaction, including one currently underway for L&M Lignite Ltd to investigate the economic viability of building a 3.7 US$bn, 50,000bbl/day FT plant near their mining operations in Southland/Otago [CANZ 2006].

Reasons for considering CTL as an option for NZ at this time include:

- The abundant Southland lignite reserve could provide security of transport fuel supply and reduce reliance on crude oil imports.
- The key components of CTL technology have been advanced significantly over the last 20 years; gasification technology has been developed for chemical processes and integrated gasification combined cycle turbine (IGCC) power plants; FT synthesis technology has been improved with increasing experience through the deployment of gas-to-liquid (GTL) plant.
- The liquid fuels produced by CTL have advantages over other "alternative" fuels in that they are compatible with the existing infrastructure for distribution of the fuels and with current engine technologies.

The potential barriers to the uptake of CTL in NZ include:

- Few commercial-scale CTL plants have been built so far worldwide and none include the advanced CTL processes, with the co-production of liquid fuels and electricity.
- CTL plants have high capital and operational costs. As they can only be economic on a large scale, the associated high investment risks may deter investment.
- There are uncertainties about the future of world oil production and the price of crude oil that can affect the economic viability of CTL plant.
- Carbon dioxide emissions over the full lifecycle of the fuel are more than double those for the crude oil equivalents if no carbon capture and storage (CCS) is used during production (the burning of the fuel in vehicle engines releases the same amount of carbon dioxide to the atmosphere as conventional fuels would have done).
- Even with efficient (and as yet unproven) CCS technology, carbon dioxide emissions over the full life-cycle of the fuel would still be at least 5% higher than for crude oil based products.
- A large increase in coal mining and production may be unacceptable to the public.

None-the-less, CTL plant has the potential to make significant reductions in NZ's reliance on imported crude oil and the costs and benefits need to be weighed up objectively against the alternative options. This process starts with the techno-economic analysis of CTL in this report.

3   Liquid Fuels from Coal

The synthetic petrol and diesel produced by CTL processes require no further refining and are direct replacements for conventional petrol and diesel fuels; no modification is necessary to distribution infrastructure or engines and they can be blended with standard petrol or diesel to any ratio. Table 1 shows some properties of FT diesel and petrol compared to Number 2 diesel.

<p align="center">Table 1: Physical properties of FT fuels compared to Number 2 diesel [NREL 2003]*.</p>

	Number 2 diesel	Low temperature FT (FT diesel)	High temperature FT (FT petrol)
Energy content (HHV), MJ/kg	43-48	45-48	45-48
Density at 15°C, kg/l	0.82-0.85	0.77-0.79	0.80
Cetane number	44.9	>74	~50
Sulphur content, ppm	300	<1	<1
Total Aromatics, %	~30	0.1-2.0	~10
Hydrogen wt%	13-13.5	~15	~14.4

*Current New Zealand requirements are 50 ppm sulphur (max) and minimum cetane number 47

The energy density per kilogram of FT fuel is similar to petrodiesel but its lower volumetric density results in an overall lower energy density per litre for FT fuels. The difference is at most 10% and may be as low as a few percent for some individual fuels. Where it is possible to do so, a relatively minor adjustment to the engine management and fuel injection systems should allow similar performance to be achieved. From the average values of energy content and density, it was calculated that the average energy density of the FT fuels was 36.5MJ/litre (equivalent to 27.4litre/GJ), compared to around 38.3 MJ/litre for petrodiesel.

The cetane number of FT diesel is much higher than for standard diesel; above a cetane number of 55 diesel engine noise and NOx emissions are significantly reduced using modern engines [EPA 2002]. In practical studies the NOx emissions were reduced by 13% on average by using FT diesel [NREL 2003].

The fuel may have low lubricity, which can be rectified by the addition of fuel additives as used with low sulphur fuels from crude oil.

The concentrations of aromatic compounds, sulphur and high chain length hydrocarbons in FT fuel are much lower than for standard petrodiesel. As a result lower exhaust particulate emissions are expected (to the order of 26% lower in tests reported [NREL 2003, EPA 2002]).

Carbon monoxide emissions are also observed to decrease with FT diesel, but the results for hydrocarbon emissions have been found to be more variable [NREL 2003].[2]

Because of the favourable attributes of FT diesel, it can be considered as a premium fuel and may have greater value in countries with particular focus on emissions from vehicles.

4   Production Technology

Coal-to-liquid processes are divided into pyrolysis and liquefaction, with the latter subdivided into direct and indirect liquefaction. Demonstration pyrolysis processes exhibit very low yields and so pyrolysis was not considered further. Direct liquefaction involves the dissolution of coal in a solvent at elevated temperature and pressure followed by hydro-cracking the dissolved coal using hydrogen. The resultant synthetic crude must be further refined into synthetic gasoline and diesel fuels. Pilot and demonstration plant have been successfully operated and, as noted above, the first commercial-scale plant is planned for construction by China's Shenhua Energy Company Ltd. Overall energy efficiencies of 60 to 70% may be feasible and the aim of the Chinese plant is to reach 55%. As no commercial-scale direct liquefaction plant is operational, techno-economic analysis in this report will centre on the more established indirect liquefaction process.

The indirect liquefaction CTL process is comprised of coal gasification, Fischer-Tropsch synthesis and finally upgrading of the FT synthetic fuels. Gasification is a well-established technology with over a hundred gasification plants operating worldwide. The gasification of coal requires heat, steam and air (or pure oxygen), often at elevated pressures, to produce synthetic gas (syngas) and ash. Feedstocks other than coal can be gasified including biomass, municipal/industrial waste and petroleum process residues. Syngas consists mostly of carbon monoxide and hydrogen and has many uses in the chemical and energy sectors other than the production of liquid synfuels using CTL technology. The gasifier syngas output is cleaned of the particulates, carbon dioxide, and sulphur (and nitrogen if air was used instead of pure oxygen for gasification) using separator units to give cleaned syngas.

The second stage is the Fischer-Tropsch synthesis in which carbon monoxide and hydrogen are reacted over a catalyst (usually iron or cobalt) at elevated temperatures to produce liquid hydrocarbons, carbon dioxide and water. Typically, the ratio of the gases is adjusted to be close to the theoretical optimal and stoichiometric ratio of one molecule carbon monoxide to two

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[2] Care is required in interpreting these results as responses are very much engine and test dependent and conclusions should be drawn from a much wider sample of tests. Unfortunately there does not appear to be significant data available from which to do this.

molecules of hydrogen gas, using a water-gas-shift reactor, prior to introduction into the FT reactor. The FT catalyst and reaction temperature/pressure used can be varied to give different products; a low temperature process (200-240°C) results in heavy waxy products, which can then be cracked into synthetic diesel, kerosene and naphtha; a high temperature process (300-350°C) gives lighter products including synthetic petrol [IEA 2006]. The FT reaction is highly exothermic and maintaining the appropriate reaction temperature is a key element of reactor design. Manufacturers of FT reactors include Sasol, Exxon, Rentech, Shell, Syntroleum, BP, Statoil, IFP/ENI and PetroSA. Reactor designs can be multi-tubular fixed bed, circulating fluidised bed, fixed fluidised bed or fixed slurry bed.

Upgrading of the FT fuels includes several steps. First the carbon dioxide is removed from the syngas using acid gas removal techniques and any low molecular weight hydrocarbons are recycled back into the FT process for further reaction. The synfuel liquids and naphtha are separated using distillation. Any waxy products are converted in a hydrocracker into more synfuel/naphtha with the low molecular weight hydrocarbons produced again being recycled into the FT reactor for further reaction.

5   Techno-economic Analysis

Although no indirect liquefaction CTL plant have been built since the 1980s, techno-economic assessment of potential plant and their costs have given rise to typical figures being quoted for plant and synfuel production. For example, a CTL plant that produces 80,000bbl per day of synfuels would cost in the order of 5 US$bn [MED 2007]. Process efficiency for CTL processes using FT production of synfuels are given as approximately 40% in terms of the energy embodied in the coal input compared to the energy output in the liquid fuel [Steynberg & Nel 2004]. However, a Sasol study into the co-production of synfuel and electricity calculates that a plant producing electricity and FT synfuels from coal could improve the overall process efficiency from 40% to 50% [Steynberg & Nel 2004][33]. Other studies show typically a 10% reduction in FT synfuel costs when co-production is implemented [Yamashita & Barreto 2003, Williams & Larson 2003, and Espinoza et al. 1999]. It must be noted that the SSEB study, [SSEB 2006] used as the base for the present report, does not make allowance for the electricity output with the result that the lignite used per litre of fuel produced appears to be high for those cases where co-production is considered.

Indicative figures for a CTL plant situated by a 2-4Gt coal reserve with a coal price of US$20/t equal to US$1/GJ (NZ$28/tonne equal to NZ$1.4/GJ using an exchange rate of 1.4NZ$ = 1US$) show synfuels could be produced for US$8-10/GJ or US$40-45/bbl (NZ$11-14/GJ or ~NZ$55-65/bbl) [Williams and Larson 2003]. The lignite resource in Southland/Otago makes up 80% of the 8.6Gt [MED 2006] economically recoverable coal reserves of New Zealand and can therefore be estimated at 6.9Gt.

Studies comparing CTL to gas-to-liquid (GTL) processes using natural gas show that CTL is, in general, more expensive in terms of cost per litre of product. CTL is more capital intensive than GTL due to the additional costs associated with oxygen production and gasification of the coal. Usually, this is not quite counterbalanced by the lower cost of coal as a feedstock [IEA/ETO 2005]. For comparison to the CTL figures costs quoted, typical GTL costs are US$5-6/GJ or US$25-30/bbl (NZ$7-8.4/GJ or NZ$35-42/bbl) [Marsh et al. 2002]. However, for specific locations the feedstock costs can alter the economics significantly e.g. in the Middle East where there are significant 'stranded' reserves of natural gas which are not used locally, the GTL costs from natural gas are particularly low. Conversely, in New Zealand where the known gas reserves are diminishing and prices rising and there is a large resource of cheap lignite available, it is likely that it will be cheaper to make FT fuels from coal than from natural gas.

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[3] As described in Footnote 1 – the case studies involving co-production of electricity in the SSEB report do not make allowance for the electricity produced. The overall effect is lower FT production and a reduced efficiency (when considering FT production alone).

Some studies do not include the capture and storage of the carbon dioxide released during energy intensive CTL processing; 50% of the carbon in the coal is emitted during processing (for comparison GTL processes emit 17 to 25% of the carbon contained in the feedstock gas) [IEA/ETO 2005]. Adding the carbon dioxide emitted during processing (without CCS) to that released when the synfuel is burned in an engine, results in more than double the carbon dioxide emissions using CTL diesel compared to petrodiesel over the fuel's life-cycle [JRC 2004]. At a time when climate change is seen as a major global issue it may be the case that the national benefits of security of supply using CTL will not be sufficient to outweigh the negative global affect of greenhouse gas emissions. Therefore, CTL plant will most probably have to incorporate CCS to be considered as a serious option. Even with CCS removing 90% of carbon dioxide from processing, full life-cycle carbon dioxide emissions will be at least 5% higher for CTL petrol compared to petrol [Gray 2005].

This study aims to ensure that the figures used have relevance to New Zealand and that costs for carbon capture and storage are included. The techno-economic assessment of lignite to liquid plant for this study is based on the 2006 review of CTL plant options by Mitretek Systems Ltd. for the Southern States Energy Board as part of a larger study "American Energy Security: Building a Bridge to Energy Independence and to a Sustainable Future" [SSEB 2006]. The SSEB study considered US bituminous, sub-bituminous and lignite as feedstocks for 14 FT diesel production plants of various sizes; two further cases incorporate 10 or 20% of woody biomass as a co-feedstock with coal. The SSEB study aim was to assess economic viability by calculating the crude oil price per barrel that would be necessary for any of these plants to produce a 15% return on capital investment. However, in the current study the requirement was to estimate the bare production costs of FT fuels in NZ$/litre, the lignite used to produce FT fuels in kg/litre, and the carbon dioxide emissions in gCO_2/litre of FT fuel for plant including CCS.

The SSEB study considered 10,000, 30,000 and 60,000bbl/day FT diesel production plants using lignite feedstock. Five lignite based case studies were considered; Cases 1, 3 and 5 were for the three plant capacities, including recycling of most of unconverted syngas back into the FT reactor (a small amount of syngas used to produce power for the plant); Cases 2 and 4 were for the smaller two plant sizes in which all the un-reacted syngas was used to generate power for the plant and any excess was exported to the grid. Recycling un-reacted syngas and low molecular weight hydrocarbons gave a higher yield of FT fuels but a lower output of electricity.

The individual steps in the CTL process plant are:
- Air separation into oxygen and nitrogen.
- Solids handling - coal preparation, drying, crushing, classifying, storage and conveying.
- Gasification including feeding, quenching and slag removal.
- Syngas clean-up including:
    - Gas cooling, water gas shift, carbonyl sulphide hydrolysis, and mercury removal.
    - Acid gas removal.
    - Hydrogen recovery.
    - Sulphur polishing.
- Carbon dioxide removal including compression to 2000psi (excluding transport and injection[4]).
- Fischer-Tropsch synthesis and upgrading.
- Power generation.
- Balance of plant units for storage, water systems, electrical systems and instrumentation/control.

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[4] Strictly speaking the SSEB study does not include all the costs associated with CCS. Transport and injection costs are not included as they are very site and project specific and typically account for less that 20% of the costs associated with CCS. Their overall impact on costs of FT production is likely to be very small.

Generic operation detail for each of the five case study plants is described below with specific case study process parameters detailed in Appendix A.

A conventional cryogenic air separation unit produces oxygen at 95% purity for gasification and nitrogen for coal drying and blanket storage. The lignite is ground using a roller mill, while the moisture content is simultaneously reduced to ~10% using heated nitrogen obtained from the air separation unit; energy for heating comes from combusting some of the syngas/low molecular weight hydrocarbon products from the FT process. The ground coal is classified into size ranges and stored under nitrogen to avoid oxidation.

Gasification uses a single-step dry-feed oxygen-blown entrained-flow gasifier operating at 1400°C and 450psi; a 99% carbon conversion rate is predicted. A water spray quench system at the gasifier exit is used to remove hydrogen chloride and particulates from the syngas. Water-gas shift is then used to adjust the hydrogen/carbon monoxide molar ratio to be approximately one for the FT reactor. Carbonyl sulphide is hydrolysed to hydrogen sulphide in a specialised reactor. The syngas is cooled and mercury is removed by active charcoal filters. An acid gas separator is used to remove the carbon dioxide and hydrogen sulphide from the syngas, with an additional unit to enable recovery of elemental sulphur. Hydrogen is removed from a portion of the syngas using membranes and a pressure swing adsorption unit to give 99.99% purity, for use in hydrocracking of the waxy FT products. Zinc oxide polishing units are used to reduce hydrogen sulphide levels further to 0.03ppm by volume.

The cleaned syngas is re-heated to 200°C and fed into the bottom of numerous FT slurry-phase reactors. The syngas bubbles through liquid containing hydrocarbons and suspended iron catalysts particles. Excess heat in the reactor from the exothermic FT reaction is removed using heat exchangers. The volatiles above the reactor liquid are removed and liquid synfuels separated by cooling. The remaining tail-gas contains un-reacted carbon monoxide/hydrogen, low molecular weight hydrocarbons, carbon dioxide and some nitrogen. In the recycling cases, some of this gas may be returned to the FT reactor via an amine unit, which separates out more of the carbon dioxide. The remaining tail-gas is sent as a fuel to electricity generating gas turbine power plant fitted with turbine exhaust gases heat recovery to enable steam production for steam turbines or process use. The raw FT products are separated from the catalyst and sent for upgrading; any waxy product is cracked into hydrocarbon gases, naphtha and diesel fuel; raw naphtha and middle distillate are treated with hydrogen to saturate any olefins produced. Freshly activated catalyst is used to replace the catalyst removed with the products. A single pass conversion efficiency of 80% is predicted. The process block diagrams, with and without un-reacted syngas recycling, are shown in Figure 1 and Figure 2 respectively.
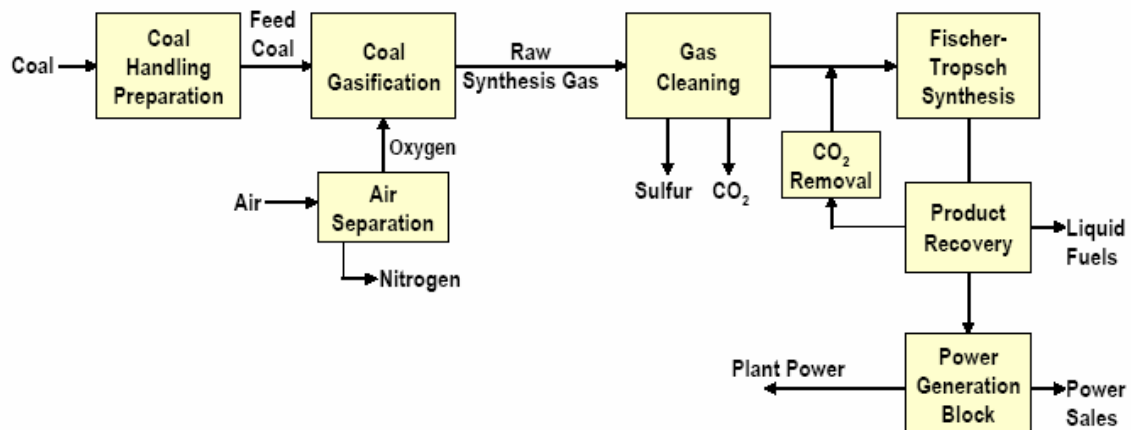

Figure 1: Process Diagram for FT CTL Plant with Un-reacted Syngas Recycling [SSEB 2006]
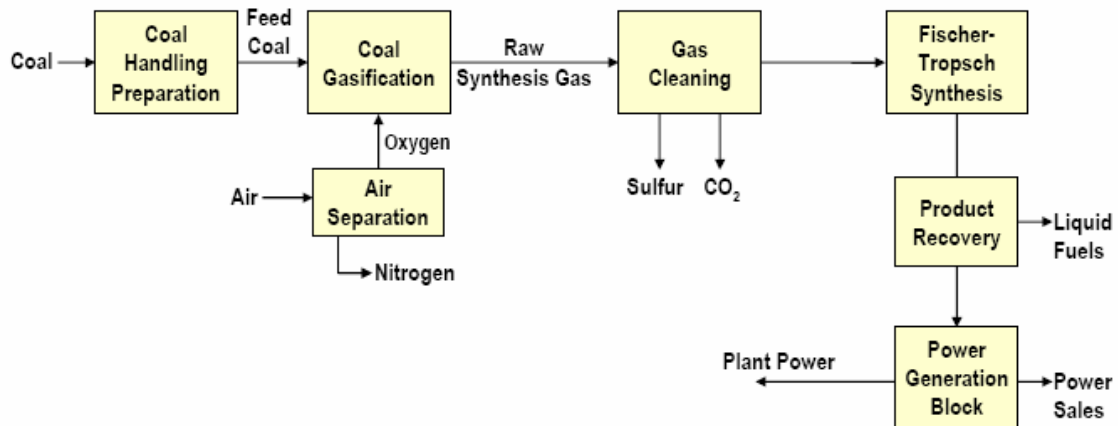
Figure 2: Process Diagram for FT CTL Plant without Un-reacted Syngas Recycling [SSEB 2006]

The SSEB study used representative data for lignite which was compared to data for New Zealand lignites to ensure that the detailed plant engineering analysis was applicable to NZ [CRL 2004]. The representative moisture content used was 36.5%, slightly lower than the NZ range of 39.6 to 42.2, the ash level at 9.84% was higher than the NZ range from 3.1 to 5.5%, but the gross calorific value used at 14.73GJ/t was within the NZ range of 14.53 to 15.25GJ/t. Overall, the data appeared similar enough that the design conditions (particularly lignite feed rate) are suitable and make the plant engineering detail useful as a first approximation for a lignite to liquid fuels plant based in Southland/Otago, New Zealand.

Various economic parameters relevant to New Zealand were required for the analysis and are detailed in Table 2. Analysis using these input data constitutes the base case around which the later sensitivity analysis was performed.

Table 2: Economic Parameters used in this Study

Economic parameter	Value
Plant lifetime, years	25
Discount rate	10%
Plant availability	90%
Electricity price, NZ$/MWh	50
Lignite cost NZ$/GJ	1.1
Lignite energy content (HHV) GJ/tonne	15.0
Lignite NZ$/tonne	16.5
Sulphur value NZ$/tonne (oversupply in NZ)	0
Exchange rate US$/NZ$	0.70

The plant lifetime and availability were the same as the original study, but the discounting rate was increased from 8% to 10% to reflect the higher interest rates in NZ compared to the US. Electricity prices were averaged from the last twelve months wholesale market report data published on the Electricity Commission website [Electricity Commission 2007]. Solid Energy reported a range of lignite prices of 0.6 to 1.6 NZ$/GJ [Solid Energy 2004] for long-term supply excluding delivery. The mid point of that range was used and delivery excluded as the plant was assumed to be placed close to the mining facility. The lignite energy content was taken as the average of samples collected from the Southland mines at Goodwin, New Vale and Waituna

[CRL, 2004]. From the cost per GJ and the energy content, the price per tonne of lignite was calculated. Sulphur value was set as zero as it is assumed that sulphur produced would be in excess of demand in NZ. This decreased the FT fuel price by half a cent at most. The prevailing exchange rate was estimated from data for the last two years[5].

The capital expenditure and annual operating costs are detailed in Appendix B. Values were converted from US$ in the original study to NZ$ using the exchange rate in Table 2 and the cost increases because of situating the plant in NZ compared to the US were considered as part of the sensitivity analysis in Section 6. The capital cost of the 60,000bbl/day plant was 4.8 US$bn, which is comparable with the 5 US$bn for an 80,000bbl/day plant reported previously [IEA/ITO 2005]

The operational design parameters, economic data and the capital/operational costs were combined to produce a simple annual cashflow sheet for each case from which a Net Present Value (NPV) was calculated. Production costs for the FT fuel were determined to be the FT fuel price at which the NPV became zero and so the fuels were effectively being produced "at cost", with no profit made by the operator/investors. For the base cases the cost of FT fuel production, lignite used per litre of fuel and carbon dioxide emitted per litre of fuel during production are shown in Table 3.

Table 3: Results of Base Analysis on the Cost, Lignite use and Emissions for CTL plant

	Case 1	Case 2	Case 3	Case 4	Case 5
Plant production scale bbl/day	10,000	10,000	30,000	30,000	60,000
Recycling un-reacted FT output?	yes	no	yes	no	yes
FT fuel cost, NZ cents/l	62.9*	67.6	51.3	52.4	47.0
FT fuel cost, NZ\$/GJ	17.2	18.5	14.1	14.4	12.9
Lignite use, kg/l FT fuel	5.97	7.84	5.93	7.19	5.57
Carbon dioxide emitted during production, (after carbon capture) gCO$_2$/l FT fuel	446	1638	514	1129	256
Overall thermal efficiency	43.9%	40.8%	45.5%	43.5%	46.7%

*The calculations leading to this FT fuel cost are given in the footnotes to Table 5 in Appendix A. Similar calculations were used to derive the costs for all five case studies.

Cases 2 and 4 cover co-production of electricity and FT fuels, whereas Cases 1, 3 and 5 effectively only consider the FT fuel production plant. Production costs ranged from 47 to nearly 68NZ cents per litre with a clear benefit for larger scale plant from economies of scale. The prices in energy terms ranged from 12.9 to 18.5NZ$/GJ, in accord with the 11 to 14NZ$/GJ range reported internationally [IEA/ITO 2005].

Lignite use ranged from 5.5 to 7.8kg/l FT fuel produced. The smallest plant used 3.5Mt/yr and the largest 19.4Mt/yr of lignite. The plants in cases 2 and 4 were effectively using some of the lignite fed to produce the electricity exported to the grid rather than to produce FT fuels. No allowance has been made for this and so the lignite used per litre of fuel produced appears to be high for those cases (and the overall efficiency lower). The reduction in lignite use with increasing plant capacity, for those plants not exporting electricity to the grid, is consistent with the increase in overall thermal efficiency.

Carbon dioxide emission ranged from 256 to 1638gCO$_2$/l FT fuel produced. The plants in cases 2 and 4 were effectively releasing much of their carbon dioxide emissions while producing electricity for export to the grid rather than during production of FT fuels. Again, no allowance has been made for this and so the emissions per litre of fuel produced appears to be high in those cases. The carbon dioxide emission from the combustion of petrodiesel and FT diesel will

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[5] from a currency dealing website, www.oanda.com

be similar. Petrodiesel emits 68.7gCO$_2$/MJ [Taylor Baines 1993], which for petrodiesel with an energy content of 38.1MJ/l equates to a rate of 2.6kgCO$_2$/l. Hence, for the largest plant with the lowest emission rate of 256gCO$_2$/l FT fuel produced, the carbon dioxide released during production of the fuel is about 10% of that during combustion of it. For smaller plant this rises to approximately 20%.

In terms of water demand, a study [Barrett 2007] of a hypothetical 11,000 bbl/day CTL plant suggests that water use could vary from 1 to 1.5 barrels of water per barrel of product for a zero-discharge air-cooled plant to 5 to 7 barrels of water per barrel of product for a plant with water cooling and less use of waste heat for process heat or co-generation. Modern gasification technology can achieve very low emissions of sulphur dioxide (SO$_2$) and particulates, has low emissions of oxides of nitrogen (NOx) and can also be designed to capture mercury readily. The FT process is not likely to add significant emissions over those from the gasifier. All plants are capable of carrying out necessary wastewater treatment on site.

6   Future Production Costs and Cost Sensitivity Analysis

Future advances to gasification technology are expected to include improved performances and reliability of air separation units. Most plants use cryogenic air separation – they consume a considerable portion of the gasifier output and account for approximately 10% of the capital cost of the CTL plant. Ion transport membrane technologies could significantly reduce the amount of electricity consumed on site during the FT process and may also result in lower capital and operational costs. Improvements in turbine technology and use of supercritical steam cycles may also result in improved efficiencies of the plant. Improvements in gas clean-up technologies, including hot gas desulphurisation, may become commercially viable by 2015, and would also lead to increased efficiencies. Improvements in FT catalysts – for example the use of more active cobalt catalyst instead of an iron based catalyst – are also targeted to give improved product yields.

The above improvements in the gasification components of the process may be expected to lead to 20 to 25% cost reductions for the gasification section [Stiegel, 2005] and similar levels of cost reduction may be realised for the FT production side.

The sensitivity of the absolute FT fuel production cost per litre was examined with respect to various economic factors and the results shown in Table 4. The production costs are shown in NZ cents/l with the percentage change from the base case given in brackets.

Table 4: Production Cost of FT Diesel from Sensitivity Analysis

	Case 1	Case 2	Case 3	Case 4	Case 5
Plant production scale bbl/day	10,000	10,000	30,000	30,000	60,000
Recycling of un-reacted FT output?	yes	no	yes	no	yes
Base case (FT cost in NZ cents/litre)	62.9	67.6	51.3	52.4	47.0
Capital costs increased by 10%	66.2 (+5.3%)	71.9 (+6.3%)	54.1 (+5.4%)	55.7 (+6.2%)	49.4 (+5.1%)
Operational costs increased by 10% (excluding lignite cost and electricity sales)	64.9 (+3.2%)	70.1 (+3.6%)	52.9 (+3.1%)	54.3 (+3.6%)	48.4 (+3.0%)
Low lignite price – lower range limit 0.6 NZ$/GJ	58.4 (-7.1%)	61.8 (-8.7%)	46.9 (-8.7%)	47.0 (-10.3%)	42.8 (-8.9%)
High lignite price – upper range limit 1.6 NZ$/GJ	67.4 (+7.1%)	73.5 (+8.7%)	55.8 (+8.7%)	57.8 (+10.3%)	51.2 (+8.9%)
Electricity wholesale price increased from 50 to 75 NZ$/MWh	62.7 (-0.4%)	61.5 (-9.1%)	50.3 (-2.1%)	47.0 (-10.4%)	46.9 (-0.1%)
Exchange rate change from base case of 0.70 US$/NZ$ to 0.60 US$/NZ$	67.0 (+6.6%)	72.9 (+7.7%)	54.7 (+6.6%)	56.4 (+7.6%)	49.9 (+6.3%)

Capital and operational costs were varied by 10%, which is not an unrealistic contingency for large-scale engineering projects and for plant situated in NZ rather than in the US. The result was a 5.1-6.3% increase for a 10% increase in capital and a 3.1-3.6% increase for a 10% increase in annual operating costs, reflecting the intensive capital nature of CTL plant.

Using the extremes of the range Solid Energy gave for lignite supply costs would vary the price per litre by 7.1% to 10.3% demonstrating the requirement to secure long-term supply contracts to maintain production cost and therefore selling price.

An increase in average electricity wholesale price from 50 to 75NZ$/MWh may be encountered if long-term increases in demand are not met by increases in firm supply (the electricity price already more than doubles the average price at times of high demand during dry spells.) A higher electricity price has clear benefits for cases 2 and 4 where synfuels are co-produced with electricity for export, but has little effect on the synfuel production-only cases.

Finally, a change in exchange rates from a base case has a significant effect, increasing fuel costs by up to 7.7%. For this analysis it was assumed that 30 to 40% of the equipment and 80-90% of the non-equipment capital and operating costs were sourced from New Zealand. It was also assumed that the exchange rate dropped by ten cents prior to completion of the plant and remained stable thereafter. This exchange rate change was applied to all the non-New Zealand sourced costs.

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Appendix A Plant Case Study Design Parameters

Table 5: Design Parameter for CTL Plant Case Studies

	Case 1***	Case 2	Case 3	Case 4	Case 5
Plant production scale bbl/day	10,000	10,000	30,000	30,000	60,000
Recycling un-reacted FT output?	yes	no	yes	no	yes
Number of gasifiers	2	3	8	9	14
Number of FT reactors	4	4	6	6	12
Lignite feed tonne/day as received	9,488	12,468	30,569	34,273	53,128
FT naphtha output bbl/day	3,507	3,507	11,362	10,521	21,042
FT diesel output bbl/day	7,495	7,495	24,284	22,485	44,970
FT total output as diesel equivalent bbl/day*	10,000	10,000	32,401	30,001	60,002
Sulphur output tonne/day	112	148	362	406	629
Gross power MW$_e$ (availability 90%)	178	384	617	960	922
Own-use power consumption MW$_e$	172	221	526	528	913
Net power for export to grid MW$_e$ (availability 90%)	6	163	91	432	9
Carbon dioxide production, tonne/day	8,079	12,038	26,398	31,722	43,891
Carbon dioxide capture rate	91%	78%	90%	83%	94%
Carbon dioxide emissions, tonne/day	709	2605	2,648	5,385	2,445
NOx emissions tonne/day	0.084	0.290	0.320	0.617	0.672
SOx emission tonne/day	0.014	0.018	0.044	0.049	0.075
Overall thermal efficiency	43.9%	40.8%	45.5%	43.5%	46.7%
Capital investment NZ$ million**	1,596	2,018	4,234	4,643	6,792
Annual O&M costs (excluding lignite) NZ$ million**	105	127	272	294	441

*NB FT diesel equivalent uses the naphtha conversion value of 0.714 times that for diesel as used in SSEB study.

**Exchange rate used for conversion was 0.7 US$ to 1 NZ$.

*** FT cost is calculated from the sum of annual fuel costs, annualised capital costs (10% for 25 years), and annual O and M costs minus annual electricity revenue.

Annual fuel cost = $16.5/tonne * 9488 * 365* 0.9 = $51.43 M (allowing for 90% plant availability)

Annualised capital investment on $1,596M at 10% over 25 years = $175.9 M

Annual O and M costs = $105 M

Annual electricity revenue = 6 MWe* 8760 * 0.9 * $50/MWh = $2.37 M

Total Annual Costs = $(51.43 + 175.9 + 105 – 2.37) = $329.96 M.

Annual Output = 10,000 bbl/day * 159 l/bbl * 365 * 0.9 = 522.3 M litres p. a.

Cost per litre = 329.96/522.3 = 0.63 $/l. (the figure differs slightly from that given in Table 3, Page 12, due to some rounding of the figures used in that Table).

Appendix B Capital and Operating Cost Breakdown

Table 6: Capital Expenditure for CTL Plant Case Studies

	Case 1	Case 2	Case 3	Case 4	Case 5
Plant production scale bbl/day	10,000	10,000	30,000	30,000	60,000
Recycling un-reacted FT output?	yes	no	yes	no	yes
Solids handling equipment	139	174	374	413	600
Gasification plant	340	440	1036	1159	1769
Air separation unit	119	144	270	293	399
Gas cleanup units	174	221	477	526	764
CO_2 capture equipment	63	77	191	114	319
Fischer-Tropsch reactors	136	136	397	371	670
Power block equipment	257	393	623	843	904
Balance of plant	66	66	164	161	279
Home office	109	139	297	326	479
Process contingency	0	0	0	0	0
Project contingency	64	83	177	194	286
License fees	36	36	36	36	36
Financing/legal	36	36	36	36	36
Non-depreciable capital	57	73	156	171	251
Total capital costs	1,596	2,018	4,234	4,643	6,792

Figures are millions of NZ$ – exchange rate used for conversion was 0.7 US$ to 1 NZ$

Table 7: Annual Operating Costs for Plant Case Studies
(Excluding Lignite and Income from Electricity Sales)

	Case 1	Case 2	Case 3	Case 4	Case 5
Plant production scale bbl/day	10,000	10,000	30,000	30,000	60,000
Recycling of un-reacted FT output?	yes	no	yes	no	yes
Royalties	6	6	6	6	6
Catalyst/chemicals	14	15	40	41	71
Labour/overhead	30	38	79	87	127
Administrative	5	6	13	14	21
Local taxes and insurance	31	39	82	89	131
Maintenance & materials	13	16	35	39	57
Other operating costs	6	7	17	18	28
Total fixed annual operating costs	105	127	272	294	441

Figures are millions of NZ$ – exchange rate used for conversion was 0.7 US$ to 1 NZ$.