CO_2 ABATEMENT BY PRODUCTION AND USE OF GAS TO LIQUIDS TRANSPORT FUELS

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Background to the Study

This report is one of the first studies by the IEA Greenhouse Gas R&D Programme to assess the potential for reducing GHG emissions from mobile sources. The study focuses on the use of remote natural gas as a transport fuel.

The abundant availability of natural gas resources with their low carbon intensity is leading to a growth of interest in natural gas as a transport fuel. Much of the future potential supply of natural gas is in remote locations, which cannot be economically exploited at present. An option seen by many as important is the conversion of this gas to liquid (GTL) fuels. These are potentially attractive alternatives to the delivery of natural gas by long-distance pipelines or transportation in ships as liquefied natural gas (LNG)

The purpose of this study is to assess the relative attractiveness of two routes by which remote gas can be brought to market:

- ‘direct use’ in which gas is liquefied, transported, vapourised, distributed through existing infrastructure and utilised in motor vehicles as compressed natural gas (CNG) – this is the base case for the study;
- ‘indirect use’ in which the gas is first converted by the Fischer-Tropsch (F-T) process into a liquid hydrocarbon fuel and exported to market using existing infrastructure. CO_2 can be captured for storage in the F-T process.

The study has been carried out by AEA Technology of the UK. It builds on the work done in an earlier IEA GHG study (Ph3/15) which examined F-T process options and the cost and effectiveness of capturing CO_2 from such processes.

It is anticipated that the IEA GHG programme will use the results of this work to help plan its future R&D programme.

Approach adopted

The approach adopted in this study was to compare the routes to market using ‘well-to-wheels’ analysis in which relevant emissions and energy efficiency at each stage of the fuel cycle are examined. In addition, the costs incurred within each stage of the fuel supply chain are also assessed. The fuel cycle is focussed on a specific scenario characterised in terms of a future time, technology, and regional market. This approach has the advantage of simplicity and identifies the high leverage stages within the fuel cycle that can be targeted for improvement. The approach does, however, have disadvantages. In particular, it is a ‘single point’ method that does not take into account the uncertainties in each stage. Such uncertainties are particularly significant when estimating the performance and cost of new technologies at some future time. In recognition of this, the study has included additional sensitivity analysis for those areas where uncertainty has a significant impact. This combination, together with a transparency of assumptions, is deemed adequate to meet the aims of the study.

The aims of the study were:

- to compare the efficiency, emissions and supply costs at each stage of 2 routes by which remote gas from a specific source can achieve an end-use service (transportation) in a selected market using best available technology;
- to identify the potential major sources of inefficiency, emissions and cost, and the likely impact of alternative technologies or of technological improvement;
- to assess the merits of CO_2 capture and storage in the F-T process as a mitigation option;
- to provide a foundation for future work on other potential options for reduction of greenhouse gas emissions from transport.

The study scenario is set in the Netherlands in 2010 and is based on a market of 1 million vehicles. Remote gas is sourced from the Middle East. The F-T process technology is as assessed in the previous IEA GHG study, in order to provide data that are both traceable and consistent. Vehicle technology is assumed to meet Euro IV emission standards, and to have improved fuel economy, compared to current models, consistent with the ACEA Agreement[1] on reducing carbon dioxide emissions from cars.

The LNG fuel cycle utilises advanced spark-ignition engine technology (this case is referred to as 'LNG' with or without CO_2 capture at the liquefaction plant), whereas the F-T process produces a diesel fraction that can be used in advanced diesel engines, most likely blended with conventional refinery diesel (this case is referred to as 'F-T diesel', with or without CO_2 capture).

In order to provide a reference with conventional fuels, additional fuel cycles have been examined. A fuel cycle based on gasoline has been selected as a primary reference, also using an advanced spark-ignition engine. In an attempt to achieve some comparability at each stage of the fuel cycle, it has been assumed that crude is supplied from the same Middle East location and refined in the Netherlands (this case is referred to as 'conventional gasoline').

A further fuel cycle based on diesel sourced from North Sea crudes was introduced although this was not the main purpose of the study; this represents a 'best case' for diesel since transportation and refining losses will be lowest (this case is referred to as 'conventional diesel').

Results and Discussion

Fig. S1 provides a summary of the results derived in this study for total greenhouse gas emissions, expressed as grams of CO_2 equivalent per kilometre travelled, for each of the fuel cycles. Emissions data are shown for each stage of the fuel supply chain and for the vehicle. The overall uncertainty has been estimated at ca. 5-15%, the higher figures applicable to the least mature technologies. Since technological development is the main source of uncertainty, data in Fig. S1 are likely to be overestimated.

The results show that by far the largest factor affecting CO_2 emissions over the entire fuel cycle is the vehicle, particularly engine efficiency. Typically, ca. 80% of GHG emissions arise from the vehicle. Improvements here reduce both the emissions from the vehicle and from the supply chain. As an example, the study has estimated that, for the gasoline reference cycle, CO_2 equivalent emissions can be reduced from 188 g/km to 129 g/km by utilising advanced hybrid engine technology. Such benefits are available irrespective of the fuel cycle.

[1] The so-called ACEA Agreement is a voluntary agreement between the European Union and European, Japanese and Korean car manufacturers to reduce the average new car fleet carbon dioxide emission to 140g CO_2 per km by 2008-2009

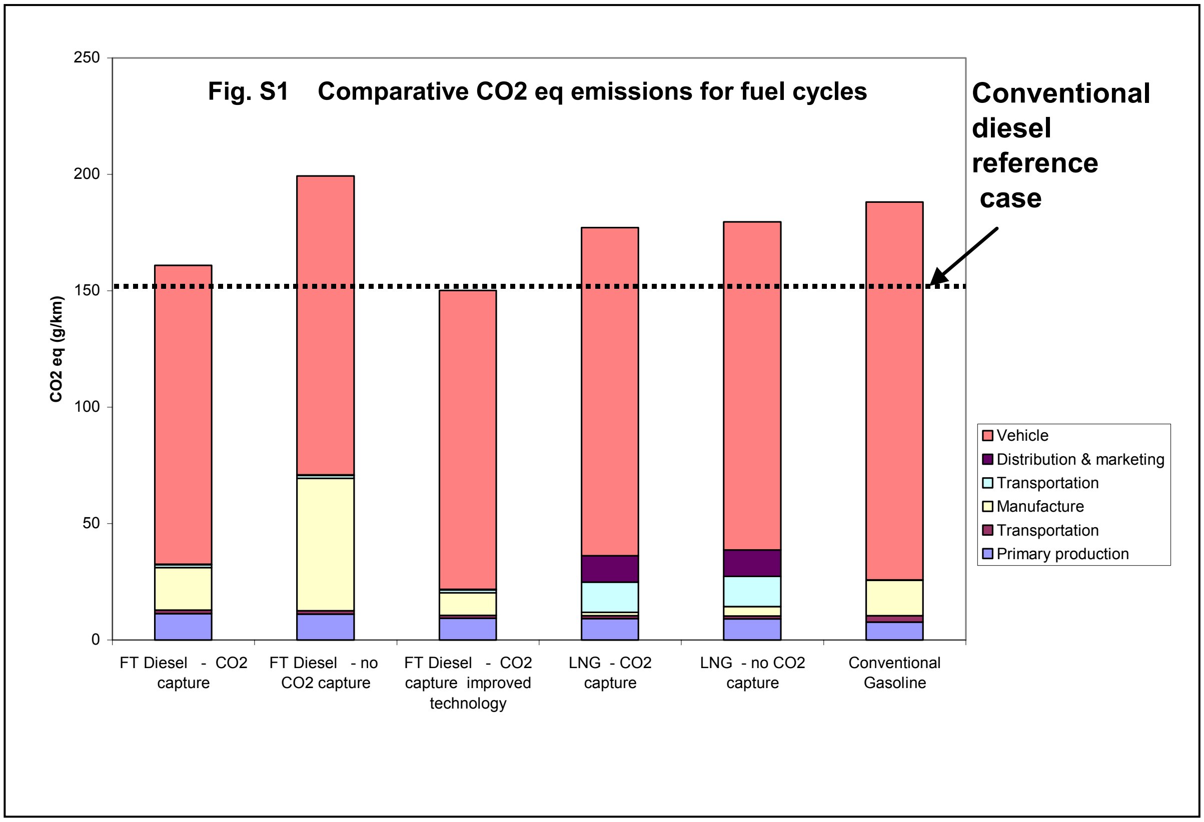


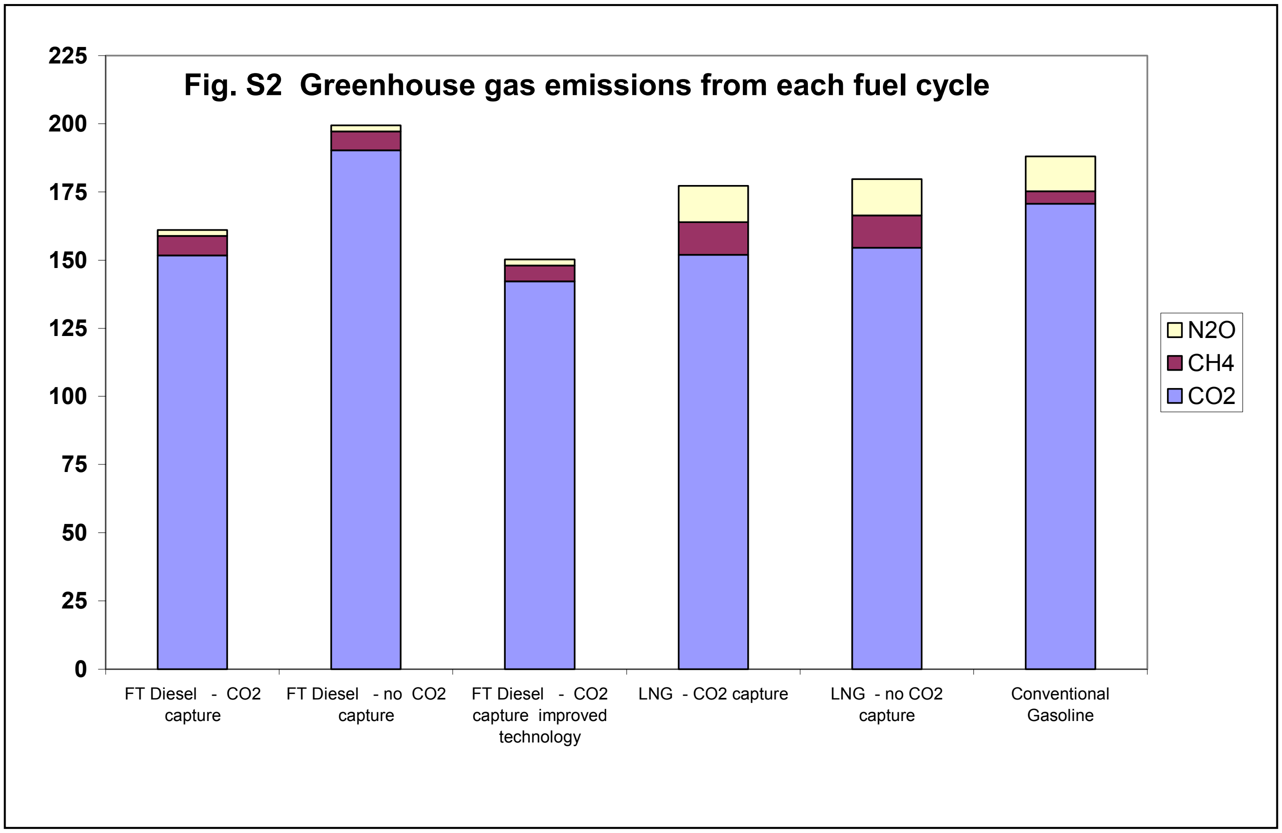
Fig. S1 Comparative CO2 eq emissions for fuel cycles

Comparing the two routes for getting gas to market, without investing in CO_2 capture at the processing stage, the LNG fuel cycle offers the lowest total greenhouse gas emissions. On the other hand, with CO_2 capture the position is reversed. The overall attractiveness of these cases is controlled by several factors: energy efficiency in the fuel processing, emissions produced during transportation and distribution stages, carbon intensity of the fuels and engine technology. F-T synthesis is a relatively inefficient process but produces a liquid fuel that can be easily transported and utilised more efficiently by the vehicle, albeit with a higher carbon intensity than natural gas. Without CO_2 capture, high CO_2 emissions from the F-T process more than offset the inherently higher efficiency of the diesel engine and the relatively low emissions generated during transportation and distribution of liquid fuels. With CO_2 capture, the benefits of the engine technology and low emissions from transportation and distribution become the controlling factors. The ranking is further improved with advanced F-T process technology. Using data for state-of-the-art technology[2], the F-T diesel fuel cycle with CO_2 capture would have greenhouse gas emissions comparable with conventional diesel. The relative immaturity of F-T technology will ensure that, as production capacity becomes established, the rate of cost and performance improvements will be faster than for the more mature, liquefaction technology. These results are therefore robust to technology improvement.

Fig. S2 provides a summary of the data broken down in terms of the individual greenhouse gases (CO_2, CH_4 and N_2O). In all cases CO_2 is the dominant greenhouse gas. Methane and Nitrous oxide do make significant contributions in some cases. Methane arises from leaks and venting and could be reduced further by changes in operating practices. Nitrous oxide emissions are higher from spark ignition engines.

[2] Private communication from Anders Ekvall

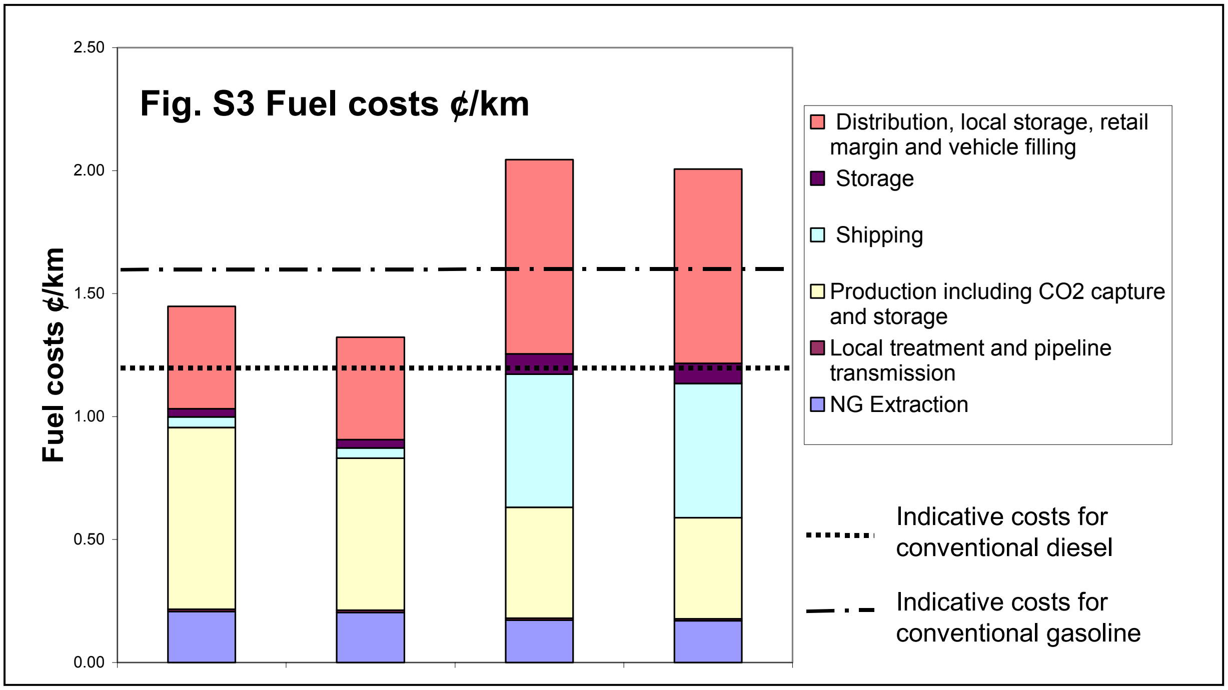
In particular the three-way catalyst fitted to these vehicles leads to increased levels of N_2O, although future advanced catalysts could have lower emissions.



Full cycle fuel costs, expressed as costs per kilometre travelled are shown in Fig S3. In this study only the costs of fuel are reported; other differential costs involved in running and owning the vehicle have not been assessed. Underlying assumptions made in the report are strongly influenced by technology development, and supply and demand balances in the international energy market. The data in Fig. S3 are, therefore, only indicative.

The findings of the study suggest that LNG is a more expensive route for getting gas to market than conversion to F-T diesel. This is true both for the cost of fuel supply and for the cost per unit of service (i.e. km travelled). Major costs drivers for LNG are in shipping the liquefied fuel and in compression for vehicle fuelling at the retail site[3]. The major cost in F-T diesel production is the manufacturing stage. As experience is gained in both conversion and capture technology, costs at this stage of the fuel cycle can be expected to fall, bringing the cost of F-T diesel more in line with conventional diesel.

[3] The introduction of CO_2 capture into the LNG system makes very little difference to the overall emissions because the captured CO_2 is only a small part of the whole cycle emissions; the incremental cost of capture is small since this has to be done anyway to condition the gas for the liquefaction process.



When F-T diesel fuel is supplied to the automotive market in the location assumed in this study, the cost is lower than the alternative way of supplying this need from the same remote gas source (i.e. through bulk shipment of LNG from a liquefaction plant using CO_2 capture, with use of the fuel in CNG vehicles). Hence, compared with this alternative, there is a cost **saving** of about \$365/tCO_2-eq. associated with the 17g CO_2-eq /km reduction in emissions. However, without capture of CO_2 in either process, the lower end-use emissions of CNG mean that use of F-T diesel increases CO_2 emissions.

Many of the published well-to-wheels studies compare fuels at the point of use (i.e. they assume similar end-use technology) rather than compare different routes for using the same fuel supply, as has been done here. To do the former rather than the latter would require comparing emissions from fuel cycles using similar engine technology. Thus the F-T fuel would be compared with conventional diesel. Unfortunately, as this was not the purpose of the study, the contractor only provided data for diesel fuel derived from North Sea crude, where little or no emissions reduction can be achieved by changing to F-T diesel. The advanced F-T process might produce a small reduction in greenhouse gas emissions, if the conventional diesel fuel were derived from a similar remote source to the natural gas. On the other hand, for the fuels which are intended for use in spark-ignition engines (i.e. CNG and gasoline), a comparison can be made; using the LNG/CNG route, emissions are 10 g CO_2-eq /km lower than the gasoline route at a cost of abatement of \$495/t CO_2-eq.

This overview has illustrated results based on a European location for the fuel cycle; the main report also includes an examination of how the results change under assumptions more appropriate for the USA.

Reviewers' comments

Comments on the draft report were received from a number of experts. Most of the debate focused on specific assumptions made in defining the fuel cycle scenarios, and the specific emission and cost factors. The authors have reviewed all comments, and have revised the draft to either clarify the text or to include additional sensitivity analysis.

An area of concern raised by a number of reviewers was the uncertainty over new technologies. In particular, F-T process technology and vehicle technology. As the analysis shows, both of these are critical to the comparative results obtained for each cycle. One expert pointed out that the assumed efficiency for the FT plant is much lower than state-of-the-art FT plant designs. For example, Shell's second-generation design has a carbon efficiency of 80% compared to the 67% used as a baseline in the study[4]. This amounts to a 40% reduction in CO_2 emissions in the production stage. The impact of such improvements is included in the sensitivity analysis and estimates of uncertainty.

Major Conclusions

This study provides an analysis of alternative routes for getting remote natural gas to market. The 'indirect' route through conversion of gas by the Fischer Tropsch process to diesel fuel is compared with a 'direct route', or base case, of gas supply as LNG for use in spark ignition engines as CNG.

The analysis shows that the results are particularly sensitive to uncertainties about the fuel efficiency of future vehicles and improvements in process technology. As a result, it is particularly difficult to draw firm conclusions when comparing the emissions from the different fuel cycles.

Nonetheless some general conclusions can be drawn:

- Emissions from all the fuel cycles are dominated by emissions from final fuel consumption by the motor vehicles. Typically, ca. 80% of CO_2 and other greenhouse gas emissions come from the vehicle.
- Capture of CO_2 in the LNG fuel cycle is of marginal benefit to greenhouse gas emissions.
- If CO_2 is captured and stored at the manufacturing stage, the route from gas to F-T liquids/diesel does give lower greenhouse gas emissions than the LNG/spark-ignition route. This is due to the higher end-use efficiency of diesel vehicles and lower emissions produced during transportation and distribution of liquid fuels.
- The attractiveness of the F-T diesel fuel cycle can be expected to improve further relative to LNG as the technology matures.
- The F-T diesel fuel cycle, with CO_2 capture, produces greenhouse gas emissions that are slightly higher than the reference diesel fuel cycle. If a more advanced GTL conversion plant had been used, the emissions from the 2 fuels would have been comparable.
- The F-T diesel fuel cycle is less expensive than the LNG fuel cycle in terms of cost per vehicle kilometre (by virtue of the higher fuel efficiency of diesel engine vehicles). With the most

[4] Private communication from Anders Ekvall

advanced gas to liquids conversion plant and with cost reductions gained through experience, costs could approach those of conventional diesel.

- Based on emissions and costs, this study indicates that the F-T route is the more effective one for exploiting remote gas as a transport fuel.

Recommendations

The study shows that the conclusions are particularly sensitive to assumptions made about engine efficiency and the rate at which F-T technology is expected to improve relative to liquefaction technology. Further work should be done in the following areas:

- Assessment of alternative engine technologies to establish whether the conclusions reached in this report about the end-use efficiency of the diesel cycle remain robust.

- Assessment of emissions and costs of second generation F-T technology relative to the baseline Sasol technology used in this report. This would be a suitable topic for IEA GHG to examine as its second study on technology "stretch" following the IGCC "stretch" study which is underway at present.

Carbon Dioxide Abatement by Gas to Liquids Transport Fuels

A report produced for the IEA Greenhouse Gas R&D Programme

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Executive Summary

Transport, and in particular road transport, is a large and growing source of GHG emissions. For example in the European Union (EU) road transports related greenhouse gas emissions have increased by almost 20% between 1990 and 2000.

One option for reducing greenhouse gas emissions from road transport is to replace refinery gasoline and diesel fuels with less carbon intensive alternatives. However, this presents considerable problems because of the energy density and combustion properties required from viable transport fuels, and the costs involved in modifying established fuel distribution systems.

In order to bring remote natural gas to market, conversion into a liquid form is an alternative to piping it or shipping it by tanker. Gas-to-liquids (GTL) conversion can produce a fuel which is directly suitable for use in the transport sector. Indeed, liquids produced by the Fischer Tropsch (F-T) process are said to be "cleaner" than refinery diesel fuel, so their use would contribute to reducing emissions from vehicles. Moreover, the F-T process can be modified to incorporate CO_2 removal – if the CO_2 is subsequently stored, for example in a geological reservoir, this would reduce greenhouse gas emissions.

The IEA Greenhouse Gas R&D Programme has initiated an investigation to assess whether this growing interest in gas to liquid fuel conversion offers an opportunity to develop a technically and economically viable option for introducing less carbon intensive fuels into the road transport sector. As a first step the programme sponsored a techno-economic assessment of state of the art Fischer-Tropsch (F-T) conversion technology for producing diesel fuel from natural gas. The work included an assessment of the efficacy and cost of capturing the carbon dioxide produced in the conversion process.

This report describes a follow up to the earlier work, which aimed to assess the potential for carbon dioxide emissions abatement based on the use of F-T products as road transport fuels, and thereby help the IEA-GHG R&D Programme to plan further action on the subject. This involved "full fuel cycle" assessments to determine the emissions and costs of a set of hypothetical fuel cycles supplying fuel to 2010 specification passenger cars, namely:

- F-T diesel production, based on remote natural gas located in the Middle East (Iran), which is shipped to the North East coast of The Netherlands for distribution.
- A direct use reference involving LNG production commencing in the same Middle East location with shipment to the North East coast of The Netherlands for vaporisation and distribution through the natural gas network to compressed natural gas (CNG) filling stations.
- A gasoline fuel cycle based on crude oil extracted in the same Middle East location and shipment to The Netherlands for refining and distribution. This fuel cycle enables comparison between F-T diesel, LNG and the "continued development" of petroleum based fuel to a 2010 specification and use in advanced vehicle technology.

In addition existing data on a refinery diesel fuel cycle involving the refining of North Sea crude oil in a North European refinery was included as an additional benchmark. This fuel cycle is not directly comparable to the others since it does not start from a Middle East location. It was used to enable comparison with the "best case" for diesel production and supply in Northern Europe.

The assessment considered emissions and costs for the full fuel cycles from primary extraction to end-use. However, it did not consider secondary emissions from such areas as plant construction or vehicle manufacture. Sensitivity studies have been made to assess the implications on costs and emissions of relocating the market for the fuels to North America.

The main findings of this study have been presented in terms of emissions and costs per vehicle kilometre for each of the fuel cycles.

Greenhouse gas emissions for all the fuel cycles (excepting hybrid vehicles) lay within 35% of each other, and this margin narrowed when recent improvements to the conversion efficiency of gas to liquid plant were taken into consideration. Further, with vehicle emissions dominating total emissions from the fuel cycles, the results were particularly sensitive to uncertainties over the fuel efficiency of future vehicles. Consequently it is difficult to draw firm conclusions when comparing the emissions from different fuel cycles.

Nonetheless two key conclusions on emissions are:

- The F-T diesel fuel cycle, with carbon capture, does not reduce greenhouse gas emissions from road transport when substituted for refinery diesel. With the most advanced gas to liquids conversion plant such a substitution would be about neutral on emissions.
- F-T gas to liquids technology does give lower greenhouse gas emissions than LNG when both are used as transport fuels. This is mainly due to the higher end-use efficiency of diesel vehicles.

Using the "baseline" results and sensitivity assessments other, more detailed, results are:

- The F-T diesel fuel cycle with CO_2 capture has carbon dioxide emissions about 5% higher than a refinery diesel fuel cycle. When the other greenhouse gases involved in the fuel cycle are considered, namely methane and nitrous oxide, the difference increases. However, advances in process systems could significantly improve the conversion efficiency of F-T plant, which would reduce the difference in emissions between refinery and F-T diesel (with carbon capture) to a negligible level.
- The higher emissions from the F-T fuel cycle when all greenhouse gases are considered is due to fugitive methane emissions in the up stream parts of the fuel cycle. These emissions are less in the refinery diesel fuel cycle, which, being based on crude oil from the North Sea, assumed more tight control of fugitive emissions.
- The LNG fuel cycle with CO_2 capture gave a 10% reduction in CO_2 emissions compared to the refinery gasoline fuel cycle. This abatement is reduced to 5%, when all three of the greenhouse gases associated with the fuel cycle are considered. These "baseline" estimates are conservative, and taking account of uncertainties in the analysis would give a higher comparative reduction in emissions.
- Emissions from all the fuel cycles are dominated by emissions from final fuel consumption by the motor vehicles. Thus with the F-T fuel cycle over 80% of CO_2 and

all greenhouse gas emissions come from the vehicle. In the case of the LNG fuel cycle the corresponding value is over 79%.
- The F-T diesel fuel cycle gives 10% lower greenhouse gas emissions than the LNG fuel cycle per kilometre of vehicle travel when both have CO_2 capture. This advantage is due to the better and fuel efficiency of diesel engines, compared with spark ignition engines.
- F-T diesel fuel cycle does not retain this advantage with non-CO_2 capture technologies due to its higher upstream emissions of greenhouse gases.
- Increasing the conversion efficiency of gas to liquids plant from the 55% used as baseline in the study to the 67% attained in recent systems makes the F-T diesel emissions less than LNG emissions both with and without carbon capture.

The cost of vehicle travel, for each of the fuel cycles, has been assessed assuming that the fuels are used in the same specification of vehicle, with the fuels supplying a fleet of one million vehicles in 2010. With such a large fleet it was also assumed that economies of manufacture would be sufficient to ensure that gas fuelled vehicles would have the same costs as for diesel or gasoline vehicles.

Using the "baseline" results and sensitivity assessments the main findings from the cost analysis were:

- F-T diesel with CO_2 capture is 20% more expensive than refinery diesel in terms of cost per vehicle kilometre.
- Scale up cost savings and conversion efficiency improvements could reduce F-T diesel costs to a level comparable to refinery diesel.
- The LNG fuel cycle with CO_2 capture is 33% more expensive than the refinery gasoline fuel cycle in terms of cost per vehicle kilometre.
- The F-T diesel fuel cycle is 41% less expensive than the LNG fuel cycle in terms of cost per vehicle kilometre (by virtue of the higher fuel efficiency of diesel engine vehicles), showing that it is the most cost effective route for exploiting remote gas as a transport fuel.

The above data can be combined to assess the cost of abating CO_2 and total greenhouse gases with the F-T diesel and LNG fuel cycles. The main results are:

- The F-T diesel fuel cycle may have comparable to higher costs and greenhouse gas emissions compared to refinery diesel. Consequently replacement of refinery diesel with F-T diesel seems unlikely to give a reduction in greenhouse gas emissions.
- The cost of abating CO_2 emissions by replacing refinery gasoline with the LNG fuel cycle is $280/tonne CO_2. The corresponding cost for the three greenhouse gases involved in the fuel cycles is $500/tonne CO_2 equivalent. Note the higher cost for the three gases is because the level of abatement is less while the costs stay the same. These values are high compared to options for carbon capture in power generation, which are typically $50-70/ tonne CO_2.
- It should be noted that if the F-T diesel fuel cycle were compared to the gasoline fuel cycle, then abatement costs would be negative, i.e. there would be a net saving per tonne of CO_2 abated. This is because F-T diesel is cheaper per vehicle kilometre travelled and has lower greenhouse gas emissions than gasoline. However, it was assumed in the study that diesel would not necessarily be used as a replacement for gasoline.

Contents

1. Introduction

Transport, and in particular road transport, is a large and growing source of GHG emissions. For example in the European Union (EU) road transports related greenhouse gas emissions have increased by almost 20% between 1990 and 2000. Data for North America show a similar trend, with transport related emissions increasing 23% between 1990 and 2000.

One option for reducing greenhouse gas emissions from road transport is to replace refinery gasoline and diesel fuels with less carbon intensive alternatives. However, this presents considerable problems because of the energy density and combustion properties required from viable transport fuels, and the costs involved in modifying established fuel distribution systems.

A considerable part of the world's natural gas reserves occur in locations that are remote from existing markets and are not easily transportable by pipeline systems. Interest has developed in using gas to liquid conversion technologies to exploit these reserves. The main options are the production of liquid fuels such as diesel and the more established liquefaction of natural gas to LNG.

The IEA Greenhouse Gas R&D Programme has initiated an investigation to assess whether this growing interest in gas to liquid fuel conversion offers an opportunity to develop a technically and economically viable option for introducing less carbon intensive fuels into the road transport sector. As a first step the programme sponsored a techno-economic assessment of state of the art Fischer-Tropsch (F-T) conversion technology for producing diesel fuel from natural gas. The work included an assessment of the efficacy and cost of capturing the carbon dioxide produced in the conversion process.

This report describes a follow up to the earlier work, which aimed to assess the potential for carbon dioxide emissions abatement based on the use of F-T products as road transport fuels, and thereby help the IEA-GHG R&D Programme to plan further action on the subject. This involved "full fuel cycle" assessments to determine the emissions and costs of a set of hypothetical fuel cycles supplying fuel to 2010 specification passenger cars, namely:

- F-T diesel production, based on remote natural gas located in the Middle East (Iran), which is shipped to the North East coast of The Netherlands for distribution.
- A direct use reference involving LNG production commencing in the same Middle East location with shipment to the North East coast of The Netherlands for vaporisation and distribution through the natural gas network to compressed natural gas (CNG) filling stations.

- A gasoline fuel[1] cycle based on crude oil extracted in the same Middle East location and shipment to The Netherlands for refining and distribution. This fuel cycle enables comparison between F-T diesel, LNG and the "continued development" of petroleum based fuel to a 2010 a specification and use in advanced vehicle technology.

In addition existing data on a refinery diesel fuel cycle[2] involving the refining of North Sea crude oil in a North European refinery was included as an additional benchmark. This fuel cycle is not directly comparable to the others since it does not start from a Middle East location. It was used to enable comparison with the "best case" for diesel production and supply in Northern Europe.

The assessment considered emissions and costs for the full fuel cycles from primary extraction to end-use. However, it did not consider secondary emissions from such areas as plant construction or vehicle manufacture. Sensitivity studies have been made to assess the implications on costs and emissions of relocating the market for the fuels to North America.

2. Definition of the Fuel Cycles

The three main fuel cycles examined in the study were:

- Fischer-Tropsh Diesel Fuel Cycle
- LNG Fuel Cycle
- Gasoline Fuel Cycle

These are illustrated in Figures 1 to 3, and are described in detail in Appendix 1. In all cases the fuel cycles were scaled to meet the annual requirements of 1 million cars based in The Netherlands, which infers an output of about 7 MNm^3/day of natural gas or 16,000 bbl/day (89TJ/day) of diesel for the F-T fuel cycle. The information required to characterise each stage of the fuel cycles consisted of:

- Emissions to the atmosphere (i.e. CO_2, CH_4, N_2O, SO_2, NO_x, CO, NMVOCs – non-methane volatile organic compounds- and particulate material - PM).
- Conversion efficiency and energy consumption.
- Capital and operating costs of technologies deployed.

A range of assumptions was needed to complete these characterisations, and these assumptions had to be made in a way that facilitated comparisons between the fuel cycles. Moreover, the study aimed to assess the fuel cycles in the year 2010, therefore

[1] The gasoline fuel cycle assumed a nominal 2010 gasoline specification based on the current EU standard but with the sulphur and aromatics concentrations reduced in line with the European Commission's proposals set out in COM(2001) 241 final (CEC, 2001).
[2] The diesel fuel cycle assumed a diesel specification based on the current EU standard, but with the sulphur level reduced in line with the European Commission's proposals set out in COM(2001) 241 final (CEC, 2001).

assumptions had to be made on the likely price of the primary energy sources (i.e. natural gas and crude oil) as well as the cost and performance of the vehicles that would utilise the refined fuels. Details of the definition of the fuel cycles are given in Appendix 1, while the key assumptions are described below.

The study deliberately aimed to gather performance data on the same size and specification of car across all three of the fuel cycles. This implicitly assumed that all three vehicles would benefit equally from developments in chassis design, weight reduction, reduced rolling resistance, etc. It therefore focused the assessment on the different fuel efficiencies and emissions characteristics of the drive systems, which linked directly to the choice of fuels.

2.1 FISCHER-TROPSCH DIESEL FUEL CYCLE

- The natural gas supply for this plant was assumed to come from a hypothetical inland field located in Iran some 150 km from the coast.
- The gas is transported by pipeline to the F-T plant, which is sited on the coast.
- The cost and performance of the F-T plant were taken from the previous IEA-GHG study (IEA GHG, 2000), which examined a plant based on the Sasol system. This system has a product stream consisting of roughly 60% diesel and 40% naphtha on the basis of energy content. Energy consumption, costs and emissions were divided proportionately between the product streams, and each was assumed to be of equal value (i.e. no credit was given for the possibility of getting a premium price for the naphtha).
- The study examined F-T plant with and without carbon dioxide capture facilities. When CO_2 was captured, it was assumed to be transported 150 km by pipeline and disposed of by injection into a spent gas field.
- The diesel was shipped to The Netherlands by product tanker.
- The diesel was mixed with conventional refinery diesel and distributed through the established system. Consequently no new or additional distribution and fuelling infrastructure was needed, and distribution costs were taken to be the same as for refinery diesel.
- F-T diesel has a higher cetane number than refinery diesel, which could enable it to command a premium price. However, because the properties of refinery diesel are uncertain for 2010 no credit was taken for this in the assessment.
- The sulphur content of F-T diesel meets the specification proposed by the European Commission for 2010 (i.e. < 10 ppm S). For the purpose of the price comparison, the cost of reducing sulphur in refinery diesel to this level was assessed and included in the refinery diesel price estimates.
- The diesel was used in a medium sized (e.g. Volkswagen Golf, Ford Focus) car produced in 2010 and powered with a compression ignition engine. This was assumed to meet Euro IV standards[3] on emissions other than carbon dioxide. Also it was assumed to have improved fuel economy, compared to current models,

[3] The EuroIV emission standards for gasoline and diesel cars come into force on 1st January 2005. As yet no decision has been made on longer term, more stringent emission standards similar to the EuroV standards for heavy duty vehicles scheduled for October 2008.

consistent with the ACEA Agreement[4] on reducing carbon dioxide emissions from cars.

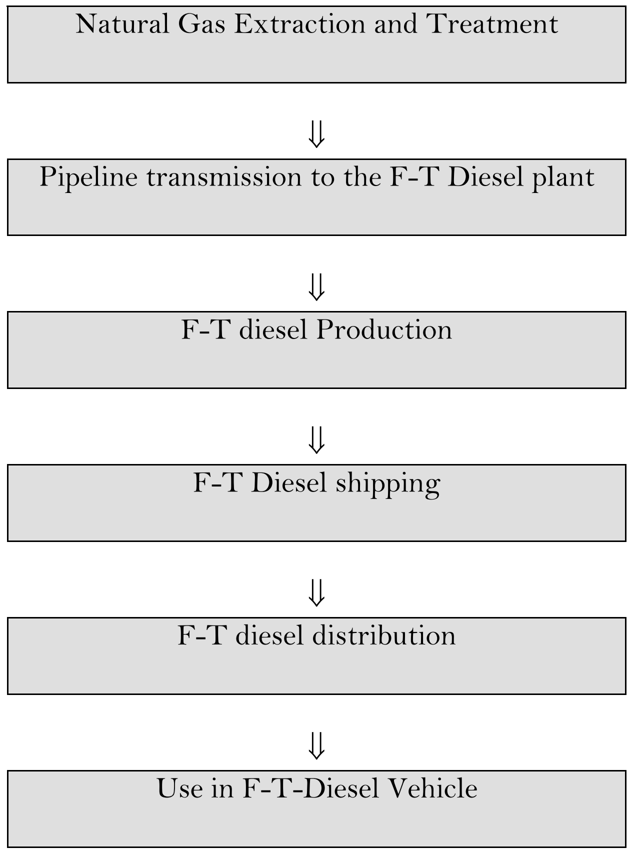

Figure 1 Stages considered in the F-T Diesel Fuel Cycle

2.2 LNG FUEL CYCLE

- Natural Gas was obtained from the same source as for the F-T diesel fuel cycle.
- The gas was transported by pipeline to the coast where the LNG plant was located.
- The study examined LNG plant with and without carbon dioxide capture facilities. When CO_2 was captured, it was assumed to be transported 150 km by pipeline and disposed of by injection into a spent gas field.
- The LNG was shipped to The Netherlands.
- On arrival in The Netherlands the LNG was stored in tanks before being vaporised and distributed to car filling stations through The Netherlands' gas transmission

[4] The so-called ACEA Agreement is a voluntary agreement between the European Union and European, car manufacturers to reduce the average new car fleet carbon dioxide emission to 140 gms per km by 2008-2009. A similar (JAMA/KAMA) agreement exists with Japanese and Korean car manufacturers.

and distribution network. Since the volume of gas involved is less than 2% of the current system capacity, it was assumed that there would be no need to invest in additional capacity.

- At the filling stations the gas is compressed and dispensed to cars through new forecourt facilities. It was assumed that one sixth of Netherlands filling stations would need to invest in these facilities (i.e. about 670 stations) since the fleet of 1 million cars considered in this study approximates to one sixth of the current passenger car stock.
- The gas was used in a medium sized (e.g. Volkswagen Golf, Ford Focus) car produced in 2010 and powered with a spark ignition engine. This was assumed to meet Euro IV emission standards, and to have improved fuel economy, compared to current gasoline spark ignition models fuelled with CNG, consistent with the ACEA Agreement on reducing carbon dioxide emissions from cars.

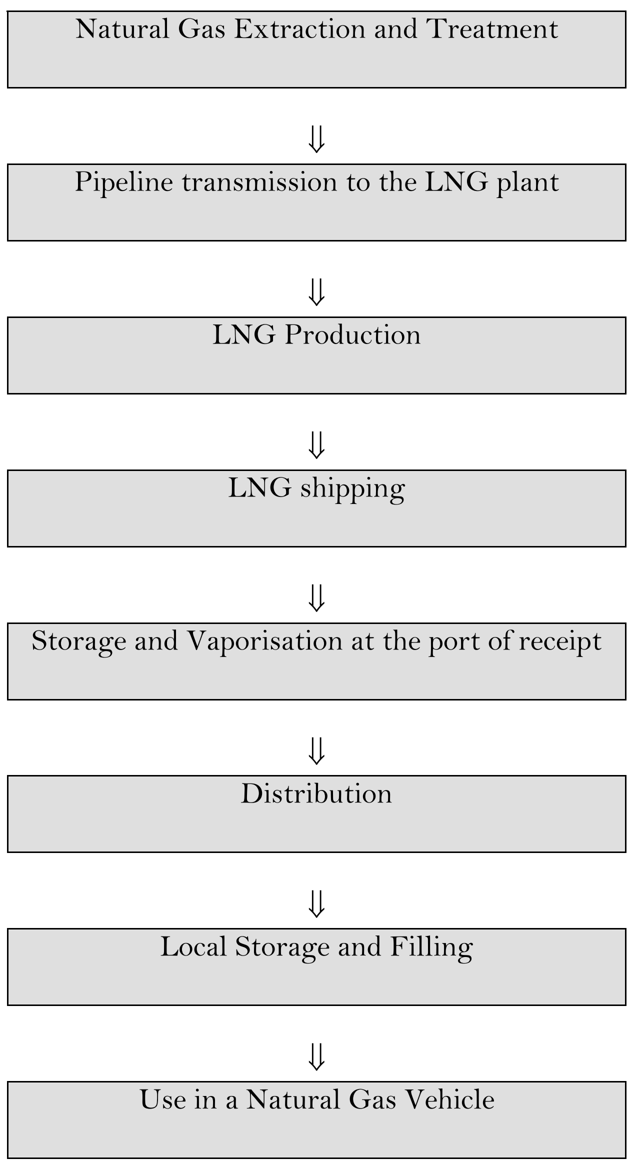

Figure 2 Stages Considered in the LNG Fuel Cycle

2.3 GASOLINE FUEL CYCLE

- Crude oil was assumed to be shipped from the Iranian coast to The Netherlands for refining.
- Gasoline was distributed to filling stations in The Netherlands
- The gasoline was used in a medium sized (e.g. Volkswagen Golf, Ford Focus) car produced in 2010 and powered with a spark ignition engine. This was assumed to meet Euro IV emission standards, and to have improved fuel economy, compared to current gasoline spark ignition models, consistent with the ACEA Agreement on reducing carbon dioxide emissions from cars.
- As an additional assessment the use of gasoline in a medium size car powered with a hybrid drive system was also examined.

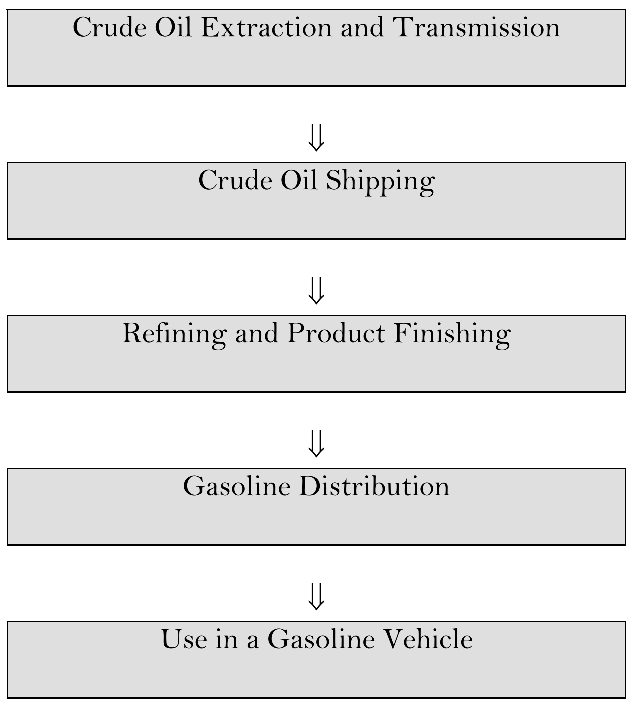

Figure 3 Stages Considered in the Gasoline Fuel Cycle

2.4 STANDARD DIESEL FUEL CYCLE

In addition data on a refinery diesel fuel cycle involving the refining of North Sea crude oil in a North European refinery was included as an additional benchmark. This fuel cycle is not directly comparable to the others since it does not start from a Middle East location. It was used to enable comparison with the "best case" for diesel production and supply in Northern Europe.

Suitable data were gathered from previous studies of greenhouse gas emissions from the refinery diesel fuel cycles (Appendix 2). Fuel economy was assumed to be the same as for the F-T diesel vehicle.

3. Assessment of Fuel Cycle Emissions

3.1 BASELINE ESTIMATES

The initial assessment used single "baseline" values for emissions from each stage of the fuel cycles to estimate total fuel cycle emissions. These were taken from previous work or estimated from related data (e.g. on energy consumption), and were conservative values. Where a range of values was found this has been reported and a single value used from within the range. Results of the assessment of the total emissions for each of the fuel cycles covered in the study are listed in Table 1. Details of the analysis, which yielded these results, and the individual emissions from each stage of the fuel cycles, are given in Appendix 2.

The lowest CO_2 emissions per vehicle km travelled arise from the use of gasoline in a vehicle with a hybrid drive system, due mainly to the high fuel efficiency of the hybrid vehicle. For conventional drive vehicles, the lowest CO_2 emissions arise from the refinery diesel fuel cycle. Emissions from the F-T diesel fuel cycle with CO_2 separation are about 5% more than from refinery diesel. F-T diesel without CO_2 separation has emissions that are about 30% higher than for refinery diesel.

When the diesel fuel cycles are compared in terms of the global warming potential of their total greenhouse gas emissions (i.e. including methane and nitrous oxide in addition to carbon dioxide[5]) the difference between the F-T fuel cycle and the refinery diesel fuel cycle increases to 9% (Table 1). This is because a greater amount of methane is expected to escape in the "up stream" stages of the F-T diesel fuel cycle compared to the refinery diesel fuel cycle. These fugitive methane emissions arise during natural gas extraction, pipeline transmission and in the F-T plant. In comparison the benchmark refinery diesel fuel cycle was based on refining crude oil from a North Sea field, and assumes that up stream methane emissions were more tightly controlled.

The LNG fuel cycle had lower CO_2 (10%) and total greenhouse gas (5%) emissions than the gasoline fuel cycle, which used the same type of spark ignition engine. However, the greenhouse gas emissions from this cycle are about 10% higher than for the F-T diesel, when both have CO_2 capture, by virtual of the higher efficiency of the diesel engine vehicles. F-T diesel does not retain this advantage when both fuel cycles do not have CO_2 capture because of its greater upstream emissions of greenhouse gases.

[5] 100 year Global Warming Potentials for methane and nitrous oxide of 23 and 296 respectively are used to calculate total greenhouse gas emissions in terms of carbon dioxide equivalent (IPCC, 2001).

Figure 4 compares the total greenhouse gas emissions arising in the "up stream" parts of the fuel cycles with the emissions produced from final consumption of the fuels in their respective vehicles. The diagram shows that down stream vehicle emissions dominate all fuel cycles. Up stream greenhouse gas emissions are higher for the remote gas fuel cycles because of the great levels of methane emissions, and in the case of F-T diesel the relatively low efficiency of the conversion process.

Table 1 Full Fuel Cycle Emissions (g/km)

Fuel Cycle	**CO_2**	**CH_4**	**N_2O**	**SO_2**	**NO_x**	**PM**	**NMVOC**	**CO**		**CO_2-eq**
F-T diesel production with CO_2 capture	151.7	0.31	0.01	0.03	0.32	0.03	0.14	0.41		161.0
F-T diesel production without CO_2 capture	190.2	0.31	0.01	0.03	0.32	0.03	0.14	0.41		199.4
LNG production with CO_2 capture	152.6	0.53	0.04	0.01	0.14	0.00	0.16	0.05		178.0
LNG production without CO_2 capture	157.6	0.52	0.04	0.01	0.14	0.00	0.16	0.05		182.9
LNG production with CO_2 capture (improved vehicle)	147.2	0.51	0.04	0.01	0.14	0.00	0.15	0.05		171.6
Gasoline spark ignition	170.6	0.201	0.043	0.179	0.163	0.013	0.562	1.010		188.1
Gasoline hybrid	128.4	0.151	0.033	0.135	0.112	0.012	0.397	0.032		141.5
Gasoline improved hybrid	116.7	0.137	0.030	n.e	n.e	n.e	n.e	n.e		128.6
Refinery diesel	145.0	0.03	0.01	ne	ne	ne	ne	ne		147.9

Note

The CO_2 Equivalent (CO_2 -Eq) is the sum of global warming potentials of the three greenhouse gases **CO_2, CH_4** and $N_2$2. (See Footnote 5)

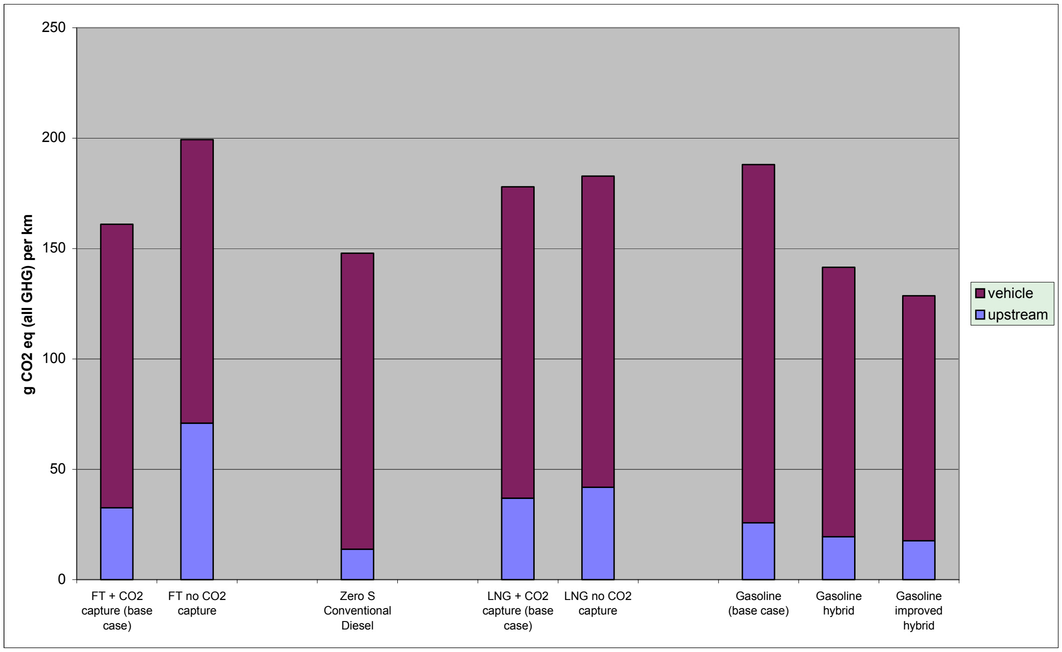

Figure 4 Upstream and vehicle greenhouse gas emissions from each fuel cycle[6]

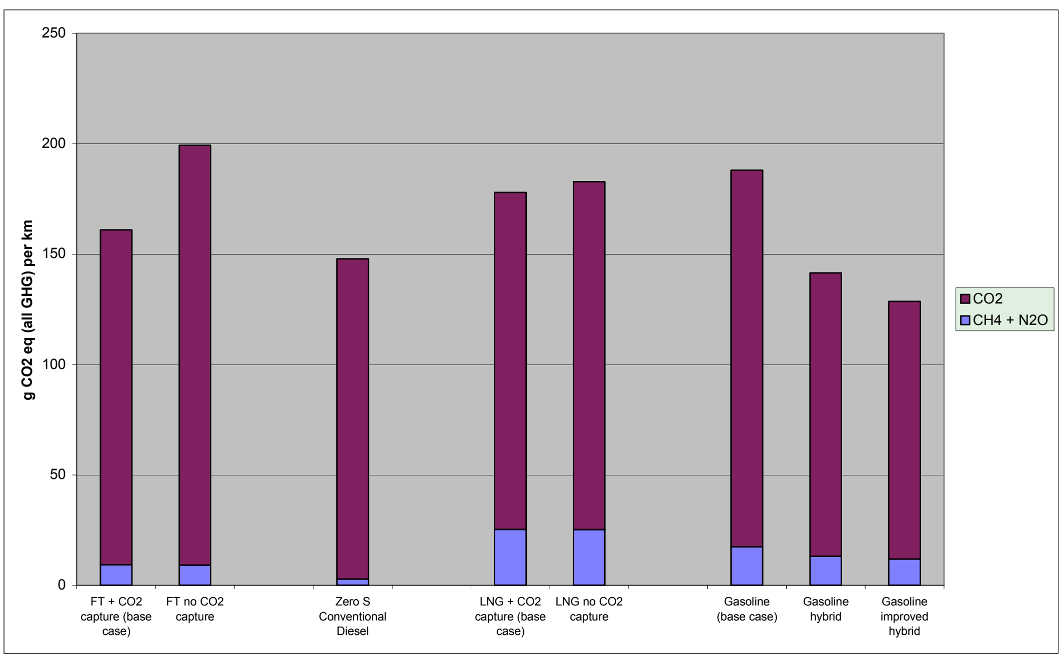

Figure 5 CO_2 and Non-CO_2 greenhouse gas emissions from each fuel cycle

Figure 5 shows the fuel cycles' greenhouse gas emissions in terms of composition. While CO_2 is the main gas in all cases there are significant differences between the fuel

[6] "Zero Sulphur" is the terminology used to refer to gasoline and diesel with a sulphur content below 10 ppm.

cycles in relation to their methane and nitrous oxide emissions. As mentioned above methane emissions are higher in the fuel cycles involving remote gas. Additionally nitrous oxide emissions are higher in the LNG and gasoline fuel cycles because of the higher emissions of this gas from the vehicles that use these fuels. In particular the three-way catalyst fitted to these vehicles leads to increased levels of N_2O[7], although future advanced catalysts could have lower emissions.

3.2 UNCERTAINTIES AFFECTING BASELINE ESTIMATES

The main types of uncertainty involved in assessing the emissions from fuel cycles are:

- uncertainties in the efficiency of processes and vehicle technologies,
- uncertainties in emissions arising directly from processes (e.g. methane releases during gas production),
- uncertainties in the factors used to calculate emissions from fuel combustion.

Uncertainties in the emissions factors used for fuel combustion are common to all fuel cycles. They vary according to the pollutant and for the greenhouse gases they are typically (Charles et al, 1998):

CO_2 - 1 to 6% depending on fuel
CO_2 - 50%
N_2O – 100%

While the uncertainties in the emissions factors for CH_4 and N_2O are large, the contribution of these emissions from fuel combustion to total GHG emissions in the fuel cycles is relatively low (Table 1). Since these uncertainties act in the same direction for all fuel cycles (i.e. the error will not be positive for one cycle when it is negative for another), and because CO_2 dominates emissions from all cycles, they have not been considered explicitly when comparing fuel cycles.

To give an assessment of the other sources of uncertainty, calculations have been made to examine the impact of improvements in the process steps that make a significant contribution to upstream emissions. Also the implications of changes in vehicle efficiency have been examined. This analysis is described in Appendix 2 and the results are summarised in Table 2. The main findings are:

Efficiency of the F-T Plant - The Sasol system considered herein had an energy efficiency of about 55% (with carbon dioxide capture) while more advanced designs could increase this to 67%. Such an improvement would reduce overall carbon dioxide emissions by about 14% without capture and 7% with capture. This improvement makes the GHG emissions from F-T diesel with CO_2 capture comparable with the conventional diesel fuel cycle.

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[7] It is thought that new catalysts to meet future emissions standards will have lower N_2O emissions, but quantitative data is not yet available .

[9] One exception to this approximation is LNG cars that require pressurised fuel tanks, which, even with economies of mass production, are likely to cost more than unpressurised gasoline and diesel fuel tanks. This will further reduce the cost competitiveness of the LNG fuel cycle.

Reduced Venting During Natural Gas Production - In the baseline fuel cycles fugitive emissions of methane at the well-head were taken to be 74.1 kg/TJ. This is high compared to North Sea standards so the impact of halving this release was investigated for both the F-T diesel and LNG fuel cycles. This reduced total GHG emissions, expressed in kg/km, by between 1 and 2%, and did not effect the ranking of the fuel cycles in terms of emissions.

Reduced Energy Consumption During LNG Shipping - The baseline analysis assumed 8% of LNG was consumed in a round trip of a LNG tanker between The Gulf and The Netherlands. Other sources suggested this was towards the high side of fuel combustion, and a sensitivity assessment was made for a 4% consumption rate. This fed through directly reducing the full fuel cycle GHG emissions by 4% (Table 2).

Improved Efficiency of the LNG Plant - In the baseline assessment the energy efficiency of the LNG plant was taken to be 95% without carbon dioxide capture and 93% with capture. The effect of improving both these efficiencies by two percentage points was investigated. This reduced GHG emissions for the non-capture plant by 2%, but only by 0.4% with carbon dioxide capture.

Reduced Fugitive Emissions from Natural Gas Transmission and Distribution - Fugitive emissions of methane during gas distribution were assumed to be 99kg/TJ in the baseline analysis. The effect of halving these releases was to reduce total GHG emissions from both LNG fuel cycles by 1%.

Reduced Vehicle Efficiencies - It was shown in Figure 4 that the main source of GHG emissions in all fuel cycles was final combustion of the fuels in the vehicles. Furthermore, any improvement in fuel efficiency reduces energy consumption per kilometre travelled, and hence the associated emissions in the up-stream parts of the fuel cycle. Consequently the emission estimates are particularly sensitive to the values taken for future vehicle efficiencies. In line with the actions anticipated to attain the ACEA Agreement targets spark ignition engined vehicles were expected to improve efficiency by 20% and compression ignition vehicles by 10% relative to current values. If both sets of vehicles only attained half the target efficiency improvement then emissions from the diesel vehicles would increase by 5% and the gasoline and LNG vehicles by 10%.

3.3 SUMMARY OF EMISSION RESULTS

The above analyses infer that the overall uncertainty affecting the F-T diesel and LNG fuel cycle emissions is of the order of 5-15%. Because the baseline estimates were conservative this uncertainty is more likely to be reflected in lower rather than higher estimates. Uncertainties affecting the more well established gasoline and diesel fuel cycles will be less.

The baseline results inferred that F-T diesel with CO_2 capture releases about 9% more greenhouse gases compared to a refinery diesel source when compared over their full fuel cycles. However, the improved energy and carbon efficiency of advanced gas to liquids plant reduces this to less than 2%. This value is well within the uncertainty range for the results.

In terms of minimising greenhouse gas emissions, F-T diesel (with CO_2 capture) is a better method for using remote gas as a fuel for the transport sector compared to the "direct" LNG fuel cycle. This conclusion is robust to uncertainties over plant conversion efficiencies, assumptions on fugitive methane emissions and end-use vehicle efficiencies.

Without CO_2 capture the F-T diesel cycle produces slightly more greenhouse gas emissions than the LNG cycle even when uncertainties are taken into account.

If the aim is to reduce greenhouse gas emissions from a refinery fuel cycle then the above results show that within the range of uncertainty the effect of replacing refinery diesel with F-T diesel (with CO_2 capture) could range from neutral to an increase in emissions of about 9%.

The replacement of gasoline with natural gas would yield a reduction in emissions of 5 to 10% for LNG plant fitted with CO_2 capture, and a smaller improvement for LNG without CO_2 capture. These conclusions are robust to the uncertainties affecting the data.

Replacement of gasoline with any one of the diesel fuel cycles would yield a greater reduction in emissions than replacement with LNG by virtue of the higher fuel efficiency of diesel vehicles.

Table 2 Impact of Changes in Critical Parts of the Fuel Cycles on overall GHG Emissions

Fuel Cycle	CO_2 only (g CO_2/km)			All GHG (g CO2 eq/km)			Change
	upstream	vehicle	total	upstream	vehicle	total	
F-T + CO2 capture (base case)	25.5	126.2	151.7	32.6	128.4	161.0	-
F-T + CO2 capture, improved F-T plant	15.9	126.2	142.2	21.8	128.4	150.2	-7%
F-T + CO2 capture, reduced gas venting	25.5	126.2	151.7	29.7	128.4	158.2	-2%
F-T no CO2 capture (base case)	64.0	126.2	190.2	70.9	128.4	199.4	-
F-T no CO2 capture, improved F-T plant	36.7	126.2	162.9	42.6	128.4	171.0	-14%
F-T no CO2 capture, reduced gas venting	64.0	126.2	190.2	68.1	128.4	196.6	-1%
LNG + CO2 capture (base case)	25.2	127.4	152.6	36.9	141.0	178.0	-
LNG + CO2 capture, reduced gas venting	25.2	127.4	152.6	34.6	141.0	175.6	-1%
LNG + CO2 capture, reduced shipping fuel	18.6	127.4	146.0	30.0	141.0	171.0	-4%
LNG + CO2 capture, reduced fugitive emissions	25.2	127.4	152.6	34.4	141.0	175.4	-1%
LNG + CO2 capture, improved liquefaction efficiency	24.6	127.4	152.0	36.2	141.0	177.2	-0.4%
LNG no CO2 capture (base case)	30.2	127.4	157.6	41.9	141.0	182.9	-
LNG no CO2 capture, reduced gas venting	30.2	127.4	157.6	39.5	141.0	180.5	-1%
LNG no CO2 capture, reduced shipping fuel	23.3	127.4	150.8	34.7	141.0	175.7	-4%
LNG no CO2 capture, reduced fugitive emissions	30.2	127.4	157.6	39.3	141.0	180.3	-1%
LNG no CO2 capture, improved liquefaction efficiency	27.1	127.4	154.5	38.7	141.0	179.7	-2%
Gasoline (base case)	21.5	149.2	170.6	25.8	162.3	188.1	-
Diesel (base case)	13.2	131.8	145.0	13.9	134.0	147.9	-

4. Assessment of Fuel Cycle Costs

4.1 BASELINE ESTIMATES

A detailed description of the cost analysis made in this study is presented in Appendix 3. The output costs of the fuel cycles in 2010, "at the pump" but before tax, are listed in Table 3.

Table 3 Estimated Output Costs of the Fuel Cycles at the pump in 2010($/GJ)

Fuel Cycle	Cost ($/GJ)
F-T diesel production with CO_2 capture	8.14
F-T diesel production without CO_2 capture	7.43
LNG production with CO_2 capture	9.15
LNG production without CO_2 capture	8.99
Refinery gasoline	7.15
Refinery diesel	6.76

The lowest cost fuel is refinery diesel followed by refinery gasoline. F-T diesel is 20% more expensive than refinery diesel when produced with CO_2 capture, falling to 10% more expensive without CO_2 capture. LNG is the most expensive of the fuels examined, mainly because there are additional infra-structure costs associated with the distribution of this fuel, which are avoided by F-T diesel because it can be distributed through the existing system.

The fuel cycles are compared on the basis of the cost of one kilometre of travel with each fuel in Figure 6. These costs do not include the costs of the vehicles, because it has been assumed that these will be the same for all fuels, and therefore will not affect the relative cost effectiveness of the fuel cycles. This assumption is considered to be reasonable because the analysis assumed the deployment of a fleet of 1 million vehicles in 2010, which should be sufficient to give economies of scale in production[9].

The most striking feature of these results is the high cost of LNG, when assessed in terms of cost per vehicle kilometre. This result is due to the initial high cost of natural gas delivered to motor vehicles combined with the lower fuel efficiency of the spark ignition engines, which use natural gas, in comparison to diesel engines.

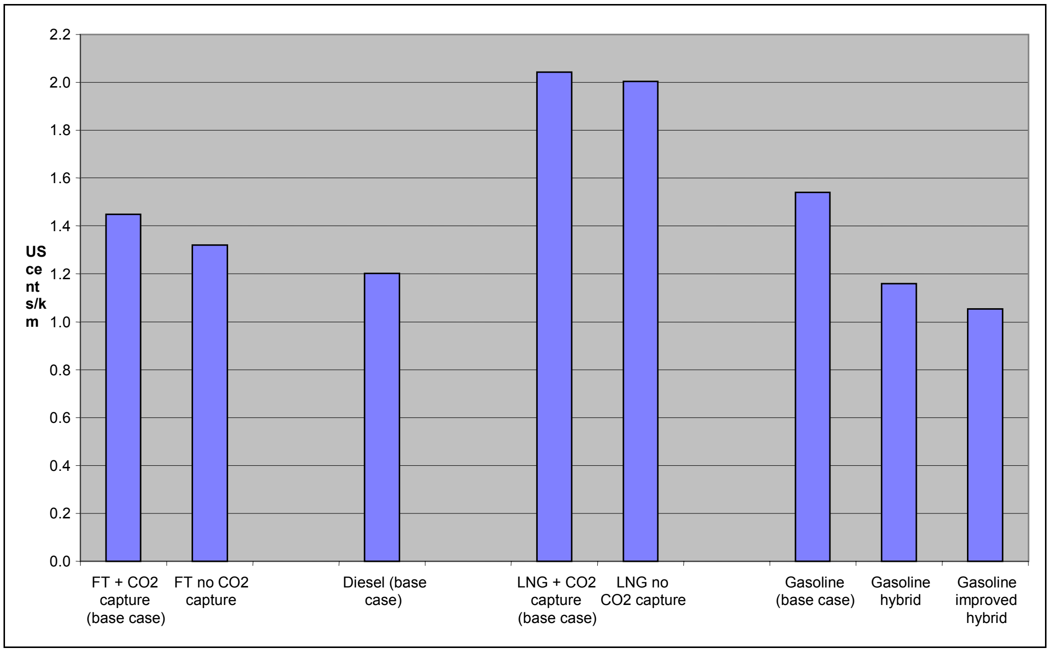

Figure 6 Costs of Fuel Cycles Measured in Terms of Cost per Vehicle Kilometre

Figure 6 also shows the benefit to be gained by the gasoline fuel cycle from the introduction of more fuel efficient "hybrid" vehicles. These developments could also improve the cost competitiveness of natural gas as a transport fuel, although the cost per vehicle kilometre is not likely to be reduced to a level comparable with F-T diesel. Moreover, hybrid drive system technology could also benefit diesel vehicles.

4.2 UNCERTAINTIES AFFECTING BASELINE ESTIMATES

The main uncertainties affecting the above cost estimates are:

- Future market prices for natural gas and oil.
- Changes in the capital and operating costs of fuel conversion plant.
- Profit margins applied to gasoline and diesel.
- Vehicle prices.

Future market prices of natural gas and crude oil are particularly uncertain. However, feedstock prices make up only 14% of F-T diesel and 8% of LNG supply costs at the pump (with CO_2 capture) compared to about 50% of gasoline costs (before tax). Therefore the conventional fuel cycles are more vulnerable to feedstock price increases than the natural gas based fuel cycles.

Changes in the capital costs of conversion plant are most likely for F-T diesel, which is a less mature technology than oil refining or LNG production. The work described above was based on the assessment of the F-T process made in an earlier report to IEA (IEA GHG, 2000). This assessment examined a plant having a production capacity of 10,000 bbl per day (56 TJ/day) made up of about 6,000 bbl diesel and 4,000 bbl naphtha. However, about 26,000 bbl per day (145 TJ/day) production (about 16,000 bbl per day diesel) were required to fuel a fleet of 1 million cars. However, no allowance was made for potential economies of scale to be gained in moving to the higher level of production.

To assess the potential benefit of economies of scale the capital cost of the F-T plant was adjusted assuming that this would increase by $2.6^{0.6}$ in up sizing to a 26,000 bbl per day output. The factor of 0.6 is generally accepted as a fairly representative scale up factor such economies of scale (Clark, 2002)[10].

With this adjustment the cost of F-T diesel was reduced from $8.14/GJ to $6.83/GJ (with CO_2 separation), a reduction of 19%. This would make F-T diesel costs comparable with refinery diesel.

An additional small reduction in F-T diesel costs would come from an improvement in conversion efficiency, which was about 55% for the plant considered herein. For example an improvement to 65% efficiency, which is considered likely with new systems would reduce F-T diesel costs by about 2%.

Vehicle Prices were not considered in the analysis because a general assumption was made that the vehicles in the fuel cycles would have broadly similar prices. This approach yielded prices that supported comparisons between fuel cycle costs. However, it should be noted that fuel costs (excluding duties) only account for about 6-7% of total vehicle operating costs per kilometre. Consequently these cost differences will appear quite small to motorists and may not be the dominant factor determining their choice of vehicle/fuel combination.

5. Location of the fuel cycles in the USA

Sensitivity analyses were made to investigate the implications for carbon dioxide emissions and costs of relocating the fuel cycles in North America.

In the sensitivity analysis all fuel extraction and production of F-T diesel and LNG were still located in the Middle East. Oil refining was located in the US with crude oil coming from the Middle East[11]. The changes examined were:

- The impact of longer shipping distances: - energy use and emissions associated with shipping of F-T diesel, LNG and crude oil were increased in direct proportion to the increase in shipping distance.
- Lower conversion efficiency of US refineries compared to European refineries:- a value of 85% as used in the Argonne National Laboratories GREET model (Wang, 1999) was taken.

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[10] This assumes that scale up would involve the construction of a single unit 2.6 times larger than the F-T plant considered in the IEA GHG Programmes study. Cost savings would be less if capacity was increased by building multiple units.
[11] This assumption may be unrealistic because the USA also imports crude from Canada and Latin America. However, it facilitates a clear comparison between fuel cycles and with the European results.

- Fuel efficiencies for a typical US vehicle (a full size pick-up truck) were taken from the General Motors Corporation /Argonne National Laboratory study (GMC et al 2001). These are simulation results from General Motors' proprietary Hybrid Powertrain Simulation for vehicle concepts, which will meet a given set of performance requirements and emissions standards.
- Emissions from distribution are small compared to other stages of the fuel cycle and so were not re-estimated.

Total CO_2 emissions from the US fuel cycles are shown Table 4. As for the European situation the F-T diesel fuel cycle results in higher carbon dioxide emissions than the LNG fuel cycle. However, the difference is greater in this case because a smaller differential in fuel efficiency between diesel and spark ignition engines (17% compared to 20%) was assumed for the larger USA vehicles with a different duty cycle.

If LNG is considered as a replacement for gasoline in a spark ignition engine vehicle, it offers a reduction in CO_2 emissions of about 15%, but this abatement is likely to be less if the overall greenhouse gas emissions (i.e. including methane and nitrous oxide) of the fuel cycles were compared.

The F-T fuel cycle is however the more cost effective method for exploiting remote gas as a transport fuel (Table 4).

Table 4 Total CO_2 Emissions from US Fuel Cycles (g CO_2 per vehicle km)

	CO_2 Emission			Cost
	Upstream	in vehicle	total	cents/km
F-T Diesel + CO_2 capture	46	225	271	2.38
LNG + CO_2 capture	45	217	262	3.51
Gasoline	49	259	308	2.82
Gasoline hybrid	41	214	255	2.33

6. Abatement Costs

The costs of both carbon dioxide and total greenhouse gas abatement have been calculated for LNG with CO_2 separation relative to refinery gasoline (Table 5), as it is reasonable to assume that the LNG fuel cycle will be used to replace gasoline in spark ignition engines. Note the higher cost for the three greenhouse gases is because the level of abatement is less while the costs stay the same.

It should be noted that if the F-T diesel fuel cycle were compared to the gasoline fuel cycle, then abatement costs would be negative, as F-T diesel is cheaper and has lower greenhouse gas emissions than gasoline. This is because F-T diesel is cheaper per vehicle kilometre travelled and has lower greenhouse gas emissions than gasoline. However, it was assumed in the study that diesel would not necessarily be used as a replacement for gasoline.

These abatement costs are high compared to the cost of carbon capture applied to power generation, which is estimated to be about $50-75/ tonne CO_2.

Table 5 Abatement Costs for CO_2 and Total Greenhouse Gases

	Abatement Cost ($/tonne CO_2 eq)	
	CO_2 only	All Greenhouse Gases
LNG/gasoline	279	498

7. Conclusions

The main findings of this study have been presented in terms of emissions and costs per vehicle kilometre for each of the fuel cycles.

Greenhouse gas emissions for all the fuel cycles (excepting hybrid vehicles) lay within 35% of each other, and this margin narrowed when recent improvements to the conversion efficiency of gas to liquid plant were taken into consideration. Further, with vehicle emissions dominating total emissions from the fuel cycles, the results were particularly sensitive to uncertainties over the fuel efficiency of future vehicles. Consequently it is difficult to draw firm conclusions when comparing the emissions from different fuel cycles.

Nonetheless two key conclusions on emissions are:

- The F-T diesel fuel cycle, with carbon capture, does not reduce greenhouse gas emissions from road transport when substituted for refinery diesel. With the most advanced gas to liquids conversion plant such a substitution would be about neutral on emissions.
- F-T gas to liquids technology does give lower greenhouse gas emissions than LNG when both are used as transport fuels. This is mainly due to the higher end-use efficiency of diesel vehicles.

Using the "baseline" results and sensitivity assessments other, more detailed, results are:

- The F-T diesel fuel cycle with CO_2 capture has carbon dioxide emissions about 5% higher than a refinery diesel fuel cycle. When the other greenhouse gases involved in the fuel cycle are considered, namely methane and nitrous oxide, the difference increases. However, advances in process systems could significantly improve the conversion efficiency of F-T plant, which would reduce the difference in emissions between refinery and F-T diesel (with carbon capture) to a negligible level.
- The higher emissions from the F-T fuel cycle when all greenhouse gases are considered is due to fugitive methane emissions in the up stream parts of the fuel cycle. These emissions are less in the refinery diesel fuel cycle, which, being based on crude oil from the North Sea, assumed more tight control of fugitive emissions.

- The LNG fuel cycle with CO_2 capture gave a 10% reduction in CO_2 emissions compared to the refinery gasoline fuel cycle. This abatement is reduced to 5%, when all three of the greenhouse gases associated with the fuel cycle are considered. These "baseline" estimates are conservative, and taking account of uncertainties in the analysis would give a higher comparative reduction in emissions.
- Emissions from all the fuel cycles are dominated by emissions from final fuel consumption by the motor vehicles. Thus with the F-T fuel cycle over 80% of CO_2 and all greenhouse gas emissions come from the vehicle. In the case of the LNG fuel cycle the corresponding value is over 79%.
- The F-T diesel fuel cycle gives 10% lower greenhouse gas emissions than the LNG fuel cycle per kilometre of vehicle travel when both have CO_2 capture. This advantage is due to the better fuel efficiency of diesel engines, compared with spark ignition engines.
- F-T diesel fuel cycle does not retain this advantage with non-CO_2 capture technologies due to its higher upstream emissions of greenhouse gases.
- Increasing the conversion efficiency of gas to liquids plant from the 55% used as baseline in the study to the 67% attained in recent systems makes the F-T diesel emissions less than LNG emissions both with and without carbon capture.

The cost of vehicle travel, for each of the fuel cycles, has been assessed assuming that the fuels are used in the same specification of vehicle, with the fuels supplying a fleet of one million vehicles in 2010. With such a large fleet it was also assumed that economies of manufacture would be sufficient to ensure that gas fuelled vehicles would have the same costs as for diesel or gasoline vehicles.

Using the "baseline" results and sensitivity assessments the main findings from the cost analysis were:

- F-T diesel with CO_2 capture is 20% more expensive than refinery diesel in terms of cost per vehicle kilometre.
- Scale up cost savings and conversion efficiency improvements could reduce F-T diesel costs to a level comparable to refinery diesel.
- The LNG fuel cycle with CO_2 capture is 33% more expensive than the refinery gasoline fuel cycle in terms of cost per vehicle kilometre.
- The F-T diesel fuel cycle is 41% less expensive than the LNG fuel cycle in terms of cost per vehicle kilometre (by virtue of the higher fuel efficiency of diesel engine vehicles), showing that it is the most cost effective route for exploiting remote gas as a transport fuel.

The above data can be combined to assess the cost of abating CO_2 and total greenhouse gases with the F-T diesel and LNG fuel cycles. The main results are:

- The F-T diesel fuel cycle may have comparable to higher costs and greenhouse gas emissions compared to refinery diesel. Consequently replacement of refinery diesel with F-T diesel seems unlikely to give a reduction in greenhouse gas emissions.
- The cost of abating CO_2 emissions by replacing refinery gasoline with the LNG fuel cycle is $280/tonne CO_2. The corresponding cost for the three greenhouse gases involved in the fuel cycles is $500/tonne CO_2 equivalent. Note the higher

cost for the three gases is because the level of abatement is less while the costs stay the same. These values are high compared to options for carbon capture in power generation which are typically \$50-70/ tonne CO_2.

- It should be noted that if the F-T diesel fuel cycle were compared to the gasoline fuel cycle, then abatement costs would be negative, i.e. there would be a net saving per tonne of CO_2 abated. This is because F-T diesel is cheaper per vehicle kilometre travelled and has lower greenhouse gas emissions than gasoline. However, it was assumed in the study that diesel would not necessarily be used as a replacement for gasoline.

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Appendices

CONTENTS

Appendix 1

Definition of the Fuel Cycles

1. Introduction

This Appendix describes the three fuel cycles assessed in the study, namely:

- Natural gas to Fischer-Tropsch diesel and utilisation in an advanced compression ignition car (F-T Diesel Fuel Cycle)
- Natural gas to LNG and utilisation in an advanced spark ignition car (LNG Fuel Cycle)
- A reference cycle involving a petroleum based fuel and utilisation in an advanced spark ignition car (Gasoline Fuel Cycle)

The three fuel cycles all assume implementation in 2010, and so include advanced vehicle designs likely to be available by this time. They are based around the provision of fuel for the annual consumption of a fleet of 1 million vehicles. It is assumed that the proposed EU fuel quality standards which require zero sulphur fuels (<10 ppm S) are in force.

A gasoline fuel cycle was has been chosen as the reference fuel cycle as firstly, gasoline spark ignition vehicles are still likely to be the most common type of vehicle in 2010, and secondly, data is available on the performance and emissions of gasoline spark ignition hybrid vehicles. Hybrid vehicles tend to offer greater benefits in urban drive cycles, and while diesel hybrid vehicles are feasible, and would offer an improvement in performance over non-hybrid diesel vehicles, they have been given less consideration by the vehicle industry.

Preliminary results from the study showed that emissions and costs per km are dominated by vehicle fuel efficiency rather than up stream emissions. Therefore, a further benchmark for comparison of the F-T diesel cycle, involving the refining of North Sea crude oil in a North European refinery was included as an additional benchmark. This fuel cycle is not directly comparable to the others since it does not start from a Middle East location. It was used to enable comparison with the "best case" for diesel production and supply in Northern Europe.

In order to allow a fair a comparison as possible across the fuel cycles, a common vehicle type, a medium sized (Ford Focus, Volkswagen Golf type) was assumed for all three fuel cycles. It was assumed that all vehicles met the EURO IV standards, which will apply from 2005[12]. Fuel consumptions assumed for the vehicles are shown in Table 1. The derivation of the energy use and emissions associated with each fuel cycle is described in Appendix 2, and of the costs associated with each fuel cycle in Appendix 3.

[12] The EuroIV emission standards for gasoline and diesel cars come into force on 1st January 2005. As yet no decision has been made on longer term, more stringent emission standards similar to the EuroV standards for heavy duty vehicles scheduled for October 2008.

Table 1 Fuel Consumption of Vehicles

Fuel Type	Fuel consumption MJ/km
F-T diesel, compression ignition	1.78
Natural gas, spark ignition	2.23
Gasoline , spark ignition	2.15
Gasoline hybrid	1.62
Improved natural gas	2.15
Improved gasoline hybrid	1.47

2. F-T Diesel Fuel Cycle

2.1 SOURCE OF NATURAL GAS

The study is based on natural gas (NG) extracted from an (hypothetical) inland field located in Iran, 150 km from the coast, and producing only NG rather than mixed products. The NG is assumed to have the same composition (Table 2) as that used in the IEA's Fischer-Tropsch (F-T) Diesel study (IEA GHG, 2000). Several of the recent discoveries of gas in Iran have had this profile, i.e. non –associated, sweet gas fields, located in the south of the country, relatively close to the Gulf Coast.

Table 2 Assumed Natural Gas Composition

	mol %
CH_4	94.476
C_2H_6	3.438
C_3H_8	0.856
iC_4H_{10}	0.098
nC_4H_{10}	0.176
iC_5H_{12}	0.024
nC_5H_{12}	0.024
N_2	0.471
CO_2	0.437
H_2S	4 mg/Nm^3

2.2 PIPELINE TRANSMISSION TO THE F-T DIESEL PLANT

To run 1 million cars for a year in The Netherlands (annual travel 16,300 km) requires 5.8 Million barrels per year (32PJ/year) of F-T diesel (given the vehicle fuel efficiencies assumed for the study). Production of this amount of F-T Diesel requires about 7.4 MNm^3/day (224 TJ/day) of gas. This is small compared to the capacities of typical pipelines, but there is presently considerable growth in LNG supply from the Middle East, and consequently there is no spare pipeline capacity. Therefore the study assumed a new commercial sized pipeline is constructed, and runs 150 km from the gas field to the coast, with the project taking a fraction of its capacity. This approach seems reasonable given the planned growth in gas extraction and shipping planned by the region.

2.3 F-T DIESEL PLANT AND SUPPORT FACILITIES

The F-T diesel needed to fuel 1 million cars is about 16,000 bbl/day, so would require a plant more than twice the size of the facility examined in the report on F-T synthesis produced for the IEA Greenhouse Gas R&D Programme, which produced 6068 bbl/day (IEA GHG, 2000). The O_2 blown slurry type reactor (Sasol Type) process has been chosen as representative of F-T technology as recommended in the previous report. It is assumed that the CO_2, which is captured, is compressed and piped away (150 km) for underground storage, in a disused gas reservoir. As a sensitivity study, a plant with no CO_2 capture was also examined. The key characteristics of the 10,000 bbl/day plant are summarised in Table 3. The plant with no CO_2 capture is self sufficient in power, generating enough electricity through the steam turbine-driven power generator to meet the facilities normal operating power requirements. The plant with CO_2 capture requires 10.6MW of power.

Table 3 Characteristics of the F-T Plant

	F-T plant with CO_2 capture	**F-T plant without CO_2 capture**
Natural gas feed	100 MMSCF/day	100 MMSCF/day
Products		
F-T diesel	6,068 bbl/day	6,173 bbl/day
F-T naphtha	4,063 bbl/day	4,163 bbl/day
Plant efficiency	55%	56.1%

2.4 F-T DIESEL SHIPPING AND RECEPTION STORAGE

F-T diesel is transported to The Netherlands in tankers, and stored in product tanks before onward distribution.

2.5 F-T DIESEL DISTRIBUTION, LOCAL STORAGE AND VEHICLE FILLING

F-T diesel is distributed by pipeline from the port to bulk terminals, from where it is distributed by road to filling stations in The Netherlands, using the existing networks for diesel distribution, i.e. principally by road tanker. It is assumed that the proposed EU fuel quality standards for 2011, which require zero sulphur fuels (<10ppm S) are in force. F-T diesel would meet this standard. The potential issue of cross contamination (with higher sulphur fuels) if existing pipelines and tankers were used to distribute F-T diesel has been raised in other studies, but as the proposed fuel standards are assumed to be in force this would not be an issue in this study. It is likely that due to its higher cetane number F-T diesel would be blended with lower quality diesel at the bulk terminals, to obtain a diesel which could be sold through existing forecourt pumps. However, because the properties of refinery diesel are uncertain for 2010 no credit was taken for this in the assessment.

Delivery from bulk storage to filling station is assumed to be an average of 100 km round trip.

3. LNG Fuel Cycle

3.1 SOURCE OF NATURAL GAS

As for F-T Diesel Fuel Cycle

3.2 PIPELINE TRANSMISSION TO THE LNG PLANT

As for F-T Diesel Fuel Cycle

3.3 LNG PLANT AND SUPPORT FACILITIES

The NG needed to fuel 1 million cars will only use a fraction of the annual production from a single LNG train (about 15 - 20%). Therefore for the purposes of the study, production in a commercial sized plant was assumed with other LNG from the plant being exported for other uses. As with the F-T plant, the LNG plant is assumed to be situated on the Gulf Coast, 150 km from the gas field.

CO_2 emissions from a LNG liquefaction plant arise from the gas treatment unit, and from energy use in refrigeration and power generation. In this fuel cycle, it is assumed that these streams are combined and then passed through to a CO_2 separation plant, and that this CO_2 is then compressed and transmitted via a 150 km pipeline to a disused gas field for reinjection and storage. CO_2 separation for the volumes of CO_2 generated from the liquefaction plant would require a very small-scale plant. It is therefore assumed that another larger CO_2 generating plant, e.g. a natural gas fired power station is located close to the liquefaction plant and that the liquefaction plant and power station share a CO_2 separation plant. The separation plant itself requires energy to operate, and it is assumed that heat and electricity for the plant are supplied by the power station, and that the CO_2 emissions associated with this additional energy provision also go through the separation plant.

3.4 LNG SHIPPING

LNG will be transported to The Netherlands in specialised LNG tankers, which are fuelled by boil-off of LNG. The tankers were assumed to have a capacity of 125000m^3 (2713TJ) and the journey length is 25 days each way.

3.5 STORAGE AND VAPORISATION AT THE PORT OF RECEIPT

LNG will be unloaded from tankers into storage tanks and then vaporised to gas, using a seawater evaporative vaporiser, and introduced into The Netherlands' distribution network.

Modern LNG tankers have capacities of around 125,000 to 150,000m3. This volume of LNG represents about 10% of the annual fuel requirements of 1 million vehicles. Consequently, if fuel supply to NG vehicles is considered in isolation, this would require considerable storage capacity in The Netherlands. It therefore seems more realistic to assume that LNG arriving in The Netherlands is immediately introduced into the gas distribution system to be used by all consumers. In this way storage capacity can be optimised and maximum use can be gained from unloading jetties, etc.

3.6 DISTRIBUTION

The Netherlands' existing distribution network is used to carry NG from the port terminal to vehicle filling stations. At the filling stations the gas is compressed ready for fuelling NG vehicles.

The gas needed to fuel 1 million vehicles represents about 2% of Netherlands current gas consumption, and it is therefore assumed that no expansion of the gas network capacity is need to accommodate this increase in gas use.

The Netherlands currently has a car vehicle stock of about 6 million the majority of which have spark ignition engines. It is assumed that one sixth of filling stations, some 670, will need to invest in CNG fuelling facilities to serve 1 million cars. This assumption seems reasonable for a country like The Netherlands where the average distance between filling stations is small. However, it could be argued that this might in practice limit the service of CNG vehicles to local travel with possibly lower than average utilisation. Nonetheless, for this study it is assumed that CNG vehicles have the same utilisation and journey patterns as the average vehicle.

4. Gasoline Fuel Cycle

4.1 CRUDE OIL EXTRACTION AND PIPELINE TRANSMISSION

Crude oil is extracted in a Middle East onshore field, and then piped 150 km to a marine terminal on the Gulf Coast.

4.2 CRUDE OIL STORAGE AND SHIPPING

The crude oil is stored at the port and then loaded onto large super tankers and shipped to the NE coast of Netherlands via the Horn of Africa.

4.3 REFINING AND PRODUCT FINISHING

The crude oil is unloaded in The Netherlands at a refinery. The refinery is assumed to be a Fluid Catalytic Cracker (FCC) refinery. An extra desulphurisation step is required compared to current practice to reduce S levels to <10ppm to meet the proposed fuel quality standards assumed to be in force in 2010. Finished gasoline is stored at the refinery before distribution.

4.4 GASOLINE DISTRIBUTION

Gasoline is distributed by pipeline from the refinery to bulk terminals, and then dispatched by road to filling stations. A tanker capacity of 31,650 litres and a round trip distance of 100 km are assumed.

5. Sensitivity Analysis

A number of sensitivity analyses were carried out. Changes in the fuel cycle which were considered and which affect both costs and emissions were:

- Increased conversion efficiency of F-T diesel and LNG plant;
- reduced fugitive emissions of methane from natural gas production and transmission/distribution;
- improved fuel efficiency of LNG shipping;
- no CO_2 capture and storage at the F-T diesel and LNG liquefaction plant;
- reductions and improvements in the efficiency of the natural gas and gasoline vehicles, including a gasoline hybrid car ;
- impact of moving the fuel cycle to the US.

For the US sensitivity analysis fuel cycle, it was assumed that F-T diesel and LNG were produced in the Middle East and then shipped to an east coast US port, and revised costs and emissions were estimated for this shipping stage. Similarly crude oil was assumed to be shipped from the Middle East to an East Coast port.

Emissions associated with transmission of gas and distribution of diesel were assumed to be the same in the US as Europe (as they are a very small contribution to overall emissions, any error from this assumption is small). Costs for distribution of diesel were re-estimated based on US data. Emissions associated with refining were re-estimated based on efficiencies for US refineries that typically use more energy in processing because of their higher complexity and deeper conversion characteristics compared to those in Europe. Finally the choice of vehicle and corresponding fuel consumption were changed to reflect the US situation.

Appendix 2

Analysis of Fuel Cycle Emissions

1. Introduction

This Appendix describes the key assumptions made in estimating the efficiency of each stage of the fuel cycles and process and energy related emissions of greenhouse gases and air pollutants:

- carbon dioxide (CO_2)
- methane (CH_4)
- nitrous oxide (N_2O)
- sulphur dioxide (SO_2)
- nitrogen oxide and dioxide (NO_x)
- particulate matter (PM)
- non-methane volatile organic compounds (NMVOC)
- carbon monoxide (CO)

It also describes how the fuel consumption and emissions arising from final fuel use in vehicles were estimated. All fuel use and emissions for vehicles are based (for the main Europe based cases) on the EU combined cycle test.

The methodology used in this work involves estimating the emissions from each stage in the fuel cycles per unit of input. The efficiency of each stage is also estimated in terms of the ratio of output to input. For convenience inputs and outputs are expressed in energy units (TJ) although volume or mass units could have been used. When external energy such as electricity is used to power a stage in the fuel cycle the emissions associated with producing the electricity are included in the emissions from that stage. However, this external energy is not included in the calculation of the efficiency of each stage, which, as discussed above, is concerned with the amount of product entering and leaving each stage.

Overall emissions from a fuel cycle are calculated as the sum of the emissions from all the individual stages. This calculation takes account of the need to feed more than one unit of product into the first stage of the fuel cycle in order to get one unit of product out of the final stage. For example with a three stage process with efficiencies of 90%, 50% and 90% the inputs and outputs would be as follows:

Stage 1	90% efficient	
	Input	2.2/0.9 = 2.5 units
	Output	2.2 units
Stage 2	50% efficient	
	Input	1.1/0.5 = 2.2 units
	Output	1.1 units
Stage 3	90% efficient	
	Input	1/0.9 = 1.1 units
	Output	1 Unit

The initial assessment used single "baseline" values for emissions from each stage of the fuel cycles to estimate total fuel cycle emissions. These were taken from previous work or estimated from related data (e.g. on energy consumption), and were conservative values. Where a range of values was found this has been reported and a single value used from within the range.

2. Fischer-Tropsch Diesel

2.1 NATURAL GAS EXTRACTION AND TREATMENT

Emissions from gas extraction arise from energy use, principally the combustion of natural gas, to provide power for extraction and treatment, and methane emissions from venting of gas, incomplete combustion of gas in flares and leakage from compressors, pneumatic devices, etc. No specific data on energy used for gas extraction in Iran could be found. Energy use for gas extraction in the North Sea has been calculated as 2.2 % (Bates, 1995) and 2.8% (ETSU, 1996) of throughput; the US GREET lifecycle model assumes energy consumption of 3% (Wang, 1999). A value of 3% was assumed for this study. Emissions are estimated assuming combustion in gas turbines, using emissions factors taken from Goodwin et al (2000).

Fugitive methane emissions associated with gas extraction in the Middle East are estimated from a previous IEA Greenhouse Gas R&D programme study on methane losses associated with oil and gas extraction (IEA, 1997) as 74 g/GJ (0.4% leakage by mass). CO_2 and NMVOC emissions associated with leakage are calculated from this and the gas composition.

Emissions from this stage of the fuel cycle are shown in Table 1.

Table 1 Emissions from Natural Gas Extraction (per TJ gas extracted)

Fuel Cycle Stage	Eff'cy %	t/TJ	kg/TJ						
		CO_2	CH_4	N_2O	SO_2	NO_x	PM	NMVOC	CO
Gas extraction and local conditioning	97.0	1.7	74.1	0.00	0.00	3.00	0.03	7.95	0.08

2.2 PIPELINE TRANSMISSION TO THE F-T DIESEL PLANT

Gas is piped 150 km to the F-T diesel plant located on the coast. Energy consumption was estimated based on data showing consumption of 2% of throughput for a distance of 1600 kms (IEA/AFIS, 1996), i.e. a consumption of 0.1875% of throughput for a distance of 150 kms. Emissions are estimated assuming combustion in gas turbines. Fugitive emissions of methane (and CO_2 and NMVOCs) are estimated as 0.07% of throughput, based on estimates from a previous IEA study (IEA GHG, 1997) of losses of 15 g/GJ from gas transport in the Middle East. Estimates of methane losses from the UK transmission system are also of this order (Bates, 1995; Goodwin et al, 2000; DTI, 2000). Total emissions from this stage of the fuel cycle are shown in Table 2.

Table 2 Emissions from Natural Gas Transmission to the Coast (per TJ gas input)

Fuel Cycle Stage	Eff'cy %	t/TJ	kg/TJ						
		CO_2	CH_4	N_2O	SO_2	NO_x	PM	NMVOC	CO
Pipeline transmission	99.8	0.1	15.0	0.00	0.00	0.19	0.00	1.60	0.00

2.3 F-T DIESEL PLANT AND SUPPORT FACILITIES

F-T diesel is produced in a 26,000 bbl/day O_2 blown slurry type reactor (Sasol Type) process as described in the report on F-T synthesis produced previously for the IEA Greenhouse Gas R&D Programme (IEA GHG, 2000). CO_2, which is captured, is compressed and piped away (150 km) for underground storage in a disused gas field.

The plant with no CO_2 capture is self sufficient in energy, but the plant with CO_2 capture imports 10.6 MW of electricity. Emissions from this imported electricity were calculated assuming the power is generated in a CCGT power station with CO_2 recovery, as described in a previous IEA study on gas power station generation (IEA GHG, 1997a).

CO_2 emissions from the production process (including compression of the CO_2 for transmissions to the disposal site) are taken from the previous IEA report on F-T production (IEA GHG, 2000). Emissions of CO and NO_x and NMVOCs were based on data used in the GREET Model for F-T production (Wang, 1999), and emissions of other pollutants are based on the emission factors for the combustion of gas in an industrial furnace (Goodwin et al, 2000). Total emissions from this stage of the fuel cycle are shown in Table 3.

Emissions from the F-T plant are averaged over the two products, i.e. no differentiation is made between diesel and naphtha.

Table 3 Emissions from F-T Diesel Production (per TJ gas input to process)

Fuel Cycle Stage	Eff'cy %	t/TJ	kg/TJ						
		CO_2	CH_4	N_2O	SO_2	NO_x	PM	NMVOC	CO
F-T Production – with CO_2 capture	55.0	5.6	2.47	0.07	0.00	11.3	0.70	17.1	17.2
F-T Production - no CO2 capture	56.1	17.8	2.47	0.06	0.00	10.3	0.70	17.0	17.2

2.4 F-T DIESEL SHIPPING

F-T diesel is transported to The Netherlands in tankers. Fuel consumption for a small tanker for a journey from the Gulf to the Rotterdam is 10 kg of bunker oil per tonne crude oil (IEA/AFIS) and is assumed to be similar per tonne F-T diesel. Emissions from the use of bunker fuel in marine shipping are taken from Goodwin et al (2000). Energy use (and hence emissions) from loading and unloading is insignificant compared to fuel use in shipping, and is not estimated. Total emissions from this stage of the fuel cycle are shown in Table 4.

Table 4 Emissions from F-T Diesel Shipping (per TJ F-T Diesel input)

Fuel Cycle Stage	Eff'cy %	t/TJ	kg/TJ						
		CO_2	CH_4	N_2O	SO_2	NO_x	PM	NMVOC	CO
F-T shipping	99.0	0.7	0.1	0.05	12.86	12.99	0.24	0.48	1.69

2.5 F-T DIESEL DISTRIBUTION

F-T diesel is distributed by pipeline from the port to bulk terminals, from where it is distributed by road tanker to filling stations. Electricity consumption for pumping from the refinery to bulk terminal is taken as 3.51 kWh per tonne fuel (Lewis, 1997). Emissions from electricity generation in 2010 are taken from a study looking at projections of full fuel cycle emissions from future electricity generation scenarios in the UK, and assume a 'Green Scenario' where generation is predominantly from gas CCGTs (ETSU, 1996). Diesel is then distributed in a tanker of capacity of 31,650 litres, with a round trip distance of 100 km. Fuel consumption (38 litres per 100km) and vehicle emissions are based on projections of the HGV fleet average in 2010 (Murrels, 2001).

Total emissions from this stage of the fuel cycle are shown in Table 5. Emissions from the pumping stage are negligible compared to emissions from road distribution.

Table 5 Emissions from F-T Diesel Distribution (per TJ F-T Diesel input)

	Eff'cy %	t/TJ	kg/TJ						
		CO_2	CH_4	N_2O	SO_2	NO_x	PM	NMVOC	CO
F-T distribution	99.7	0.1	0.1	0.00	0.06	0.35	0.01	0.04	0.11

2.6 F-T-DIESEL VEHICLE

The F-T diesel is used in a medium sized (e.g. Volkswagen Golf, Ford Focus) car produced in 2010 and powered with a compression ignition engine. This was assumed to meet Euro IV emission standards, and to have improved fuel economy (of 1.78

MJ/km), compared to current models. This is consistent with the ACEA Agreement[14] on reducing carbon dioxide emissions from cars. Emissions of CO_2 are calculated from fuel consumption and carbon content of F-T diesel assuming 100% complete combustion of the fuel. Emissions of PM, NO_x and NMVOCs are Euro IV limit values (with NMVOCs taken as the difference between the N_2O and HC+NO_x limit). The emission factor for CO is based on test results for a 1.8 litre Ford Focus. SO_2 emissions are based on a10 ppm S content, emissions of N_2O and CH_4 are based on emissions factors for diesel vehicles given in IPCC (1997).

Table 6 Emissions from a Vehicle Using F-T Diesel (per TJ F-T Diesel and per km)

Emissions	CO_2	CH_4	N_2O	SO_2	NO_x	PM	NMVOC	CO
	t/TJ	kg/TJ						
per TJ fuel	71.0	2.0	4.0	4.6	140.5	14.1	28.1	195.0
	g/km							
per km driven	126.2	0.004	0.007	0.008	0.250	0.025	0.050	0.347

2.7 TOTAL EMISSIONS FROM THE F-T DIESEL FUEL CYCLE

Total emissions from the fuel cycle (i.e., taking account of the cumulative efficiency of each stage of the fuel cycle are shown in Table 7 and Table 8 for an F-T plant, with and without CO_2 capture respectively. The overall energy efficiency of the two cycles is 53% and 54% respectively. Emissions per km driven are shown in Table 9.

2.8 REFINERY DIESEL BENCHMARK

In order to provide a 'benchmark' for the F-T diesel fuel cycle, suitable data from previous fuel cycle studies on greenhouse gas emissions was compiled (Table 10). 'Upstream' emissions of CO_2 and CH_4 were taken from Lewis (1997); N_2O emissions were not estimated in this study. The CO_2 emissions given in this study were for a fuel specification containing 30 ppm S. Additional CO_2 emissions from the desulphurisation to 10 ppm S were based on EUROPIA's estimate of 27 kt CO_2/Mt fuel. Fuel economy was assumed to be the same as for the F-T diesel vehicle and CO_2 emissions were calculated in the same way, i.e. based on the carbon content of the fuel. N_2O and CH_4 are based on emissions factors for diesel vehicles in IPCC (1997).

[14] The so-called ACEA Agreement is a voluntary agreement between the European Union and European, Japanese and Korean car manufacturers to reduce the average new car fleet carbon dioxide emission to 140 gms per km by 2008-2009.

Table 7 Total Emissions over all of Fuel Cycle per TJ energy delivered at pump (F-T Diesel plant with CO_2 capture)

Fuel Cycle Stages	**t**	**kg**	**kg**	**kg**	**kg**	**kg**	**kg**	**kg**		**t CO_2-eq**
	CO_2	**CH_4**	**N_2O**	**SO_2**	**NO_x**	**PM**	**NMVOC**	**CO**		**all GHG**
Gas extraction and local conditioning	3.1	139.6	0.01	0.00	5.65	0.06	14.98	0.15		6.36
Pipeline transmission	0.2	27.4	0.00	0.00	0.34	0.00	2.91	0.01		0.82
F-T production- CO2 capture	10.1	4.5	0.1	0.0	20.6	1.3	31.17	31.34		10.28
F-T shipping	0.7	0.1	0.05	12.89	13.03	0.24	0.48	1.69		0.73
F-T distribution	0.1	0.1	0.00	0.06	0.35	0.01	0.04	0.11		0.13
Upstream Total	***14.3***	***171.7***	***0.2***	***13.0***	***39.9***	***1.6***	***49.6***	***33.3***		***18.3***
Use in vehicle	71.0	2.0	4.0	4.6	140.5	14.1	28.1	195.0		72.2
Total for cycle	**85.3**	**173.7**	**4.2**	**17.5**	**180.4**	**15.6**	**77.7**	**228.3**		**90.5**

Table 8 Total Emissions over all of Fuel Cycle per TJ energy delivered at pump (F-T Diesel plant without CO_2 capture)

Fuel Cycle Stages	**t**	**kg**	**kg**	**kg**	**kg**	**kg**	**kg**	**kg**		**t CO_2-eq**
	CO_2	**CH_4**	**N_2O**	**SO_2**	**NO_x**	**PM**	**NMVOC**	**CO**		**all GHG**
Gas extraction and local conditioning	3.1	136.9	0.01	0.00	5.54	0.06	14.69	0.15		6.23
Pipeline transmission	0.2	26.9	0.0	0.0	0.3	0.0	2.86	0.01		0.81
F-T production- no CO2 capture	31.8	4.4	0.11	0.00	18.42	1.26	30.34	30.67		31.97
F-T shipping	0.7	0.1	0.05	12.89	13.03	0.24	0.48	1.69		0.73
F-T distribution	0.1	0.1	0.0	0.1	0.4	0.0	0.0	0.1		0.13
Upstream Total	***35.9***	***168.3***	***0.2***	***13.0***	***37.7***	***1.6***	***48.4***	***32.6***		***39.9***
Use in vehicle	71.0	2.0	4.0	4.6	140.5	14.1	28.1	195.0		72.2
Total for cycle (per TJ)	**106.9**	**170.3**	**4.2**	**17.5**	**178.19**	**15.62**	**76.5**	**227.66**		**112.0**

Table 9 Total Emissions from F-T diesel fuel cycle as g per km

Fuel Cycle	CO_2	CH_4	N_2O	SO_2	NO_x	PM	NMVOC	CO		CO_2-eq
F-T diesel production with CO_2 capture										
Upstream	25.4	0.31	0.00	0.02	0.07	0.00	0.09	0.06		32.6
Use in Vehicle	126.3	0.00	0.01	0.01	0.25	0.03	0.05	0.35		128.4
Total	151.7	0.31	0.01	0.03	0.32	0.03	0.14	0.41		161.0
F-T diesel production without CO_2 capture										
Upstream	63.9	0.31	0.00	0.02	0.07	0.00	0.09	0.06		71.0
Use in Vehicle	126.3	0.00	0.01	0.01	0.25	0.03	0.05	0.35		128.4
Total	190.2	0.31	0.01	0.03	0.32	0.03	0.14	0.41		199.4

Table 10 Benchmark emissions from refinery diesel fuel cycle (per TJ fuel)

Fuel Cycle Stages	t	kg	kg
	CO_2	**CH_4**	**N_2O**
Upstream	7.4	15.8	n.e.
Use in vehicle	74.1	2.0	4.0
Total	81.5	17.8	4.0
	g/km	**g/km**	**g/km**
Total	145	0.031	0.01

3. LNG Fuel Cycle

3.1 NATURAL GAS EXTRACTION AND TREATMENT, AND TRANSMISSION

These stages are the same as for the F-T diesel fuel cycle (Tables1 and 2). The LNG liquefaction plant is situated 150 km from the gas field on the Gulf Coast. Emissions from these stages are shown in Table 11

Table 11 Emissions from natural gas extraction and transmission (per TJ gas input)

Fuel Cycle Stage	Eff'cy %	t/TJ	kg/TJ						
		CO_2	CH_4	N_2O	SO	NO_x	PM	NMVOC	CO
Gas extraction and local conditioning	97	1.7	74.1	0.003	0.000	3.00	0.034	7.95	0.08
Pipeline transmission	100	0.1	15.0	0.000	0.000	0.19	0.002	1.59	0.01

3.2 LNG LIQUEFACTION PLANT

CO_2 emissions from a LNG liquefaction plant arise from the gas treatment unit, and from energy use in refrigeration and power generation. In this fuel cycle, it is assumed that these streams are combined and then passed through to a CO_2 separation plant, and that this CO_2 is then compressed and transmitted via a 150 km pipeline to a disused gas field for reinjection and storage. CO_2 separation for the volumes of CO_2 generated from the liquefaction plant would require a very small scale plant. It is therefore assumed that another large CO_2 generating plant, e.g. a natural gas fired power station is located close to the liquefaction plant and that the liquefaction plant and power station share a CO_2 separation plant. The separation plant itself requires energy to operate, and it is assumed that heat and electricity for the plant are supplied by the power station, and that the CO_2 emissions associated with this additional energy provision also go through the separation plant. CO_2 emission from a liquefaction plant (without CO_2 recovery) were calculated in a previous IEA Greenhouse Gas R&D study (IEA GHG, 1997a); this also looked at emissions from a gas fired power station with and without CO_2 recovery. This data was used to estimate CO_2 emissions from the liquefaction plant (emissions due to CO_2 removal were adjusted to take account of the different composition of the feedstock gas) and from the CO_2 separation operation. In the case of the latter, a proportion of the additional CO_2 emissions from the power station due to operation of the CO_2 separation plant were allocated to the liquefaction plant based on the amounts of CO_2 which were treated.

Emissions of other pollutants were calculated assuming that gas is burnt for power in the liquefaction plant in gas turbines, and using emission factors from Goodwin et al (2000). Total emissions are shown in Table 12.

Table 12 Emissions from LNG production (per TJ gas input)

Fuel Cycle Stage	Eff'cy %	t/TJ	kg/TJ						
		CO_2	CH_4	N_2O	SO_2	NO_x	PM	NMVOC	CO
LNG production (no CO_2 capture)	95	2.7	0.2	0.005	0.000	4.81	0.055	0.19	0.12
LNG production (CO_2 capture)	93	0.8	0.3	0.007	0.000	6.52	0.074	0.26	0.17

3.3 LNG SHIPPING

The LNG tanker is assumed to be fuelled entirely from boil off of gas (in practice a small amount of fuel oil may also be used). Journey length from the Gulf to the NE coast of The Netherlands is 25 days each way and boil off use is 0.22% per day on the trip out and 0.12% per day on the return journey (IEA/AFIS, 1996a). For a tanker capacity of 125,000m^3, 8.6% of the gas is consumed for shipping.

In addition to combustion related emissions from this fuel use, there are emissions of methane and NMVOCs from venting of boil off gas. This has been estimated previously (IEA GHG, 1997a) as happening on 5 days a year. Emissions of methane and NMVOC from this venting were calculated using the composition of the gas.

Table 13 Emissions from LNG Shipping (per TJ of LNG shipped)

Fuel Cycle Stage	Eff'cy %	t/TJ	kg/TJ						
		CO_2	CH_4	N_2O	SO_2	NO_x	PM	NMVOC	CO
Emissions from combustion		4.80	0.34	0.01	0.00	8.58	0.10	0.34	0.22
Emissions from venting			12.04	0.00	0.00	0.00	0.00	2.96	
Total – LNG shipping	**91**	**4.8**	**12.4**	**0.01**	**0.000**	**8.58**	**0.10**	**3.30**	**0.22**

3.4 STORAGE AND VAPORISATION AT THE PORT OF RECEIPT

LNG is unloaded from tankers into storage tanks vaporised to gas using a sea water evaporative vaporiser, and then introduced into The Netherlands' gas distribution network.

The power requirements for pumps in a sea water evaporative vaporiser were taken from the previous IEA study on use of LNG in a power station (IEA GHG, 1997a) and equate to 159.9 kWh/TJ LNG. The same emissions for electricity generation were taken as in the F-T diesel fuel cycle (Section 2.5), and this gives the emissions shown in Table 14 for this stage of the fuel cycle. No information could be found on possible fugitive emissions, or venting losses from this operation.

Table 14 Emissions from storage and vaporisation (per TJ LNG delivered to port)

Fuel Cycle Stage	Eff'cy %	t/TJ	kg/TJ						
		CO_2	CH_4	N_2O	SO_2	NO_x	PM	NMVOC	CO
LNG storage and vaporisation	100	0.1	0.09	0.001	0.13	0.16	0.011	0.01	0.01

3.5 DISTRIBUTION

The Netherlands' existing distribution network is used to carry natural gas from the port terminal to vehicle filling stations. The energy consumption of the gas transmission and distribution system in the UK in 2000 was 0.57% (DUKES, 2001) and this value is taken as representative for a northern European network. Energy consumption is primarily gas burnt in turbines to power compressors. Fugitive emissions are estimated based on information from The Netherlands National Greenhouse Gas Inventory, which gives losses from pipeline leakage etc. as 99 kg/TJ (about 0.5% of gas throughput).

Table 15 Emissions from Natural Gas Transmission (per TJ gas input)

Fuel Cycle Stage	Eff'cy %	t/TJ	kg/TJ						
		CO_2	CH_4	N_2O	SO_2	NO_x	PM	NMVOC	CO
Combustion related		0.3	0.02	0.001	0.00	0.57	0.01	0.02	0.01
Fugitive			99.00					10.48	
Total NG transmission	**99**	**0.3**	**99.02**	**0.001**	**0.00**	**0.56**	**0.01**	**10.50**	**0.01**

3.6 LOCAL STORAGE AND FILLING

Electricity use for compression at the filling stations is 0.2 kWh/m^3 (ETSU, 1996). Emissions are calculated using the same electricity emission factors as used previously.

Table 16 Emissions from local storage and filling of natural gas vehicles (per TJ gas input)

Fuel Cycle Stage	Eff'cy %	t/TJ	kg/TJ						
		CO_2	CH_4	N_2O	SO_2	NO_x	PM	NMVOC	CO
Local storage and filling	98	2.4	3.2	0.050	4.44	5.56	0.389	0.50	0.44

3.7 NATURAL GAS VEHICLE

The natural gas is used in a medium sized (e.g. Volkswagen Golf, Ford Focus) car produced in 2010 and powered with a spark ignition engine. This is assumed to meet Euro IV emission standards, and to have improved fuel economy (of 2.23 MJ/km) compared to current gas powered spark ignition models. The gas is assumed to have a zero sulphur content so there are no SO_2 emissions; PM emissions are also assumed to be zero. CO emissions are based on results from tests on a converted Ford Focus. NO_x and HC emissions are the EURO IV limits for gasoline vehicles, and CH_4 and N_2O are based on emissions factors for gasoline vehicles in IPCC (1997) as no data could be found on emissions of these gases from gas powered vehicles.

No data on fuel consumption could be found for a dedicated natural gas vehicle, only for after market conversions. In theory, there is no reason why the fuel efficiency of a natural gas powered vehicle should be significantly less than a gasoline powered spark ignition vehicle. Consequently a sensitivity study (for CO_2 emissions only) was carried out assuming that a future natural gas vehicle would have the same fuel efficiency as a gasoline powered vehicle (2.15 MJ/km; see Section 4.5)

Table 19 Emissions from combustion of gas in vehicle (per TJ of gas and per km)

Emissions	CO_2	CH_4	N_2O	SO_2	NO_x	PM	NMVOC	CO
	t/TJ	kg/TJ						
per TJ fuel	57.1	7.0	20.0	0.0	35.8	0.0	44.8	22.4
per km driven	g/km							
gas vehicle	127.4	0.02	0.04	0.00	0.08	0.00	0.10	0.05
improved gas vehicle	122.9	0.02	0.04	0.00	0.08	0.00	0.10	0.05

3.8 TOTAL EMISSIONS FROM THE FUEL CYCLE

Total emissions from the fuel cycle (i.e., taking account of the cumulative efficiency of each stage of the fuel cycle are shown in Table 20and Table 21 for LNG production, with and without CO_2 capture respectively. The overall energy efficiency of the two cycles is 79% and 80% respectively. Emissions per km driven are shown in Table 22.

Table 20 Total Emissions over all of LNG Fuel Cycle per TJ energy delivered at pump (LNG plant with CO_2 capture)

Fuel Cycle Stages	**t**	**kg**	**kg**	**kg**	**kg**	**kg**	**kg**	**kg**		**t CO_2-eq**
	CO_2	**CH_4**	**N_2O**	**SO_2**	**NO_x**	**PM**	**NMVOC**	**CO**		**all GHG**
Gas extraction and local conditioning	2.1	92.3	0.00	0.00	3.74	0.04	9.91	0.10		4.21
Pipeline transmission	0.1	18.1	0.00	0.00	0.23	0.00	1.93	0.01		0.54
LNG production (CO2 capture)	0.9	0.3	0.01	0.00	7.87	0.09	0.31	0.21		0.93
LNG shipping	5.4	14.0	0.01	0.00	9.67	0.11	3.72	0.25		5.73
LNG storage and vaporisation	0.1	0.1	0.00	0.13	0.16	0.01	0.01	0.01		0.07
NG transmission	0.3	100.0	0.00	0.00	0.57	0.01	10.61	0.02		2.62
Local storage and filling	2.4	3.2	0.05	4.44	5.56	0.39	0.50	0.44		2.44
Upstream Total	*11.3*	*228.1*	*0.07*	*4.58*	*27.80*	*0.65*	*26.99*	*1.04*		*16.54*
Use in vehicle	57.1	7.0	20.00	0.00	35.82	0.00	44.8	22.4		63.14
Total for cycle	**68.3**	**235.1**	**20.07**	**4.58**	**63.62**	**0.65**	**71.77**	**23.43**		**79.68**

Table 21 Total Emissions over all of LNG Fuel Cycle per TJ energy delivered at pump (LNG plant without CO_2 capture)

Fuel Cycle Stages	**t**	**kg**	**kg**	**kg**	**kg**	**kg**	**kg**	**kg**		**t CO_2-eq**
	CO_2	**CH_4**	**N_2O**	**SO_2**	**NO_x**	**PM**	**NMVOC**	**CO**		**all GHG**
Gas extraction and local conditioning	2.0	90.7	0.00	0.00	3.67	0.04	9.73	0.10		4.13
Pipeline transmission	0.1	17.8	0.00	0.00	0.22	0.00	1.89	0.01		0.53
LNG production (no CO2 capture)	3.2	0.2	0.01	0.00	5.69	0.06	0.23	0.15		3.21
LNG shipping	5.4	14.0	0.01	0.00	9.67	0.11	3.72	0.25		5.73
LNG storage and vaporisation	0.1	0.1	0.00	0.13	0.16	0.01	0.01	0.01		0.07
NG transmission	0.3	100.0	0.00	0.00	0.57	0.01	10.61	0.02		2.62
Local storage and filling	2.4	3.2	0.05	4.44	5.56	0.39	0.50	0.44		2.44

Upstream Total	***13.5***	***226.0***	***0.07***	***4.58***	***25.55***	***0.63***	***26.69***	***0.98***		***18.73***
Use in vehicle	57.1	7.0	20.00	0.00	35.82	0.00	44.8	22.4		63.14
Total for cycle	**70.6**	**233.0**	**20.07**	**4.58**	**61.38**	**0.63**	**71.47**	**23.37**		**81.87**

Table 22 Total Emissions from Fuel Cycle as g per km

Fuel Cycle	**CO_2**	**CH_4**	**N_2O**	**SO_2**	**NO_x**	**PM**	**NMVOC**	**CO**		**CO_2-eq**
LNG production with CO_2 capture	152.6	0.53	0.04	0.01	0.14	0.00	0.16	0.05		178.0
LNG production without CO_2 capture	157.6	0.52	0.04	0.01	0.14	0.00	0.16	0.05		182.9
LNG production with CO_2 capture (improved vehicle)	147.2	0.51	0.04	0.01	0.14	0.00	0.15	0.05		171.59

4. Specification of the Gasoline Fuel Cycle

4.1 CRUDE OIL EXTRACTION AND TRANSMISSION

Crude oil is extracted in a (hypothetical) Middle East onshore field. Energy use in oil extraction is 2.2% of the energy value of crude extracted in the UK North Sea fields (Bates, 1995) and estimated as 1 to 3% in the US (Wang, 1999). However, efficiencies may be lower in the rest of the world. As no specific data was available for the Middle East, a value of 2.5 % is assumed. The main energy source is gas, which is combusted in turbines. An estimate of methane emissions from oil extraction in the Middle East (0.074 t/TJ crude oil), due to venting and flaring of associated gas, and from process vents is taken from a previous IEA study on methane emissions from the oil and gas industry (IEA GHG, 1997).

As with the gas field in the other two fuel cycles, it is assumed that the field is located 150 km from the Gulf Coast, and that oil is pumped to a marine terminal on the coast. The energy associated with this pumping is included in the values for energy used in oil extraction given above.

Table 22 Emissions from crude oil extraction (per TJ crude extracted)

Fuel Cycle Stage	Eff'cy %	t/TJ	kg/TJ						
		CO_2	CH_4	N_2O	SO_2	NO_x	PM	NMVOC	CO
Oil extraction	98	1.4	74.1	0.0	0.0	2.5	0.0	7.9	0.1

4.2 CRUDE OIL SHIPPING

Crude oil is stored at the marine terminal and then loaded onto tankers and shipped to the north east coast of The Netherlands. There are some fugitive emissions of methane and NMVOCs during loading and unloading of the crude oil (Goodwin et al, 2000). Other emissions arise from bunker fuel use in tankers (14.85 kg bunker fuel per tonne crude oil) (IEA/AFIS, 1996). Emissions associated with bunker fuel use and loading and unloading are taken from Goodwin et al (2000).

Table 23 Emissions from shipping of crude oil to Europe (per TJ crude shipped)

Fuel Cycle Stage	Eff'cy %	t/TJ	kg/TJ						
		CO_2	CH_4	N_2O	SO_2	NO_x	PM	NMVOC	CO
Combustion related	99	1.1	0.1	0.1	19.3	19.5	0.4	0.7	2.5
Fugitive during loading			0.6					41.2	
Total	**99**	**1.1**	**0.7**	**0.1**	**19.3**	**19.5**	**0.4**	**41.9**	**2.5**

4.3 REFINING AND PRODUCT FINISHING

Refining and product finishing has been examined in a number of other fuel cycle studies, e.g. previous AEA transport fuel cycle work has examined UK refineries (ETSU, 1996; Lewis, C A, 1997) and the Argonne National Laboratory Greet model examined US refineries (Wang, 1999). These studies analysed refinery operations and allocated energy use and emissions to particular operations in the refinery, allowing energy use and emissions associated with particular refinery products to be estimated. Emissions associated with gasoline production are taken from ETSU 1996 for a fluid catalytic converter plant; the energy efficiency for gasoline production is 90.4%. As emissions of CH_4, N_2O and PM were not calculated in the original study these were estimated from details of fuel use and emission factors contained in Goodwin et al (2000).

An extra desulphurisation step will be required to meet the proposed fuel standards it is assumed are in place in 2010. EUROPIA (the European Petroleum Industries Association) has estimated the CO_2 penalty associated with this step as 25 kt CO_2 per Mt gasoline (CEC, 2001, Marsh et al, 2000).

Table 24 Emissions from refining to gasoline (per TJ input)

Fuel Cycle Stage	Eff'cy %	t/TJ	kg/TJ						
		CO_2	CH_4	N_2O	SO_2	NO_x	PM	NMVOC	CO
Gasoline refining	90	6.4	0.1	0.0	51.5	12.1	0.8	61.2	1.4

4.4 GASOLINE DISTRIBUTION

Gasoline is distributed by pipeline from the refinery to bulk terminals, from where it is distributed by road tanker (capacity of 31,650litre) to filling stations with a round trip distance of 100 km. Emissions from these stages are calculated as for the distribution of F-T diesel. Evaporative emissions of VOCs during refinery dispatch, from depots and service stations are estimated as 3.93 kt/Mt of gasoline (EMEP/CORINAIR).

Table 25 Emissions from gasoline distribution (per TJ input)

Fuel Cycle Stage	Eff'cy %	t/TJ	kg/TJ						
		CO_2	CH_4	N_2O	SO_2	NO_x	PM	NMVOC	CO
Distribution	99.7	0.1	0.01	0.00	0.00	0.29	0.01	0.1	0.11
Evaporative emissions								90.3	
Total for distribution	99.7	0.1	0.01	0.00	0.00	0.29	0.01	90.4	0.11

4.5 USE IN GASOLINE VEHICLE

The gasoline is used in a medium sized (e.g. Volkswagen Golf, Ford Focus) car produced in 2010 and powered with a spark ignition engine. This is assumed to meet Euro IV emission standards, and to have improved fuel economy (of 2.15 MJ/km), compared to current spark ignition models. This is consistent with the ACEA Agreement[15] on reducing carbon dioxide emissions from cars. Emissions of CO_2 are calculated from fuel consumption and carbon content of gasoline assuming 100% complete combustion of the fuel. Emissions of CO, NO_x and NMVOCs (taken as equivalent to HCs) are Euro IV limit values (with NMVOCs taken as the difference between the NO_x and HC+NO_x limit). SO_2 emissions are based on a10 ppm S content in the gasoline, emissions of N_2O and CH_4 are based on emissions factors for gasoline vehicles in IPCC (1997).

As a sensitivity study, use in a parallel hybrid car such as the Toyota Prius is also considered. The current Toyota Prius has a fuel efficiency of 1.62 MJ/km; emissions data for CO, NO_x and NMVOCs are taken from test data for the Prius. Parallel hybrids have only recently become available on the market, and as a further sensitivity analysis, an analysis of CO_2 emission only was undertaken, assuming the fuel efficiency of the hybrid improves to 1.47 MJ/km by 2010.

Table 26 Emissions from combustion of gas in vehicle (per TJ of gasoline and per km)

Emissions	CO_2	CH_4	N_2O	SO_2	NO_x	PM	NMVOC	CO
per TJ fuel	t/TJ	kg/TJ						
spark ignition	69.3	7.00	20.00	4.60	37.15	4.64	46.44	464.38
per km driven	g/km							
spark ignition	149.2	0.02	0.04	0.01	0.08	0.01	0.10	1.00
hybrid	112.2	0.01	0.03	0.01	0.05	0.01	0.05	0.03
improved hybrid	102.0	0.01	0.03	0.01	0.05	0.01	0.05	0.03

[15] The so-called ACEA Agreement is a voluntary agreement between the European Union and European car manufacturers to reduce the average new car fleet carbon dioxide emission to 140 gms per km by 2008-2009. A similar (JAMA/KAMA) agreement exists with Japanese and Korean car manufacturers.

4.6 TOTAL EMISSIONS FROM THE FUEL CYCLE

Total emissions from the gasoline fuel cycle (i.e. taking account of the cumulative efficiency of each stage of the fuel cycle) are shown in Table 27. The overall energy efficiency of the cycle is 86.5%. Emissions per km driven are shown in Table 28.

Table 27 Total Emissions over all of Fuel Cycle per TJ energy delivered at pump (gasoline)

Fuel Cycle Stages	t	kg	kg	kg	kg	kg	kg	kg	t CO_2-eq
	CO_2	CH_4	N_2O	SO_2	NO_x	PM	NMVOC	CO	all GHG
Oil extraction	1.6	85.4	0.00	0.0	2.88	0.03	9.14	0.08	3.6
Crude oil shipping	1.2	0.8	0.08	21.7	21.95	0.40	47.11	2.85	1.2
Refining	7.1	0.1	0.02	57.0	13.40	0.89	67.70	1.50	7.1
Distribution	0.1	0.0	0.00	0.0	0.29	0.01	90.38	0.11	0.1
Upstream Total	*10.0*	*86.3*	*0.11*	*78.7*	*38.52*	*1.33*	*214.33*	*4.54*	*12.0*
Use in vehicle	69.3	7.00	20.00	4.6	37.15	4.64	46.44	464.38	75.4
Total for cycle	**79.2**	**93.3**	**20.11**	**83.3**	**75.67**	**5.97**	**260.77**	**468.92**	**87.3**

Table 28 Total Emissions from Fuel Cycle as g per km

Fuel Cycle	CO_2	CH_4	N_2O	SO_2	NO_x	PM	NMVOC	CO	CO_2-eq
spark ignition	170.6	0.201	0.043	0.179	0.163	0.013	0.562	1.010	188.1
hybrid	128.4	0.151	0.033	0.135	0.112	0.012	0.397	0.032	141.5
improved hybrid	116.7	0.137	0.030	n.e	n.e	n.e	n.e	n.e	**128.6**

5. Sensitivity Assessments

The initial assessment used single “baseline” values for emissions from each stage of the fuel cycles to estimate total fuel cycle emissions. These were taken from previous work or estimated from related data (e.g. on energy consumption), and were conservative values. Where a range of values was found this has been reported and a single value used from within the range.

The main types of uncertainties involved in assessing the emissions from fuel cycles are:

- uncertainties in the efficiency of processes and vehicle technologies,
- uncertainties in emissions arising directly from processes (e.g. methane releases during gas production),
- uncertainties in the factors used to calculate emissions from fuel combustion.

Uncertainties in the emissions factors used for fuel combustion are common to all fuel cycles. They vary according to the pollutant and for the greenhouse gases they are typically (Charles et al, 1998):

CO_2 - 1 to 6% depending on fuel
CO_2 - 50%
N_2O – 100%

While the uncertainties in the emissions factors for CH_4 and N_2O are large, the contribution of these emissions from fuel combustion to total GHG emissions in the fuel cycles is relatively low (Table 1). Since these uncertainties act in the same direction for all fuel cycles (i.e. the error will not be positive for one cycle when it is negative for another) they have not been considered explicitly when comparing fuel cycles.

To give an assessment of the other sources of uncertainty, calculations have been made to examine the impact of improvements in the process steps that make a significant contribution to upstream and vehicle emissions. Also the implications of changes in vehicle efficiency have been examined. Results are summarised in Table 29.

Efficiency of the F-T Plant
There is potential to reduce emissions from the F-T diesel fuel cycle through improvements in the conversion efficiency of the plant. The Sasol system considered herein had an energy efficiency of about 55% (with carbon dioxide capture) while more advanced designs could increase this to 67%. Such an improvement would reduce overall carbon dioxide emissions by about 14% without capture and 7% with capture. This improvement makes the GHG emissions from F-T diesel with CO_2 capture comparable with the conventional diesel fuel cycle.

Reduced Venting during Natural Gas Production

In the baseline fuel cycles fugitive emissions of methane at the wellhead were taken to be 74.1 kg/TJ. This is high compared to North Sea standards so the impact on total emissions of halving this release was investigated for both the F-T diesel and LNG fuel cycles. This reduced total GHG emissions, expressed in kg/km, by between 1 and 2%, and did not effect the ranking of the fuel cycles in terms of emissions.

Reduced Energy Consumption during LNG Shipping
The baseline analysis assumed 8% of LNG was consumed in a round trip of a LNG tanker between The Gulf and The Netherlands. Other sources suggested this was towards the high side of fuel combustion, and a sensitivity assessment was made for a 4% consumption rate. This fed through directly reducing the full fuel cycle GHG emissions by 4% (Table 2).

Improved Efficiency of the LNG Plant
In the baseline assessment the energy efficiency of the LNG plant was taken to be 95% without carbon dioxide capture and 93% with capture. The effect of improving both these efficiencies by two percentage points was investigated. This reduced GHG emissions for the non-capture plant by 2%, but only by 0.4% with carbon dioxide capture.

Reduced Fugitive Emissions from Natural Gas Transmission and Distribution
Fugitive emissions of methane during gas distribution were assumed to be 99kg/TJ in the baseline analysis. The effect of halving these releases was to reduce total GHG emissions from both LNG fuel cycles by 1%.

Reduced Vehicle Efficiencies
It was shown in the above analysis that the main source of GHG emissions in all fuel cycles was final combustion of the fuels in the vehicles. Consequently the emission estimates are particularly sensitive to the values taken for future vehicle efficiencies. In line with the actions anticipated to attain the ACEA Agreement targets spark ignition engined vehicles were expected to improve efficiency by 20% and compression ignition vehicles by 10% relative to current values. Therefore there is probably less confidence in the gasoline and LNG vehicles attaining their emissions performance compared to the diesel fuelled vehicles. For example if both sets of vehicles only attained half the target efficiency improvement then emissions from the diesel vehicles would increase by 5% and the gasoline and LNG vehicles by 10%.

Table 29 Impact of Changes in Critical Parts of the Fuel Cycles on overall GHG Emissions

Fuel Cycle	CO_2 only (g CO_2/km)			All GHG (g CO2 eq/km)			Change
	upstream	vehicle	total	upstream	vehicle	total	
F-T + CO2 capture (base case)	25.5	126.2	151.7	32.6	128.4	161.0	-
F-T + CO2 capture, improved F-T plant	15.9	126.2	142.2	21.8	128.4	150.2	-7%
F-T + CO2 capture, reduced gas venting	25.5	126.2	151.7	29.7	128.4	158.2	-2%
F-T no CO2 capture (base case)	64.0	126.2	190.2	70.9	128.4	199.4	-
F-T no CO2 capture, improved F-T plant	36.7	126.2	162.9	42.6	128.4	171.0	-14%
F-T no CO2 capture, reduced gas venting	64.0	126.2	190.2	68.1	128.4	196.6	-1%
LNG + CO2 capture (base case)	25.2	127.4	152.6	36.9	141.0	178.0	-
LNG + CO2 capture, reduced gas venting	25.2	127.4	152.6	34.6	141.0	175.6	-1%
LNG + CO2 capture, reduced shipping fuel	18.6	127.4	146.0	30.0	141.0	171.0	-4%
LNG + CO2 capture, reduced fugitive emissions	25.2	127.4	152.6	34.4	141.0	175.4	-1%
LNG + CO2 capture, improved liquefaction efficiency	24.6	127.4	152.0	36.2	141.0	177.2	-0.4%
LNG no CO2 capture (base case)	30.2	127.4	157.6	41.9	141.0	182.9	-
LNG no CO2 capture, reduced gas venting	30.2	127.4	157.6	39.5	141.0	180.5	-1%
LNG no CO2 capture, reduced shipping fuel	23.3	127.4	150.8	34.7	141.0	175.7	-4%
LNG no CO2 capture, reduced fugitive emissions	30.2	127.4	157.6	39.3	141.0	180.3	-1%
LNG no CO2 capture, improved liquefaction efficiency	27.1	127.4	154.5	38.7	141.0	179.7	-2%
Gasoline (base case)	21.5	149.2	170.6	25.8	162.3	188.1	-
Diesel (base case)	13.2	131.8	145.0	13.9	134.0	147.9	-

6. US Sensitivity Study

Changes in emissions (of CO_2 only) and costs, which would arise if the fuels were used in the US, were considered as a sensitivity analysis. All fuel extraction and production of F-T diesel and LNG still occurs in the Middle East. Oil refining takes place in the US. The changes, which were examined, were:

- the impact of longer shipping distances:- Energy use and emissions associated with shipping of F-T diesel, LNG and crude oil were increased in direct proportion to the increase in shipping distance.
- lower efficiency of US refineries compared to European refineries:- a value of 85% as used in the Argonne National Laboratories GREET model (Wang, 1999) was taken.
- fuel efficiencies for a typical US vehicle (a full size pick-up truck) were taken from the General Motors Corporation /Argonne National Laboratory study (GMC et al 2001). These are simulation results from General Motors' proprietary Hybrid Powertrain Simulation for vehicle concepts which will meet a given set of performance requirements and emissions standards. Fuel efficiencies and CO_2 emissions in tonnes per TJ and g per km are given in Table 30.

Emissions from distribution are small compared to other stages of the fuel cycle and so were not re-estimated.

Total CO_2 emissions from the US fuel cycles are shown in Table 31

Table 30 US vehicle fuel efficiencies and CO_2 emissions

	miles per US gallon	MJ/km	CO_2	CO_2
	Petrol equivalent		g/MJ	g/km
F-T diesel	23.8	3.17	71.0	225.3
Natural gas	19.8	3.82	57.1	217.7
Gasoline	20.2	3.74	69.3	259.1
Gasoline hybrid	24.4	3.10	69.3	214.5

Table 31 Total CO_2 Emissions from US Fuel Cycles (g CO_2 per km)

	upstream	in vehicle	total
F-T Diesel + CO2 capture	46	225	271
LNG + CO2 capture	45	217	262
Gasoline	49	259	308
Gasoline hybrid	41	214	255

Appendix 3

Analysis of Fuel Cycle Costs

1. Introduction

This Appendix describes the key assumptions and analyses made in estimating the cost per unit of energy produced for each stage of the fuel cycles covered in the study. It also describes the estimation of the cost per unit of distance travelled when the fuels are used in their designated cars. Detailed descriptions of the fuel cycles are presented in Appendix 1.

2. Methodology

The cost assessment is based on the year 2010, and all costs are reported in US$(2000). Capital costs were annualised over the operating life times of plant at discount rate of 10% (sensitivity tests were made with a 5% rate). Where costs were obtained in currencies other that US$ these were adjusted using the 2001 OECD Purchasing Power Parities (PPPs) for the relevant year and then to US$(2000) using OECD GDP deflators for the United States. The currency conversion factors used are listed in Section 8 of this appendix.

The data used in the study were a mix of cost and price (i.e. including profit) based values. In particular the only data available on gasoline and conventional diesel were on a price basis. For consistency in comparisons between the fuel cycles the analyses below estimates "costs" for the F-T diesel and LNG fuel cycles which include an arbitrary "profit margin" (ROI, Return On Investment) of 10%.

The assessment of fuel cycle costs was made for the year 2010. This required a set of price projections for the primary energy sources for that year. These were taken form the IEA's World Energy Outlook 2000 (IEA, 2000). They key values used were:

LNG Price - the IEA's estimate of the price of LNG landed in Japan (163$/toe)
Crude Oil - the IEA's estimate of crude prices in Europe (21$/bbl or 3.7$/GJ)

3. Fischer-Tropsch Diesel

3.1 NATURAL GAS EXTRACTION AND TREATMENT

The study is based on natural gas (NG) extracted from a (hypothetical) inland field located in Iran some 150 km from the coast, and producing only NG rather than mixed products. The NG is assumed to have the same composition as that used in the IEA's Fischer-Tropsch (F-T) Diesel study (IEA GHG R&D Programme, 2000). Several of the recent discoveries of gas in Iran have had this profile (i.e. non- –associated, sweet gas fields, located in the south of the country, relatively close to the Gulf Coast).

The starting point for the analysis was the value to be placed on the gas in 2010 at the well-head after extraction and initial treatment. This was based on the projections of LNG beach prices in Japan in 2010 given in the IEA's World Energy Outlook (IEA, 2000). The well-head value was back-calculated by subtracting the following from the Japan beach price:

- Cost of LNG transport between Ras Tunura and Yokohama (11,982 km), calculated using the same methodology as for the LNG fuel cycle (see below);
- Cost of liquefaction taken from the analysis of the LNG fuel cycle (see later).
- Cost of pipeline transmission from the wellhead to the coastal LNG facility. Again taken from the LNG fuel cycle analysis.

This approach ensured internal consistency between prices used in the study, all of which were based on the IEA's price projections for 2010.

The IEA projected price for LNG in Japan in 2010 Japan was 163 US$/toe, which gave a wellhead value of 0.64$/GJ (26.8$/toe).

A sensitivity study was performed using a price of $0.5/GJ as assumed in the IEA F-T Diesel study.

3.2 PIPELINE TRANSMISSION TO THE F-T DIESEL PLANT

Gas is piped 150 km to the F-T diesel plant located on the coast at a rate of about 7-8 MNm^3/day (224 TJ/day). Recent new gas fields in Iran have ranged from a potential 14 MNm^3/day (Khuff reservoir) up to a potential 200 MNm^3/day (South Pars reservoir, US DoE, 2001). The IEA GHG R&D Programme provided capital and operating costs for a Natural Gas pipeline based on the following assumptions:

Table 1: NG Pipeline Assumptions and Costs

Parameter	Value
Pipeline lifetime, years:	40
NG Flow rate, kg/s:	220.0
Pipeline length, km:	150
Delivery pressure of NG, bar:	33
Country:	Iran, Onshore
Terrain:	Stony desert <20% mountainous
Pipeline inlet pressure, bar:	90
Pipeline nominal diameter, mm:	900
Capital Cost, $M	62
Operating Cost, $M/y	2.5
Cost of transmission (10% discount rate), $/GJ	0.0293
Cost of transmission (5% discount rate),	0.0202

$/GJ	

3.3 F-T DIESEL PLANT AND SUPPORT FACILITIES

F-T diesel is produced in a 26,000 bbl/day O_2 blown slurry type reactor (Sasol Type) process as described in the report on F-T synthesis produced for the IEA Greenhouse Gas R&D Programme (IEA GHG, 2000). If CO_2 is captured, it is compressed and piped away (150 km) for underground storage in a depleted gas field.

Costs for the 26,000 bbl/day (145 TJ/day) plant were scaled up by a factor of 2.6 from the costs for the 10,000 bbl/day plant considered in the previous report (i.e. no economies of scale assumed). Capital and operating costs (including fuel) were used to calculate an average cost per barrel of product, which is a roughly 60:40 mix of diesel and naphtha. The cost per barrel of F-T Diesel was calculated from this product split and the relative energy contents of the two products.

Recent information in the trade press (Petroleum Economist) has suggested significant economies of scale can be gained with larger gas to liquids plant. Consequently a sensitivity analysis was made in which the capital cost of the plant was increased by a factor of $(2.6)^{0.6}$ to assess the potential implications of economies of scale in moving to a 26,000 bbl/day plant from the 10,000 bbl/day plant considered previously.

Table 2 F-T Plant Assumptions and Production Costs

Parameter	Value
Plant lifetime, years	25
Conversion efficiency, – with CO_2 capture ,%	55
Conversion efficiency, – without CO_2 capture, %	56
Load Factor, %	90
Proportion of diesel in product mix (with CO_2 capture), %	59.90
Proportion of diesel in product mix (without CO_2 capture), %	59.88
Capital Cost – with CO_2 capture, $M	1122.6
Capital Cost – without CO_2 capture, $M	999.3
Operating Cost – with CO_2 capture, $M/y	132.9
Operating Cost – without CO_2 capture, $M/y	113.6
Cost of F-T diesel (10% discount rate), $/GJ Cost – with CO_2 capture	5.334
Cost of F-T diesel (5% discount rate), $/GJ Cost – with CO_2 capture	4.403
Cost of F-T diesel (10% discount rate), $/GJ Cost – without CO_2 capture	4.649
Cost of F-T diesel (5% discount rate), $/GJ Cost – without CO_2 capture	3.819
Sensitivity Analysis (economy of scale)	
Cost of F-T diesel (10% discount rate), $/GJ – with CO_2 capture	4.022
Cost of F-T diesel (5% discount rate), $/GJ – with CO_2 capture	3.381

The results in Table 2 do not include the cost of CO_2 transmission and storage. The IEA GHG R&D Programme provided capital and operating costs for a CO_2 pipeline based on the following assumptions listed in Table 3. The CO_2 flow rate was calculated from the information presented in Appendix 2.

Table 3: F-TD Plant CO_2 Pipeline Assumptions

Parameter	Value
Pipeline lifetime, years:	40
CO_2 Flow rate, kg/s:	30.4
Pipeline length, km:	150
Delivery pressure of CO_2, bar:	100
Country:	Iran, Onshore
Terrain:	Stony desert <20% mountainous
Pipeline inlet pressure, bar:	135
Pipeline nominal diameter, mm:	300
Capital Cost $M	17
Operating Cost $M/yr.	0.8
CO_2 transmission cost (10% discount rate) $/GJ	0.021
CO_2 transmission cost (5% discount rate) $/GJ	0.015

3.4 F-T DIESEL SHIPPING

F-T diesel is transported to The Netherlands in product tankers. The cost to transport F-T diesel from the Gulf to Rotterdam was taken from the previous IEA report on gas to liquid technology (IEA GHG, 2000), which was 0.24$/GJ (1.3 $/bbl)

For the US sensitivity study, the additional cost of shipping was estimated based on the increase in journey length,

3.5 F-T DIESEL TERMINAL STORAGE

After offloading from the tanker, F-T diesel is stored at the port terminal before being distributed to bulk terminals. The cost of terminal storage was taken from the IEA Automotive Fuels Survey (IEA, 1996b), which was 0.17 $/GJ (6$/m^3).

3.6 F-T DIESEL DISTRIBUTION, LOCAL STORAGE AND VEHICLE FILLING

F-T diesel is distributed by pipeline from the port to bulk terminals, from where it is distributed by road tanker to filling stations, stored and used to fuel cars. The total cost of distribution to the filling stations, storage and filling was calculated from 1999 IEA energy price data (IEA, 1999) by taking the difference between the average price of diesel from a NW Europe refinery, and the average 1999 diesel ex-tax price in the UK. It is assumed that costs are volume dependent, so the cost per GJ was adjusted to allow for the different energy content per litre of F-T diesel compared to conventional diesel.

This gave an overall distribution cost of $2.36/GJ.

3.7 USE IN 2010 COMPRESSION IGNITION CAR

F-T diesel is used in a 2010 specification compression ignition car. The cost of fuel used (in $/km) is calculated from the input fuel cost and the vehicle energy efficiency, 0.00178 GJ/km. This gave a value of 0.0145 $/km (0.0128 $/km for 5% discount rate).

The cost of the vehicle has not been included in these calculations because it has been assumed to be the same for all fuel cycles. This is considered to be a reasonable assumption because a fleet of 1 million vehicles (the fleet size assumed in all fuel cycles) should be sufficient to yield economies of volume production.

3.8 TOTAL COSTS FROM THE F-T DIESEL FUEL CYCLE

Total costs from the F-T diesel fuel cycle (i.e. taking account of the cumulative efficiency of each stage) are shown Table 4 and Table 5 for an F-T plant, with and without CO_2 capture respectively. The overall energy efficiency of the two cycles is 55% and 56% respectively. Costs per km driven are shown in Table 6, compared to those of the benchmark refinery diesel fuel cycle (outlined in Section 6).

Table 4 Total Cost over all of Fuel Cycle per GJ energy delivered at pump (F-T Diesel plant with CO_2 capture)

Fuel Cycle Stages	**$/GJ**
Gas extraction	1.169
Local conditioning and pipeline transmission	0.051
F-T production- CO2 capture	4.151
F-T shipping	0.238
F-T storage	0.187
F-T distribution, local storage and vehicle filling	2.341
Upstream Total	***8.138***
Use in vehicle*	-
Total for cycle	**8.138**

* The cost of the vehicle has not been included in the calculations, as discussed in the previous section.

Table 5 Total Cost over all of Fuel Cycle per GJ energy delivered at pump (F-T Diesel plant without CO2 capture)

Fuel Cycle Stages	$/GJ
Gas extraction	1.146
Local conditioning and pipeline transmission	0.050
F-T production- CO2 capture	3.467
F-T shipping	0.238
F-T storage	0.187
F-T distribution, local storage and vehicle filling	2.343
Upstream Total	***7.432***
Use in vehicle*	-
Total for cycle	**7.432**

* The cost of the vehicle has not been included in the calculations, as discussed in the previous section.

Table 6 Total Costs from F-T diesel fuel cycle and benchmark from refinery diesel fuel cycle**

Fuel Cycle	$/GJ	$/km
F-T diesel production with CO_2 capture	8.138	0.0142
F-T diesel production without CO_2 capture	7.432	0.0132
Benchmark from refinery diesel fuel cycle**	6.758	0.0120

** The benchmark from the refinery diesel fuel cycle is discussed in Section 6.

4. LNG Fuel Cycle

4.1 NATURAL GAS EXTRACTION AND TREATMENT, AND TRANSMISSION

These stages are the same as for the F-T diesel fuel cycle. The LNG liquefaction plant is assumed to be situated 150 km from the gas field on the Persian Gulf Coast. As for the F-T fuel cycle the value of the natural gas arriving at the LNG plant is made up of its value at the wellhead plus pipeline transmission costs. This is 0.669 $/GJ (0.660 $/GJ for 5% discount rate).

4.2 LNG LIQUEFACTION PLANT

The cost of liquefaction in $/GJ was calculated from cost data presented in a previous IEA study (IEA GHG, 1997a). The cost of CO_2 separation is assumed to be $50/t CO_2 based on values given in the DTI and IEA publication “Carbon Capture and Storage”. (IEA, 2000)

Table 7 LNG Plant Assumptions and Production Costs

Parameter	Value
Plant lifetime, years	25
Conversion efficiency, %	91
Load Factor, %	90
Capital Cost, $M	2496
Operating Cost, $M/y	105.49
Cost of LNG (10% discount rate), $/GJ	1.674
Cost of LNG (5% discount rate), $/GJ	1.234
Cost of CO_2 capture, $/GJ of LNG	0.16

The IEA GHG R&D Programme provided capital and operating costs for a CO_2 pipeline based on the assumptions listed in Table 8. The CO_2 flow rate was calculated from the data in Appendix 2.

Table 8: LNG Plant CO_2 Pipeline Assumptions and Costs

Parameter	Value
Pipeline lifetime, years:	40
CO_2 Flow rate, kg/s:	36.6
Pipeline length, km:	150
Delivery pressure of CO_2, bar:	100
Country:	Iran, Onshore
Terrain:	Stony desert <20% mountainous
Pipeline inlet pressure, bar:	125
Pipeline nominal diameter, mm:	350
Capital Cost $M	19.8
Operating Cost $M/yr.	0.9
CO_2 transmission costs (10% discount rate)	0.0111
CO_2 transmission costs (5% discount rate)	0.0078

4.3 LNG SHIPPING

LNG will be transported to The Netherlands in specialised tankers. The cost of shipping LNG was calculated using data based on a 125,000 m^3 capacity tanker from the IEA Automotive Fuels Survey (IEA, 1996), together with information on LNG tankers from the earlier IEA LNG study (IEA GHG,1997a) - LNG loss, average speed, distance travelled (20,742 km between Ras Tunura and Rotterdam), etc. The data was used to calculate the number of round trips possible by a tanker and from this the total annual fuel and non-fuel operating costs. These were combined with the capital cost to calculate the annual cost per unit energy in $/GJ (Table 9).

4.4 LNG STORAGE AND VAPORISATION AT THE PORT OF RECEIPT

LNG will be unloaded from tankers into storage tanks and then vaporised to gas and introduced into The Netherlands' distribution network. The cost of storage and regasification was taken from the IEA Automotive Fuel Survey (IEA/AFIS, 1996) and combined with the calculated value of fuel lost through this process. The amount of fuel lost is approximately 1% according to the same report.

This gave a vaporisation and storage cost of 0.4669$/GJ.

Table 9 LNG Shipping Assumptions and Cost

Parameter	Value
Distance: Iran-NL, km	20,742
Average ship speed, km/h	34.3
Ship lifetime, yr.	25.0
Trip length, days	25.2
Days in port per voyage	2
Operating days per year	340
Number of round trips per year	6.2
Ship capacity, m3	125000
Annual transport capacity, m3	780540
% LNG loss per trip (out)	5.55%
% LNG loss per trip (in)	3.03%
Annual LNG loss, m3	66,942
Ship capital cost, $M	210
Operating cost, $M	7.35
LNG loss/use, $M	3.62
Annual transport, GJ/yr.	15,498,956
Transport Cost, $/GJ (10% discount rate)	2.59
Transport Cost, $/GJ (5% discount rate)	1.92

4.5 LNG DISTRIBUTION

The Netherlands' existing distribution network will be used to carry natural gas from the port terminal to vehicle filling stations. At the filling stations the gas will be compressed ready for fuelling natural gas cars.

The quantity of natural gas needed to run 1 million cars was calculated to represent only just over 2% of The Netherlands network's current consumption (IEA, 2001) therefore it was assumed there would be no need to enhance the network to carry additional gas. The cost to transmit the gas through The Netherlands gas network to the filling station was approximated to prices provided by the UK network operator, Transco for June 2001 (Transco GTC, 2001). The charges for National Transmission, Local Distribution (for customers taking 73,200 kWh per annum and above) and customer charges were combined to calculate a total charge for transmission.

This gave a charge of 0.3012$/GJ.

4.6 LOCAL STORAGE AND CNG VEHICLE FILLING

The Netherlands currently has a car vehicle stock of about 6 million, the majority of which have spark ignition engines. Therefore it was assumed that one sixth of filling stations, some 670, would need to invest in CNG fuelling facilities to serve 1 million cars. This assumption seems reasonable for a country like The Netherlands where the average distance between filling stations is small. However, it could be argued that this might in practice limit the service of CNG vehicles to local travel with possibly lower than average utilisation. Nonetheless, for this study it has been assumed that CNG vehicles have the same utilisation and journey patterns as the average vehicle.

Estimates for the capital and operating cost of a CNG refuelling station (compressor facilities and CNG fuelling facilities) were provided by CompAir UK (CompAir, 2001). These were based on an average station throughput of 4500 m^3/day, calculated from the number of fuel stations and the 1 million car fleet's total annual fuel requirement. A retailers margin was added to this value, scaled to the same cost margin ratio as the cost and retailer's margin for diesel derived from the IEA Automotive Fuels Survey (IEA, 1996b).

Table 10 CNG Refuelling station Costs

Parameter	Value
Capital cost, $M	0.3239
Operating Cost, $M/yr.	0.0324
Refuelling Cost (10% discount rate), $/GJ	1.518
Refuelling Cost (5% discount rate), $/GJ	1.287
Distributor Margin, $/GJ	1.771

4.7 USE IN 2010 COMPRESSION IGNITION CAR, $/KM

CNG is used in 2010 compression ignition engine cars. The cost of fuel used (in $/km) is calculated from the input fuel price and the vehicles energy efficiency, 0.00223 GJ/km. This gave a value of 0.0204 $/km (0.0167$/km for a 5% discount rate).

The cost of the vehicle has not been included in these calculations because it has been assumed to be the same for all fuel cycles. This is considered to be a reasonable assumption because a fleet of 1 million vehicles (the fleet size assumed in all fuel cycles) should be sufficient to yield economies of volume production[16].

[16] One exception to this approximation is the requirement for a pressurised fuel tank on CNG vehicles. Even with economies of mass production these are likely to cost more than unpressurised gasoline and diesel fuel tanks. This will reduce the cost competitiveness of the LNG fuel cycle.

4.8 TOTAL COSTS FROM THE LNG FUEL CYCLE

Total costs from the LNG fuel cycle (i.e. taking account of the cumulative efficiency of each stage) are shown in Table 11 and Table 12 for an LNG production plant, with and without CO_2 capture respectively. The overall energy efficiency of the two cycles is 79% and 80% respectively. Costs per km driven are shown in Table 13.

Table 11 Total Costs over all of LNG Fuel Cycle per GJ energy delivered at pump (LNG plant with CO_2 capture)

Fuel Cycle Stages	**$/GJ**
Gas extraction	0.773
Local conditioning and pipeline transmission	0.034
LNG production (CO_2 capture)	2.016
LNG shipping	2.428
LNG storage and vaporisation	0.367
NG transmission	0.245
Local storage and filling	3.289
Upstream Total	***9.152***
Use in vehicle*	-
Total for cycle	**9.152**

* The cost of the vehicle has not been included in the calculations, as discussed in the previous section.

Table 12 Total Costs over all of LNG Fuel Cycle per GJ energy delivered at pump (LNG plant without CO2 capture)

Fuel Cycle Stages	**$/GJ**
Gas extraction	0.759
Local conditioning and pipeline transmission	0.033
LNG production (CO_2 capture)	1.843
LNG shipping	2.444
LNG storage and vaporisation	0.370
NG transmission	0.247
Local storage and filling	3.289
Upstream Total	***8.985***
Use in vehicle*	-
Total for cycle	**8.985**

* The cost of the vehicle has not been included in the calculations, as discussed in the previous section.

Table 13 Total Costs from Fuel Cycle

Fuel Cycle	**GJ/km**	**$/km**
LNG production with CO_2 capture	9.152	0.0204
LNG production without CO_2 capture	8.985	0.0201
LNG production with CO_2 capture (improved vehicle)	9.152	0.0197

5. Specification of the Gasoline Fuel Cycle

A gasoline fuel cycle was chosen as the main benchmark against which to compare the cost and emissions performance of the F-T diesel and LNG fuel cycles.

5.1 REFINING AND PRODUCT FINISHING

The cost of gasoline from the refinery was calculated from 1999 IEA energy price data (IEA, 1999) and the IEA's projected crude oil price for 2010 (IEA, 2000). The gasoline cost was calculated from the 2010 crude cost using a linear regression to relate the average import price of Iranian light crude oil (Jan-Nov 1999) and the average price of gasoline from a NW Europe refinery (Jan-Nov 1999).

The cost estimates were then adjusted to allow for the extra desulphurisation to 'zero sulphur fuel' (10 ppm maximum sulphur content), which will be needed to meet proposed EU fuel standards. Estimates of the additional cost of desulphurisation in gasoline and diesel refining are available from a study carried out for the EU by Purvin and Gertz (P&G, 2000). The total annual cost was calculated from an average of the Purvin & Gertz capital and operating cost data for the northern refineries high and low cost scenarios, assuming a plant lifetime of 15 years.

This approach yielded a desulphurisation cost estimated of 0.036$/GJ and a total cost of production of 5.48$/GJ for 2010.

For the US sensitivity study, the same methodology was used, but based on data for the average price of gasoline from a US refinery.

5.2 GASOLINE DISTRIBUTION, LOCAL STORAGE AND VEHICULAR FILLING

The total cost of gasoline distribution to the filling stations, storage and filling was calculated from 1999 IEA energy price data (IEA, 1999) for the average price of gasoline from a NW Europe refinery (Jan-Nov 1999), and the average 1999 gasoline ex-tax price in the UK.

This yielded a distribution and storage cost of 1.67$/GJ in 1999 and this was assumed to remain the same for 2010.

For the US sensitivity study the appropriate US data was used.

5.3 USE IN 2010 COMPRESSION IGNITION CAR, $/KM

For comparative purposes three gasoline cars were considered:

- Standard 2010 specification car
- Current specification hybrid car (spark ignition engine plus electric drive)
- Enhanced specification hybrid car

The cost of fuel used (in $/km) is calculated from the input fuel price and the vehicles energy efficiencies in GJ/km, which were taken to be 0.00215, 0.00162 and 0.00147 GJ/km respectively.

This gave car travel costs of 0.0154$/km for the advanced car, 0.0116$/km for the hybrid car and 0.0105$/km for the enhanced hybrid car.

The cost of the vehicle has not been included in these calculations because it has been assumed to be the same for all fuel cycles. This is considered to be a reasonable assumption because a fleet of 1 million vehicles (the fleet size assumed in all fuel cycles) should be sufficient to yield economies of volume production.

5.4 TOTAL COSTS FROM THE GASOLINE FUEL CYCLE

Total costs from the gasoline fuel cycle (i.e. taking account of the cumulative efficiency of each stage) are shown in Table 14. The overall energy efficiency of the cycle is 86.5%. Costs per km driven are shown in Table 15.

Table 14 Total Costs over all of Fuel Cycle per GJ energy delivered at pump (gasoline)

Fuel Cycle Stages	**$/GJ**
Crude Oil Import Price [Oil extraction & Crude oil shipping]	4.081
Price at pump [Refining & Distribution]	3.072
Upstream Total	***7.153***
Use in vehicle*	-
Total for cycle	**7.153**

* The cost of the vehicle has not been included in the calculations, as discussed in the previous section.

Table 15 Total Costs from Fuel Cycle as $ per km

Fuel Cycle	$/km
spark ignition	0.0154
Hybrid	0.0116
Improved hybrid	0.0105

6. Diesel Fuel Cycle

To attain a more complete comparison of the F-T fuel cycle an additional benchmark was developed based on the use of standard diesel. The analysis of costs for 2010 followed the same method as for the gasoline fuel cycle:

- Refinery and product finishing costs were estimated to be 4.48$/GJ in 1999.
- Distribution, local storage and vehicle filling were estimated to be 2.28$/GJ in 1999.

Diesel fuel was assumed to be used in a 2010 specification diesel car having a fuel efficiency of 0.00178GJ/km.

This gave a travel cost of 0.0120$/km.

The cost of the vehicle has not been included in these calculations because it has been assumed to be the same for all fuel cycles. This is considered to be a reasonable assumption because a fleet of 1 million vehicles (the fleet size assumed in all fuel cycles) should be sufficient to yield economies of volume production.

Results are listed in Table 16.

7. Additional Sensitivity Analyses

GASOLINE DISTRIBUTION

A check was made on the sensitivity of gasoline distribution, storage and filling costs to the particular European country used for the analysis. The calculation described above was repeated using equivalent IEA energy price data (IEA, 1999) for:

i) Netherlands
ii) United Kingdom
iii) France

i.e.: The cost was calculated from the average price of gasoline from a NW Europe refinery (Jan-Nov 1999), $/b and the average 1999 gasoline ex-tax price in 1999 Francs or Pounds per litre, as relevant.

7.1 US GASOLINE FUEL CYCLE

To check the effect of centring the gasoline fuel cycle on the US, similar calculations were performed using equivalent IEA price data for the US (IEA, 1999) and the IEA's projected crude oil cost for 2010 (IEA, 2000).

The gasoline cost from the refinery was calculated from the 2010 crude cost using the linear regression equation for the relationship between the average import price of Iranian light crude oil (Jan-Nov 1999) and the average price of gasoline from a US refinery (Jan-Nov 1999). The cost of additional desulphurisation was assumed to be the same as for the European costs in the absence of comparable data.

The distribution cost of gasoline in the US was calculated from the average price of gasoline from an USA refinery (Jan-Nov 1999), $/b and the average 1999 gasoline ex-tax price, 1999$/l.

Table 16: Results of Sensitivity Analysis for Gasoline Distribution

	UK	France	Netherlands	**US**
Ex-refinery gasoline price in 1999, $/GJ	4.39	4.39	4.39	**4.41**
Distribution & fuelling cost in 1999, $/GJ	1.67	1.74	4.94	**2.07**
Ex-tax price at pump in 1999, $/GJ	6.06	6.13	9.33	**6.48**
Cost of additional desulphurisation, $/GJ	0.036	0.036	0.036	**0.036**
Ex-tax price at the pump in 2010, $/GJ	7.156	7.226	10.426	**7.50**

8. Conversion Factors

AREA	Convert from:	To:	Multiply by:
Crude Oil	bbl	tonne	0.136
	bbl	ton	0.15
	tonne	bbl	7.33
	ton	bbl	6.65
	tonne	ton	1.102
	ton	tonne	0.907
	lb.	kg	0.4550
	kg	lb.	2.198
Liquids	bbl	m3	0.159
	bbl	gallon (US)	42
	bbl	Imperial gallon	35
	bbl	L	159
	Imperial gallon	gallon (US)	1.201
	gallon (US)	Imperial gallon	0.8326
	m3	bbl	6.29
	L	bbl	0.00629
	Imperial gallon	L	4.546
	gallon (US)	L	3.785
Gases	cf (=ft3)	m3	0.0283
	m3	cf	35.3
Energy	toe	GJ	41.87
	GJ	toe	0.0239
	kWh	GJ	0.0036
	GJ	kWh	277.8
	therm	GJ	0.1055
	GJ	therm	9.478
	Btu	GJ	1.054E-06
	GJ	Btu	948767
Distance	mi	km	1.6093
	km	mi	0.6214
	nautical mi (nmi)	km	1.8520
	km	nautical mi (nmi)	0.5400
	ft	m	0.3048
	m	ft	3.281
	in	mm	25.4
	mm	in	0.03937

AREA	Convert from:	To:	Multiply by:
Flow	Mmcf/d	Gm3/a	0.01033
	Gm3/a	Mmcf/d	96.810
Speed	knots	nmi/h	1
	nmi/h	km/h	1.852
Other	$MMBtu/1000km	$/(kWh.1000km)	0.00341
	$/(kWh.1000km)	$MMBtu/1000km	293.255
Currency	2000£	2000$	1.53
	1990$	2000$	1.233
	1992$	2000$	1.165
	1994$	2000$	1.114
	1995$	2000$	1.090
	1996$	2000$	1.070
	1999$	2000$	1.021
	1999£	1999$	1.529
	1992£	1992$	1.538
	1999Francs	1999$	0.151
	1999Guilders	1999$	0.503

9. Fuel Conversions

Energy content **Carbon Emission factors**

ID		Gross CV, GJ/tonne	Net CV, GJ/tonne	L/tonne*	Net CV, GJ/L	toe/L	kgC/toe	% Mass Carbon	tonnesC/TJ	tonnes CO_2/TJ
1	Gasoline	47.4	43.5	1354	0.0321	0.000767	791	82.2%	18.892	69.3
2	Diesel	45.8	42.8	1202	0.0356	0.000850	846	86.5%	20.205	74.1
3	Hydrogen	141.9	120.0	12500000	0.0000096	0.000000229	0	0.0%	0.000	0.0
4	NG	53.1	48.0	1492537	0.000032	0.000000768	652	74.7%	15.561	57.1
5	LNG	53.1	48.0	2210	0.0217	0.000519	652	74.7%	15.561	57.1
6	CNG	53.1	48.0				652	74.7%	15.561	57.1
7	Biodiesel	41.22	37.8	1111	0.0340	0.000813	853	77.0%	20.370	74.7
8	Ethanol	30.0	26.68	1267	0.0211	0.000503	819	52.2%	19.565	71.7
9	Methanol		19.95	1263	0.0158	0.000377	787	37.5%	18.797	68.9
10	Kerosene	46.3	43.3	1249	0.0347	0.000828	832	86.0%	19.861	72.8
11	LPG	48.8	46.1	1746	0.0264	0.000631	752	82.8%	17.961	65.9
12	Electricity	N/A		N/A			1842		43.993	161.3
13	F-T Diesel	47.1	43.9	1275	0.0344	0.000822	810	84.9%	19.351	71.0
14	Naphtha	47.7	45.01	1448	0.0311	0.000742		83.2%	0.000	0.0
15	NG feed to F-T/LNG plant		48.8	1492537	0.0000	0.000000781	638	74.42%	15.247	55.9
16	Crude Oil	45.6	41.868	1168	0.0358	0.000856			0.000	0.0
17	HFO	43.1		1011	0.0000	0.000000			0.000	0.0

*Values for gases are for uncompressed fuel at room temperature.