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A Comparison of Life-Cycle Emissions of Liquid Biofuels and Liquid and Gaseous Fossil Fuels in the Transport Sector

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Abstract

It has been claimed that the use of transport fuels such as compressed natural gas (CNG) and liquefied petroleum gas (LPG) leads to reduced greenhouse gas emissions compared to the conventional petroleum transport fuels, motor spirit and automotive diesel fuel. While it is certainly true that the 'tailpipe' greenhouse gas emissions during combustion of CNG and LPG are lower per km travelled than those of motor spirit and diesel, on a full 'well to wheel' life-cycle analysis there is little if any difference due to the high processing overheads involved in the production of CNG and LPG. If the fugitive emissions that may occur during CNG and LPG production, transmission and use are also taken into account, then their total greenhouse gas emissions per GJ or per km travelled may actually be considerably higher than those of motor spirit and diesel.

On the other hand, the use of biofuels such as triglyceride esters and ethanol may lead to lower life-cycle greenhouse gas emissions. This paper examines some of the issues relating to the life-cycle emissions of various petroleum fuels, gaseous fuels and biofuels and provides a brief review of recent research in this area.

1. Introduction

In order to address Australia's rising greenhouse gas emissions (GHGE), it has been proposed that the use of alternative fuels such as liquefied natural gas (LNG), compressed natural gas (CNG) and liquefied petroleum gas (LPG) as replacements for 'traditional' transport liquid fuels such as motor spirit and diesel can lead to significant reductions in GHGE from the transport sector.

For example, the Australian Greenhouse Office (AGO) has actively promoted the use of CNG as a transport fuel. It has released promotional information including a brochure entitled *The Compressed Natural Gas Infrastructure Program* in which it is claimed that "Vehicles running on CNG produce far less pollution than petrol and diesel fuelled vehicles, with research indicating that a reduction of up to 50 per cent in greenhouse gas emissions is possible." (AGO, 1999a) The claim is repeated in the AGO's *CNG Facts Sheet* which states "Study results indicate that CNG as a transport fuel produces far lower greenhouse gas emissions than conventional fuels." (AGO, 1999b)

As a result of these claims, the Australian Federal Government has provided funds (via the AGO) for the conversion of certain classes of vehicles to operate on 'alternative' fuels such as CNG.

However other research has shown that while tailpipe emissions of a CNG or LPG vehicle may be lower per kilometre than from the same vehicle using motor spirit or diesel, on a life-cycle assessment this may not be the case. (Sheehan et al, 1998; Beer et al, 2000)

The AGO *CNG Fact Sheet* also states that "An environmental life cycle study of city buses comparing diesel and CNG has found carbon dioxide emissions, the main greenhouse gas, are reduced by 9 per cent". However there is considerable concern that this study, and others, have ignored various aspects of the full life-cycle analysis such as fugitive gas emissions which has resulted in a misconception as to the GHG mitigation benefits arising from the use of CNG, LNG and LPG for transport fuels.

2. Properties of Various Liquid and Gaseous Transport Fuels

Almost all fuels suitable for traditional transport vehicles are compounds containing predominantly carbon and hydrogen. In the case of fossil derived fuels, the only other constituent elements, such as nitrogen and sulphur, are generally regarded as undesirable contaminants (Environment Australia, 2000a). Compounds such as tetraethyl lead have been added in the past to modify fuel properties so as to reduce the tendency of the fuel to 'knock' while others such as nitromethane have been added to speciality fuels to improve power output (Environment Australia, 2000b; Hamilton, 2000).

Biofuels differ chemically from fossil based fuels in that they usually contain oxygen in addition to carbon and hydrogen. Like fossil fuels, they may also contain other elements, notably nitrogen, which are also regarded as undesirable impurities (Environment Australia, 2000b; Sheehan et al, 1998).

In most cases fuels consist of a mixture of compounds which varies not only with the source but also with the time of year. For example winter formulations of motor spirit tend to have a higher proportion of the more volatile components than do summer formulations to assist in easier vehicle starting in cold conditions. Likewise summer formulations are less volatile than winter formulations to retard evaporative loss and vapour lock (Environment Australia, 2000b; Hamilton, 2000).

Due to the variable nature of motor spirit and diesel, they are specified not by a specific or 'average' chemical formula but by physical and bulk chemical properties. A sample of petrol or diesel may contain as many as 500 compounds, of which perhaps 10 – 20 will comprise 60% – 80% of the total. The major parameters by which motor spirit and diesel are characterised are the octane and cetane numbers respectively.

The ***octane number*** is the resistance of the fuel's unburnt end gases to spontaneously ignite under specified test conditions. The two reference points are straight chain heptane (C_7H_{16}) which is given a rating of 0, and 2,2,4-trimethyl pentane (C_8H_{18}), also called iso-octane, which is given a reference number of 100. These two were chosen as standards since they have many similar chemical and physical properties. A fuel which behaves similarly to, for example, a mixture of 8% heptane and 92% iso-octane is thus given a Research Octane Number (RON) of 92 (Hamilton, 2000).

The ***cetane number*** is used to compare fuels used in compression ignition engines in a somewhat similar manner to the octane number is for spark ignition engines. It is a measure of the auto-ignition quality and relates to the time delay between when the fuel is injected into the cylinder and when ignition occurs. The cetane rating can influence cold startability, exhaust emissions and combustion noise. A fuel with a cetane number of 50 or more is considered 'fast' burning while 'slow' fuels have a cetane number of 40 or less. Higher cetane numbers imply more thorough combustion and thus higher efficiency and lower particulate emissions (Environment Australia, 2000a).

Other specified fuel parameters include volatility, vapour pressure, density, and the levels of polyaromatic hydrocarbons, sulphur, lead, oxygen, olefins, aromatics and benzene. Any fuel which falls within the fuel range specified for a certain engine should be suitable, regardless of its actual chemical composition since many years of experience have gone into developing the fuels to match the engines and developing the engines to match the fuels.

The fuels examined in this paper include the following.

Motor spirit is used in spark ignition engines and is available in a number of grades. For example, the recommended characteristics of Australian unleaded petrol (ULP), as of 1 January 2002 will be:

- Research Octane Number (RON) ≥ 91;
- vapour pressure ≤ 70 kPa;
- olefins $\leq 18\%$, aromatics $\leq 45\%$, benzene $\leq 3\%$, oxygen $\leq 2.7\%$ by mass and a boiling range from 27° to 250°C (Environment Australia, 2000a, 2000b).

Diesel fuel is usually used in compression ignition engines and the specifying parameters include a cetane number or index. A 'good' automotive diesel may have the following properties:

- Cetane Number = 47;
- sulphur ≤ 500 ppm (currently sulphur content in Australia sometimes exceeds 2200 ppm);

- density 820 - 860 kgm^{-3};
- viscosity 2.0 to 4.5 cSt; and
- a boiling range of 185° to 385°C (Environment Australia, 2000a, 2000b).

Liquefied Petroleum Gas may contain butane, propane, ethane, propylene and other gases although automotive LPG is usually a mixture of 60 – 70% propane and 40 – 30% butane with only small percentages of the other gases. LPG is a by-product of crude oil refining and natural gas extraction. It liquefies under pressures of ~800 kPa and can be stored in this form in inexpensive steel cylinders. As LPG has a RON of between 100 – 104 it can be used in spark ignition engines with only relatively simple modifications and retuning (Anyon, 1998). A number of vehicle manufacturers offer models with LPG fuel systems fitted as standard (AGO, 2000a). The cetane number of LPG is too low for it to be used as a single fuel in compression ignition engines without significant engine modifications as discussed further in Section 4.

Natural Gas in Australia contains methane (78% - 92%), ethane (2 – 10%) and propane, butane, pentane, CO_2 and helium in smaller percentages (AGO, 2000b). Natural gas (NG) can be liquefied (LNG) when chilled to less than -161° C or compressed into CNG to ~21 MPa and stored in steel or composite tanks. NG, LNG and CNG can be used in slightly modified spark ignition engines or in more modified compression ignition engines as can LPG (Anyon, 1998).

Methanol is the alcohol of methane, formerly called wood alcohol as it was historically made from the pyrolysis of wood. Now it is usually made from natural gas feedstock where surplus to other demands and thus is really a fossil fuel. It is also technically feasible to produce it from synthesis gas (CO and H_2) resulting from gasifying biomass.

Power ethanol is a relatively pure compound made from the yeast fermentation of sugars or starches or the acid hydrolysis of cellulitic matter and bacterial fermentation. Typically it contains 5% water and other trace impurities and has an octane number of 105 – 120 depending on whether it is used neat, requiring some engine modification and retuning, or as a blend with other fuels. Blended with motor spirit at up to 15% to form gasohol as in the USA, it can be used without engine modifications. It can also be emulsified with diesel to form diesohol and used in unmodified compression ignition engines. (One of the authors' (Calais) favourite form of ethanol which can also result in improved performance is Lagavulin 18YO or Glenmorangie 15YO, neat or over a little ice. Wild Turkey Bourbon (8YO) is also quite acceptable. The other author (Sims) prefers NZ Sauvignon Blanc).

Biodiesel is formed by the inter-esterification of animal or plant derived oils or fats using an alcohol such as ethanol or methanol and catalyst. Most natural triglyceride oils are a mixture of 2 to 10 fatty acids. This results in biodiesel being a variable mixture of esters depending on what oil was used as the feed stock. Biodiesel has very similar properties to petroleum-derived diesel fuel and hence can be used either blended with diesel at any proportion or as a 100% replacement. No engine modifications are required, though there may be cold weather problems from phase separation at ambient temperatures below 0^{o}C. Biodiesel made from rapeseed oil and methanol (RME) has a cetane number of ~48 while soy oil derived biodiesel has a cetane number of ~56. Tropical oilseed biodiesels (coconut or palm kernel oil etc) have cetane numbers of over 59 and tallow esters exceed 70 (Beer et al, 2000; Sims, 1996). In some European countries such as Germany and Austria, biodiesel is commonly available from filling stations as a neat fuel and is competitive with diesel as there is no excise tax added. In France, it is mixed with diesel at a ratio of 5% biodiesel to 95% diesel. All major European motor diesel engine manufacturers now extend their warranty for their compression ignition engine vehicles when run on these biofuels (http:/www.biodiesel.de).

3. Greenhouse Gas Emissions of Various Fuels

It is possible to calculate the CO_2 emissions of various fuels by referring to their molecular formulae, carbon-to-hydrogen ratio (C:H), energy density and other factors.

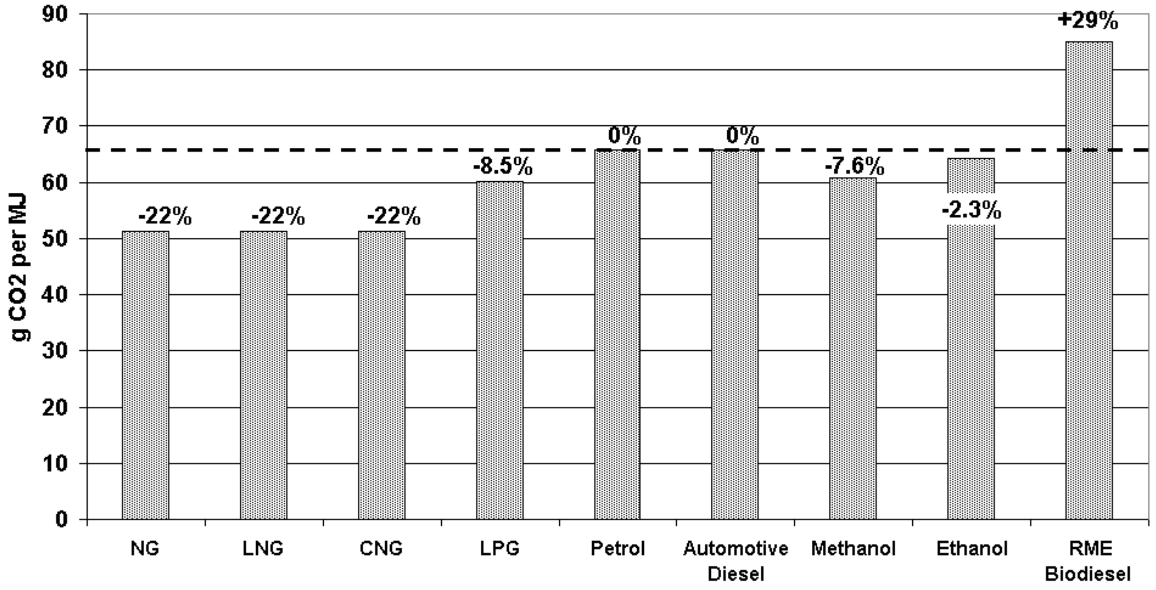
Table 1 lists a number of common fuels with their chemical composition, C:H ratio, energy density and the amount of carbon dioxide emitted during combustion on a stoichiometric basis. It is important to note that most of these fuels are a mixture of variable composition and consequently approximate values only can be given. Figure 1 shows the CO_2 emissions for the various fuels.

Table 1. Approximate compositions and properties for selected transport fossil fuels and biofuels.

Fuel	Approximate average formula	Average molecular weight	Approximate C:H ratio	Energy density MJ/L	Energy density# MJ/m^3	CO$_2$ emissions g/MJ
Natural Gas	~$CH_{3.85}$	18.2	1:3.85		38.2	51.3
LNG	~$CH_{3.85}$	18.2	1:3.85	25.0		51.3
CNG	~$CH_{3.85}$	18.2	1:3.85		38.2	51.3
LPG	~$C_3H_{7.8}$	49	1:2.6	25.7		60.2
Petrol	~$C_{5.4}H_{10.7}$	80	1:2	35.2		65.8
Automotive diesel	~$C_{15.2}H_{22.2}$	212	1:1.9	38.6		65.8
Methanol	CH_3OH	32.04	1:4	15.8		60.8
Ethanol	CH_3CH_2OH	46.07	1:3	23.4		64.3
RME biodiesel	~$C_{13}H_{29}O$	201	1:2.29	33.3		85.0

`Sources: Derived from data given by AGO, 2000; Lide et al, 1999; Anyon, 1998. # Note: at atmospheric pressure and standard temperature.`

Figure 1. CO2 emissions (g/MJ) for various transport fuels and relative difference between fuels (diesel = 100%)



From this data, it appears that the GHGEs from the NG gas based fuels are about 22% less than from an energy equivalent quantity of diesel or motor spirit and similarly the emissions from LPG would be about 8.5% less. These values agree closely with test results from vehicles converted from diesel or motor spirit to CNG or LPG. The value given by McCann (2000) for CNG as compared to diesel was also 22% less. Similarly for a petrol vehicle converted to LPG, Anyon (1998) gave a reduction of 10% while the Australian LPG Association claimed a 15% reduction.

However these values vary considerably with other reference sources such as the AGO which claims that "the use of dedicated vehicles optimised for CNG can lead to a reduction in tailpipe GHGEs of better than 50 per cent compared with petrol" (AGO, 1999b).

In order to explain this discrepancy it is necessary to examine some of the issues relating to the use of vehicle fuels as discussed in the next section.

It is also apparent from Table 1 and Figure 1 that while the methanol and ethanol have slightly lower GHGEs per km travelled than do petrol or diesel, biodiesel has appreciably more emissions than any other fuel. This is mainly due to biodiesel's excess 'baggage' in the form of an oxygen molecule which increases the mass density and decreases the energy density of the fuel. This results in a higher level of greenhouse gas emissions per unit of energy released.

4. Fuel Use in Vehicles

The technology for transport vehicle engines is optimised by the manufacturers for specific fuels such as a particular grade of motor spirit or diesel. Converting to other fuels may require engine modifications. Engine performance may also be affected due to varying properties of the fuels requiring different optimum air:fuel ratio, compression ratio, timing and other factors.

It is not within the scope of this paper to examine these issues in detail, however a brief review of some more important aspects is relevant.

The ***air:fuel volumetric ratio*** affects the quantities of fuel and oxygen that independently enter the combustion chamber which in turn affects both the engine power output and the tailpipe emissions.

Under given conditions of atmospheric pressure, ambient temperature, engine speed etc, a modern vehicle engine designed to operate on petrol inducts air into the combustion chamber (cylinder) and the fuel is injected as a mist either into the inlet manifold or directly into the combustion chamber. When the engine is converted to operate on CNG or LPG, the gas is normally metered into the inlet manifold which has two main effects.

- Since the volume of gas is considerably larger than that of the liquid fuel otherwise injected, it will displace a significant proportion of the air volume and thus reduce the total air:fuel mixture resulting in a significant loss of power.
- Improved mixing of the air:CNG/LPG mixture may lead to a slight improvement in combustion and hence engine efficiency.

The ***compression ratio*** is the ratio of the volume inside the cylinder when the piston is at bottom dead centre divided by the volume when the piston is at top dead centre. In a modern petrol powered engine the range of ratios permitted is determined by the fuel RON and ranges from about 9:1 to 10.5:1. In a diesel engine, the ratio is typically 17:1 to 23:1 as determined by fuel specifications such as the ignition temperature and cetane number.

It is important to note that the thermal efficiency of a reciprocating internal combustion engine is significantly affected by the compression ratio as a higher ratio allows a relatively longer stroke and thus more energy can be extracted from the combustion gases.

The ***octane*** or ***cetane number*** affects the efficiency as higher numbers permit higher compression ratios and thus higher thermal efficiency.

Hamilton (2000) related compression ratio and octane number to efficiency for carburetted spark ignition engines (Table 2).

Table 2. Compression ratios, octane number and thermal efficiency for carburetted spark-ignition engines.

Compression ratio	Minimum octane number	Thermal efficiency
6:1	81	25 %
7:1	87	28 %
8:1	92	30 %
9:1	96	32 %
10:1	100	33 %
11:1	104	34 %
12:1	108	35 %

The development of precise fuel injection and advanced timing methods allows lower grade fuels to be used at higher compression ratios than previously was the case. For example the 2000 Toyota Corolla, using RON 91 fuel, has a compression ratio of 10.5:1 and not 8:1 as might be expected from Table 2.

As the octane number of LPG is ~100 - 104 (Anyon, 1998), LPG can be used as a petrol replacement in modern vehicles with no major engine modifications (except of course, the addition of LPG storage tanks and fuel metering systems etc). Retuning the engine and possibly advancing the timing is all that is needed. Natural gas, on the other hand, may have an octane rating too high for use in an unmodified petrol engine and hence would ideally require an increase in compression ratio. This will lead to a significantly higher thermal efficiency and thus either a petrol engine fully modified or a purpose built "dedicated" LPG or CNG engine with a high compression ratio will be able to take full advantage of the fuel's higher octane rating. This would result in the higher reductions in emissions that are claimed by the AGO.

In the case of using LPG or CNG as a diesel replacement, a difficulty arises as both have a low cetane number and thus their auto-ignition temperatures are considerably higher that that of diesel. To achieve ignition temperatures, the compression ratio must be increased to impractically high levels (~25:1). To overcome this it is necessary to convert the engine to spark ignition which also requires decreasing the compression ratio to ~13:1, hence also reducing the thermal efficiency and increasing the greenhouse emissions as compared to a diesel only system. Alternatively using a relatively complicated 'dual-fuel' system in which a small quantity of diesel (~15% of the total fuel blend by volume) is injected into the cylinder to act as a source of ignition for the LPG or CNG. In this way the benefits of improved efficiency and reduced emissions from the higher compression ratios can be captured while using LPG or CNG.

In the cases of methanol and ethanol as a petrol replacement, their higher octane numbers (106 – 115 and 105 – 122 respectively) can lead to a similar situation as with LPG and CNG. However they have the advantage, as previously mentioned, that they can be mixed with petrol or emulsified with diesel at up to ~15% by mass and used without any engine modifications.

As noted above, biodiesel can be used in compression ignition engines without any modification and is completely miscible with diesel. (Beer, 2000; Sheehan, 1998)

So far this discussion has centred on the assumption that all road vehicles use, and will continue to use the conventional internal combustion engine drive-train. This may not be strictly correct as semi-mass produced electric vehicles, which have been available in Europe since the early 1980s, and mass produced hybrid internal combustion/electric vehicles, which have been available in Japan since 1997, have significantly different characteristics to conventional vehicles. (Calais, 1999b)

The use of hybrid systems allows considerably lower GHGEs per km travelled as compared to conventional transport systems due to their higher overall efficiency while any reductions available from 'pure' electric vehicles depends on the electricity generation mix. Current results suggest that there is little difference in GHGEs between electric vehicles using coal derived electricity and conventional internal combustion engine powered vehicles (Bernreuter, 2000). The use of NG as a coal substitute for electricity generation in combination with electric vehicles would, however, almost certainly lead to GHGE reductions.

5. 'Well to Wheel' Greenhouse Gas Emissions of various fuels

Simple calculations of the GHGE of fuels on the basis of their C:H ratio is rather naïve as it fails to factor in changes in engine efficiency resulting from the variable composition and properties of the fuels and the manner in which they are used. It also does not take into account that ethanol, biodiesel and in some cases, methanol, are derived from renewable biomass resources and thus form a part of the closed carbon loop in which CO_2 is taken from the atmosphere during photosynthesis and then released again upon combustion.

For a true comparison it is necessary to take into account the overheads involved in the fuel extraction, production and delivery – the so-called 'well to wheel' scenario – to compare the complete energy and emission life-cycles of the fuels.

Sheehan et al's (1998) study in which the energy and emission life-cycles of petroleum-based diesel and soy-methyl ester biodiesel (SME) were compared highlighted this and other authors have also contributed including Beer et al, (2000) see Table 3.

Table 3. Full fuel-cycle CO_2 emissions for a range of transport fuels– gCO_2/MJ.

Process	Diesel	LS[1] diesel	ULS[2] diesel	LPG	CNG	LNG	E95[3]	BD20[4]	BD100[5]
Fuel production	11	12	13	11	6	9	-29	2	-41
Combustion	69	69	69	69	54	55	65	73	89
Total	**80**	**81**	**82**	**80**	**60**	**64**	**36**	**75**	**48**
Reduction in emissions cf. stnd diesel (%)	**0**	**+1.25**	**+2.5**	**0**	**-25**	**-20**	**-55**	**6.25**	**-40**

Source:Beer et al, 2000; Sheehan et al, 1998. Note: [1] LS diesel = low sulphur diesel; [2] ULS diesel = ultra low sulphur diesel; [3] E95 =hydrated ethanol (95% ethanol, 5% water); [4] BD20 =80% diesel/20% biodiesel; [5] BD100 =100% biodiesel.

On this basis it can be seen that reductions in GHGEs per MJ result from substituting CNG and LNG for diesel. The reductions are even more apparent where biofuels are utilised while for LSD and ULSD there is a small penalty due to higher production overheads. However there are other factors that also need to be considered and these are discussed in Section 7.

6. Life-Cycle Energy Analysis

As well as examining the life-cycle emission of GHGEs, it is also important to analyse the life-cycle aspects of the energy used in producing the final fuel as claims have been made that the energy inputs for biofuel production can be greater than the net energy output. (AGO, 1999c)

Sheehan et al (1998), when comparing the life-cycle energy consumption of petroleum diesel with SME biodiesel in the United States, found that using current petroleum extraction and refining techniques to produce 1 MJ of diesel required 1.2007 MJ of diesel equivalent of primary energy input, giving a life cycle energy efficiency of only 83.28% (Table 4 and Figure 2).

Table 4 Primary energy inputs in terms of litres of diesel equivalent for petroleum diesel production in the USA

Stage	Primary Energy Input (MJ/MJ)	Percent Input
Domestic (US) crude oil production	0.5731	47.73%
Foreign crude oil production	0.5400	44.97%
Domestic crude oil transport	0.0033	0.28%
Foreign crude oil transport	0.0131	1.09%
Crude oil refining	0.0650	5.41%
Diesel fuel transport	0.0063	0.52%
Total	**1.2007**	**100%**

Source: Sheenan et al, 1998, pp. 10. Figures based on an weighted average to account for the relative proportions of domestic to imported crude.

While it should be pointed out that these results are location specific to the United States, the values for Australia would probably be similar due to the similarities in the ratio of diesel (or crude) imports to local production and the fuel transport distances (Gunzeleva, 1999).

By comparison Sheehan et al (1998) found that the production of one MJ of SME required only 0.311 MJ of primary (fossil fuel) input (Table 5 and Figure 3). In other words, the biodiesel life cycle produces more than three times the amount of energy that it consumes. It was assumed that the methanol used in the biodiesel production was derived from natural gas. Since this accounts for almost 50% of the fossil fuel input, the use of biomass based methanol or ethanol would significantly reduce the fossil fuel input into this process even further, giving an even higher ratio of biodiesel output to fossil fuel input.

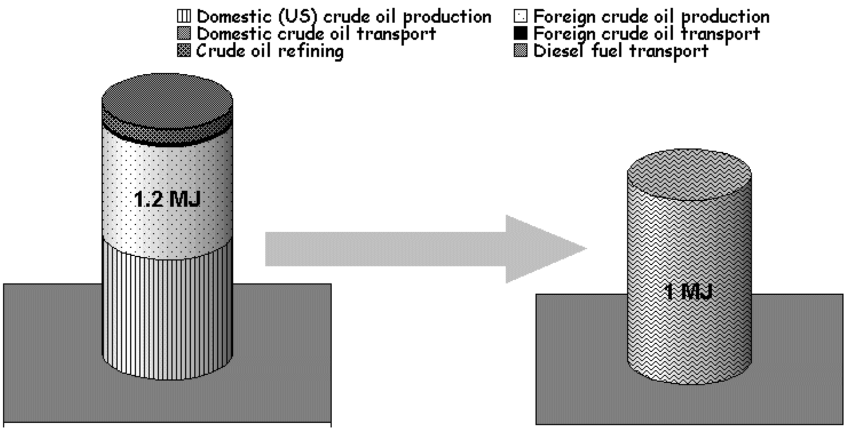
Duke (1983), quoting Harwood, gave the energy net returns from crop growth at 2:1 for soybeans, 5:1 for sunflower, 3:1 for peanuts, and 1:1 for cottonseed. Duke also quoted Goering's 1981 study of the input/output ratios of 11 oilseeds, various legumes, such as peanuts, having a ratio of 2.2:1 while unirrigated soybean was 4.6:1. Some irrigated crops had ratios of less than 1:1.

Table 5. Primary energy inputs in terms of litres of diesel equivalent for soy methyl ester biodiesel production at the commercial scale.

Stage	Fossil Energy Input (MJ/MJ)	Percent
Soybean production	0.0656	21.08%
Soybean transport	0.0034	1.09%
Soybean crushing	0.0796	25.61%
Soy oil transport	0.0072	2.31%
Soy oil conversion	0.1508	48.49%
Biodiesel transport	0.0044	1.41%
Total	**0.3110**	**100.00%**

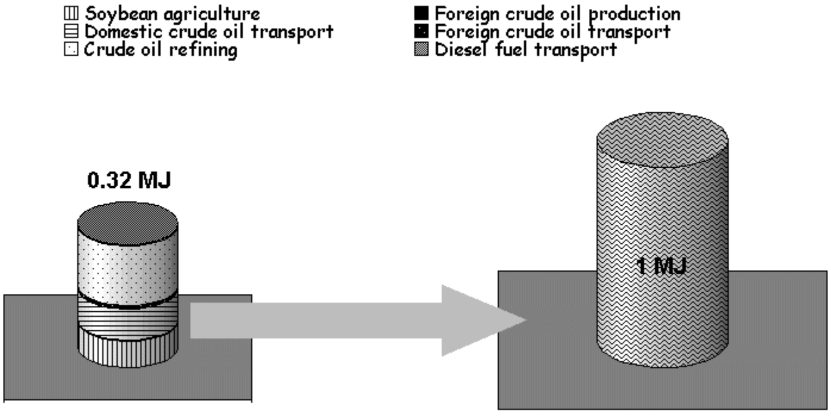
It can be seen that, while biodiesel still has significant fossil fuel inputs, at least under current farming and transport practices, the positive net energy output is significantly higher than the negative net energy output of petroleum diesel production.

Figure 2: Fossil Energy Requirement for the Petroleum Diesel Life Cycle



To make 1 MJ of diesel, 1.2 MJ is needed as the input.

Figure 3: Fossil Energy Requirement for the Biodiesel Life Cycle



To make 1 MJ of biodiesel, 0.32 MJ of diesel or biodiesel needed as the input.

7. Fugitive and Processing Losses of Gaseous Fuels

According to Beer et al (2000) the relative reduction in GHGE between diesel and CNG is 25% (see Table 3). On this basis it would appear that CNG offers relatively good mitigation performance when compared to diesel and petrol. However there is a caveat to this:

> "We have assumed CNG and LNG are compressed using gas. If it is assumed that electricity is used then the life-cycle emission of greenhouse gases from CNG and LNG exceed those of diesel." (Beer et al 2000, pp. xxi,)

Of the CNG compressors currently used in Australia for vehicle refuelling, the majority are electrically operated.

> "Fugitive emissions from filling and servicing of CNG and LNG have been incorporated into the analysis. However, no allowance has been made for possible fugitive emissions as a result of leakage from reticulated gas supplies." (Beer et al 2000, pp. xxi,)

According to various sources (Alinta Gas, 2000; AGO, 2000; Beer et al, 2000) 'unaccounted for gas' from gas transmission and distribution networks amounts to 1 – 3% of the total transmitted.

As Beer et al (2000) and others correctly point out, a large proportion of this gas loss is probably in the form of poor accounting, meter inaccuracies and gas 'theft'. However fugitive emissions from transmission and distribution networks do occur, both in the form of slow leakage (for example, on a still day 300 m down the road from my house it is quite easy to smell a gas leakage) or in the form of high rate, short term leakages as occur when back-hoe operators damage buried pipelines. Leakage also occurs during and after exploratory drilling and this is not normally taken into account during fugitive inventory accounting and analysis.

These fugitive losses may be less than 0.5% of the total gas distributed, but due to the high GHG warming potential of methane (21 times that of CO_2 on a 100 year basis), a 0.5% loss is equivalent to an increase of some 10% in CO_2 emissions. If the 'unaccounted for gas' is indeed all fugitive, then the net increase in CO_2 equivalent GHGE may be as high as 63% above the combustion emissions.

Additional fugitive emissions occur in the form of CO_2 vented at the well head or during processing. For example, Cooper Basin NG contains as much as 35% CO_2 and this is vented during processing to the atmosphere, hence adding to the total life-cycle GHGEs (Beer et al, 2000; AGO, 2000). Fugitive emissions and processing losses also increase the total life-cycle emissions of LPG, although to a lesser extent than for CNG as less energy is required to liquefy LPG than is required to compress NG.

When all these additional factors are taken into account, the actual levels of greenhouse gas emissions from CNG and LPG use are considerably higher than the greenhouse gas emissions from diesel or motor spirit. This was confirmed by Beer et al (2000, pp. 60,) who mentioned one study that gave a life-cycle increase per MJ for CNG of 45% more than the life-cycle CO_2 emissions per MJ of diesel.

8. Other Emissions

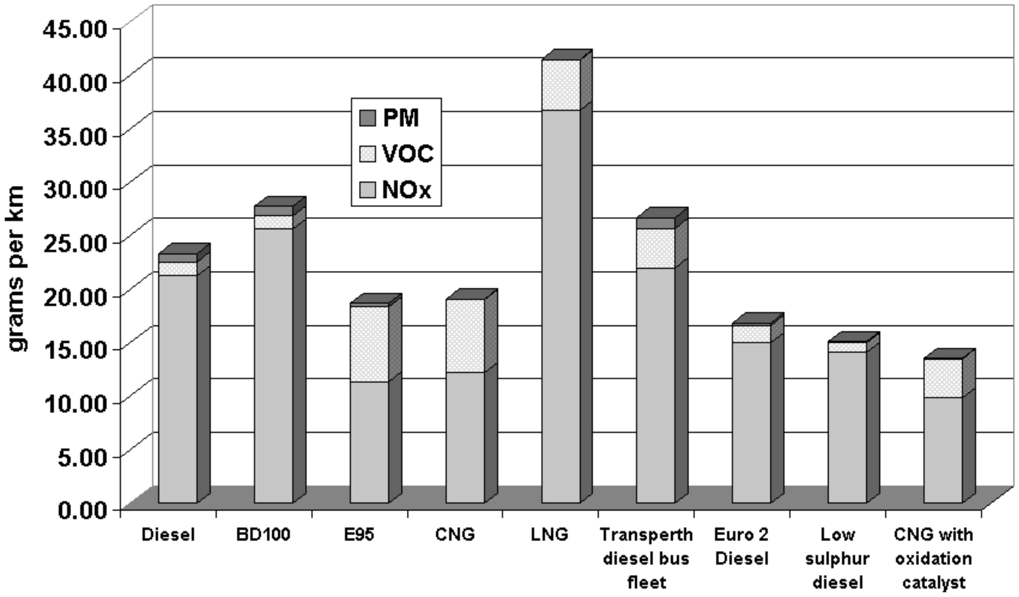
This discussion has focused on the GHGE of several fuels and has suggested that the use of CNG, LNG and LPG can actually lead to a net increase in greenhouse gas emissions over the standard use of automotive diesel and petrol. However these emissions are only one aspect of the total emissions and other emissions and pollutants such as PM (particulate matter), NOx and VOC (volatile organic compounds) should be considered (Figure 4). These emissions are important as many of them have health effects, are precursors to photochemical smog, contribute to acid rain and can cause other environmental problems.

The results of tests conducted on buses show that PM, VOC and NOx emissions vary from fuel to fuel by a factor of 3.7 for NOx (9.9 g/km for CNG and 36.7 g/km for LNG); of 8.0 for VOC (0.87g/km for LSD and 7.02g/km for E95); and of 50.0 for PM (0.02g/km for LNG and CNG and 1.0 g/km for the existing Transperth bus fleet operating on diesel).

The values for biodiesel (BD100) and diesel are similar with specific emissions being slightly higher or lower. The major exception (not shown) is that biodiesel, and also E95, are naturally very low in sulphur and thus have sulphur emissions several orders of magnitude lower than the equivalent fossil fuels (Beer et al, 2000; Sheehan et al, 1998).

The pollutant of perhaps the most concern is that of PM as it is known to cause respiratory disease and is a carcinogen (Beer et al, 2000; Sheehan et al, 1998). Particulates form due to the incomplete combustion of the fuel and this is caused by a number of factors which includes the quenching of the flame front by the colder cylinder walls and poor injector design and maintenance resulting in fuel 'dribble' into the combustion chamber at inappropriate times during the cycle.

Figure 4: emissions of PM, VOC and NOx from various fuels.



Source: Beer et al, 2000.

Particulates and other pollutants may not be such a problem in the future as it is proposed that the increasingly strict Euro 1, 2, 3 and 4 emissions standards will be introduced in Australia over the next 8 years. If enforced, this will drastically reduce the levels of PM, NOx, CO and NMHC/VOC for diesel (and biodiesel) vehicles to levels lower than those for vehicles currently using CNG or LPG (Environment Australia, 2000b).

9. Conclusion

The use of LPG and NG as transport fuels has been promoted as a part of the solution to reduce Australia's greenhouse gas emissions. However the conversion of vehicles from conventional transport fuels may not provide the expected reductions unless extensive engine modifications are made or new engines optimised for these fuels become available. Even then, on a full life-cycle assessment of LPG and NG as transport fuels, there may be little improvement over the conventional liquid fuels due to the high processing overheads and fugitive emissions. This may actually lead to an increase in greenhouse gas emissions per km travelled.

In the short to medium term however, these fuels do have other benefits as transport fuels including significantly lower emissions of particulates. Not examined in this paper was the use of LPG and NG as replacements for fossil fuels for other uses such as coal for electricity generation. It can probably be shown in this case that the replacement of coal with the gaseous fuels does indeed lead to significant reductions in life-cycle greenhouse gas emissions. Consequently the use of electric vehicles using NG/LPG-derived electricity or hybrid vehicles using on-board generation with fuel cells or optimised internal combustion engines may be the only way that NG and LPG can effect real reductions in greenhouse gas emissions over conventional transport methodologies.

Life-cycle assessments of the transport biofuels ethanol and biodiesel suggest that use of these fuels instead of automotive diesel or motor spirit do lead to significant reductions in greenhouse gas emissions. Ethanol can be used as a blend with motor spirit or as an emulsion with diesel at up to 15%

with no engine modifications. It can also be used as a neat fuel in spark ignition engines with minor modifications, although as with LPG and CNG, in order to obtain the maximum gains from the fuel, more extensive modifications or use of new optimised and dedicated engines are required. In the case of biodiesel, it is completely miscible with diesel and can be added in any proportion or used as a complete replacement fuel requiring no engine modifications.

The promotion of NG and LPG fuels as replacement transport fuels may not only lead to increased greenhouse gas emissions but also set Australia on a tangent away from fuels such as ethanol and biodiesel that do return emission reductions.

Conversion of the vehicle fleet to gaseous fuels will not reduce Australia's GHGE significantly. In the longer term the use of biofuels will be the better solution if the additional costs can be warranted.

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