

8. Compressed Natural Gas

8.1 *Background*

Natural gas (NG) is a mixture of hydrocarbons, mainly methane (CH₄), and is produced either from gas wells or in conjunction with crude oil production. The composition of natural gas used in Melbourne in 1997/98 was 91.6 percent methane, 5.0 percent ethane, 0.4 percent propane, 0.1 percent butane, 0.8 percent nitrogen and oxygen, and 2.1 percent carbon dioxide. Natural gas is consumed in the residential, commercial, industrial, and utility markets.

The interest for natural gas as an alternative fuel stems mainly from its clean burning qualities, its domestic resource base, and its commercial availability to end-users. Because of the gaseous nature of this fuel, it is stored onboard a vehicle in a compressed gaseous state (CNG), though it is also possible to liquefy it and store it in liquid form (LNG).

In Australia, CNG is compressed to around 25 MPa for on-board storage at typically 20 MPa. Refuelling of CNG vehicles is done in the following way. Natural gas is drawn from the distribution network, compressed to 25 MPa and stored in pressure vessels. When a vehicle is being filled and pressure in the storage vessel drops, the compressor draws further gas from the pipeline. The storage vessels are used only to speed up the filling process, not to hold large quantities of compressed gas. In some cases, for example 'slow-fill' refuellers, the pressure vessel stage is bypassed and the compressor compresses gas directly into the cylinder of the vehicle.

8.1.1 *Natural gas production*

Natural gas consumed in Australia is domestically produced. Gas streams produced from reservoirs contain natural gas, liquids and other materials. Processing is required to separate the gas from petroleum liquids and to remove contaminants. First, the gas is separated from free liquids such as crude oil, hydrocarbon condensate, water, and entrained solids. The separated gas is further processed to meet specified requirements. For example, natural gas for transmission companies must generally meet certain pipeline quality specifications with respect to water content, hydrocarbon dewpoint, heating value, and hydrogen-sulfide content. A dehydration plant controls water content; a gas processing plant removes certain hydrocarbon components to hydrocarbon dewpoint specifications; and a gas sweetening plant removes hydrogen sulfide and other sulfur compounds (if present). As raw natural gas is odourless, a chemical odorant (generally sulfur in the form of a mercaptan) is generally added prior to entering the local distribution system to enable expeditious identification of any gas leaks, although some gas is transmitted without odorant.

8.1.2 *Natural gas market*

Natural gas is distributed throughout Australia in pipeline systems (Figure 5.1) that extend from the well-head to the end user.

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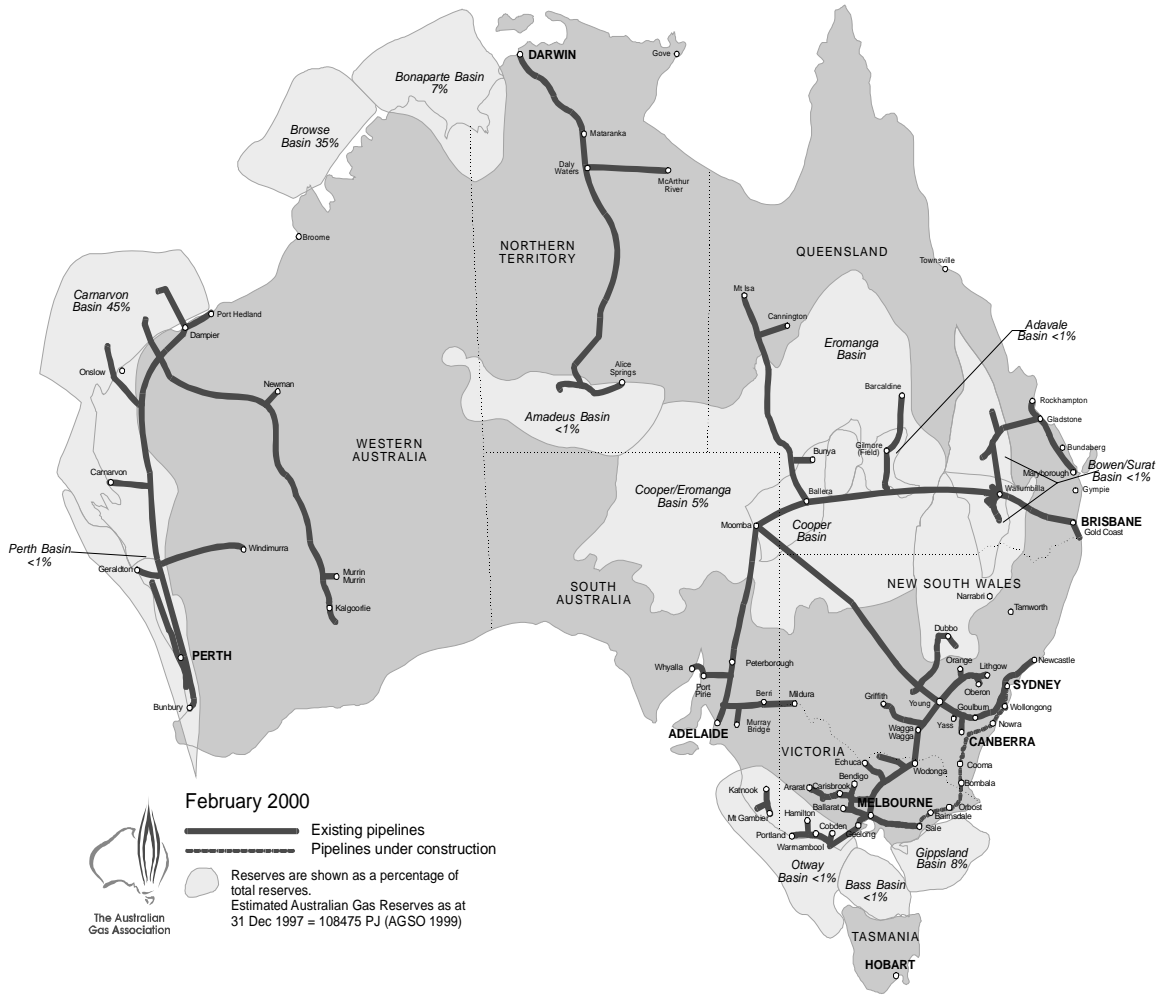


Figure 8.1
Australian gas fields and pipelines

Every mainland State and Territory has access to natural gas through pipelines. The pipeline system consists of long-distance transmission systems, followed by local distribution systems. Some underground storage is also used to help supply seasonal peak needs.

The Australasian Natural Gas Vehicles Council web site in their submission for this study point out that:

Known world reserves of natural gas now constitute over 95% of equivalent oil reserves. In Australia this ratio is more than three times the oil reserve. Proven Australian resources of natural gas currently stand at 109,051 PJ, at existing production levels, this will last 91 years compared to domestic oil reserves which are estimated to last 39 years. Historically, reticulated gas with most of the infrastructure being below ground, has survived most disasters including two world wars. Natural gas is abundant, clean, readily accessible and strategically independent of traditional oil based fuels. The last point is important in that NG is not controlled by a small number of global corporations and cartels and is not reliant on USD exchange rates or world parity pricing.

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8.1.3 Fuel characteristics

Natural gas has very different fuel characteristics from the fuels normally used in internal combustion engines. Its density, at 0.70 g/L is lighter than air. Louis (2001) cites a lower heating value of 52.9 MJ/kg.

The energy content (higher heating value) of CNG varies from 38.8 megajoules per cubic metre at atmospheric pressure in New South Wales and South Australia to 38.5 in Victoria, 37.5 in Western Australia and 41.9 in the Northern Territory (National Greenhouse Inventory Committee, 1998). The average energy content is similar to that of one litre of automotive diesel oil (38.6 megajoules), and about 12 per cent above that of one litre of gasoline (34.2 megajoules) (ABARE, 1991). Pressurised storage of a cubic metre of natural gas as CNG, however, requires a container volume of 4 to 5 litres.

A national fuel standard for CNG is to be developed in 2001-2002 under the *Fuel Quality Standards Act 2000*.

8.1.4 Implications for engine conversions

Because of its characteristics, natural gas can be used in spark ignition engines, but in compression ignition engines a proportion of diesel fuel is usually required to trigger ignition. Alternatively, diesel engines can be converted to spark ignition for natural gas use.

For diesel engines (primarily HDVs in Australia), the conversion to a compression ignition dual (mixed) fuel configuration involves use of a pilot supply of diesel to ignite the natural gas. This requires the addition of a gas fuel system alongside the existing diesel fuel system, together with a mechanism for regulating the proportion of diesel and gas for the engine speed and load conditions. According to the IEA (1993) engine efficiency for this configuration is about the same as that for a diesel engine. BTCE (1994) states that the efficiency of dual (mixed) fuel systems can be equal to or higher than for diesel at high loads, but lower at part loads. For this reason, the overall efficiency in service is lower than for diesel. This chapter deals with single fuel vehicles so that dual fuel vehicles have not been examined. It is to be expected, based on results of LPG dual fuel vehicles, that emissions reductions from dual fuel vehicles will not be as large as those from single fuel vehicles.

Conversion of diesel engines to spark ignition engines running solely on natural gas requires more extensive modification, in that the diesel fuel injectors in the cylinder head will be replaced by spark plugs, and an ignition system added to the engine. A compression ratio lower than that of the diesel is likely to be required. Also, a larger cylinder capacity than that required for a dual (mixed) fuel system may be needed, to provide the same energy content. Though conversions have been the primary source of natural gas engines in Australia to date, increasing availability of OEM engines and vehicles makes conversions less relevant.

8.2 Full Fuel Cycle

Nigge (2000) recently undertook a detailed life cycle assessment of natural gas vehicles in Germany that quantified emissions and health effects.

8.2.1 Tailpipe

The Australasian Natural Gas Vehicle Council (ANGVC) kindly provided emissions data from the latest generation of engines taken from various studies including UK test data on a Scania CNG 113M engine using Mobil CNG (Table 8.1), data from Cummins on their 8.3 litre diesel and C8.3G engine with and without catalyst (Lyford-Pike, 2001) and data from a 9.8 L Transcom

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modified Renault 620-45 natural gas engine (AEC Limited), as well as data from South Australian CNG buses (ANGVC, 2001).

Table 8.1
Scania diesel and CNG test results (g/kWh) in the UK (Andrew, 2001)

	HC	CO	NOx	PM	CO ₂
Diesel	0.864	1.442	7.014	0.373 ¹	756.3
CNG	0.212	0.018	0.962	0.007	674
LNG	0.18	0.017	1.532	0.013	698

Table 8.1 provides results of tests of the present generation of diesel engines (Scania DSC 11-21) as tested at the Millbrook Proving Ground in January 2001 (Andrew, 2001). The drive cycle was not specified. However, as the European Community requires Euro3 standards for heavy vehicles as from January 2000, we expect that both the engines and the test regime corresponded to Euro3. The specific fuel consumption during the test of the CNG vehicle was 190 g/kWh at 1100 to 1800 rpm. The minimum range of the CNG truck was 560 km. The truck achieved a range in excess of 640 km by increasing the CNG pressure from 20 MPa to 25 MPa

Table 8.2 provides results obtained in December 2000 by a Renault engine tested under the European Transient Cycle (ETC), and by Cummins engines tested in November 2000 under the US EPA 99/00 requirements. These are equivalent to ADR 80 and to Euro3 requirements.

Table 8.2
Emissions results (g/kWh) for Renault and Cummins engines

	NMHC	THC	CH ₄	NOx + NMHC	CO	NOx	PM	CO ₂
Transcom modified Renault 620-45 with catalyst	0.003	0.531			0.024	2.432		
Cummins (C8.3G) CNG with catalyst (ULEV)	0.28		6.27	2.33	1.04	2.05	0.01	678
Cummins (C8.3G) CNG without catalyst (LEV)	1.058		6.54	3.63	8.67	2.57	0.034	695
Cummins Diesel (ISC280) with catalyst					0.67	5.36	0.07	700
Cummins Diesel (ISC280) without catalyst					1.21	5.36	0.12	753

By contrast, Table 8.3 gives the emission results of tests on a MAN NL 202 bus with a D0826 LUH, 6.87 litre, turbocharged, intercooled engine, and with a D2866 DUH, 11.97 litre natural gas engine. These engines are on buses that are actually in service at present. The tests were done using the ECE R-49 cycle. The diesel engines were tested with diesel fuel (2000 ppm), low sulfur diesel (500 ppm) and with Euro3 diesel (300 ppm sulfur).

¹ This value is unduly large. Our subsequent calculations are based on the LSD value for PM in Table 8.3.

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Table 8.3
South Australian bus emissions data (g/kWh)

	HC	CO	NOx	PM
Euro 1 Diesel	0.25	0.97	7.8	0.17
Euro 2 Diesel (LSD)	0.13	0.48	6.66	0.10
Euro 3 Diesel	0.04	0.65	4.87	0.08
CNG	0.2	1	1	0.02

One problem with certification procedures based on engine dynamometers is that they may report values that substantially differ from those calculated by chassis dynamometers. The NSW EPA (Brown et al. 1999) also tested Scania 11L Turbo Euro2 technology CNG buses for their performance with, and without, a catalyst. The results are reproduced in Table 8.4.

Table 8.4
Methane and non-methanic hydrocarbon emissions (g/kWh) from CNG buses

		THC	Methane	NMVOC
Without catalyst	Bus #1	2.86	2.64	0.22
Without catalyst	Bus #2	3.37	2.92	0.45
With catalyst	Bus #1	1.88	1.85	0.03
With catalyst	Bus #2	3.02	2.78	0.24

Another source of representative data is given in Table 8.5, which reproduces the emission factors (based on emissions per MJ of fuel use) for heavy vehicles fuelled by natural gas that are given by the National Greenhouse Gas Inventory Committee (1998). Using these default figures typical methane emission are 2.5 g/km and the N₂O emissions for a natural gas-fuelled urban bus are 0.0247 g/km.

Table 8.5
Emission factors (g/MJ) for heavy vehicles fuelled by natural gas

Gas	Emission factor
CO ₂	54.4
CH ₄	0.101
N ₂ O	0.001
NOx	1.2
CO	0.2
NMVOC	0.01

We note that the estimate of tailpipe emissions of 1344 g CO₂/km for a CNG bus that Beer et al. (2000) obtained corresponds to a fuel efficiency of 24.7 MJ/km. As a typical energy content for natural gas is 39 MJ/m³ the results of Beer et al. (2000) were based on an assumed fuel economy of 1.58 km/m³. According to NSW State Transit (Hardy, pers. comm. 2000) the known fuel

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consumption of the CNG buses is 1.6 km/m³. The results of Andrew (2001) that were used in this analysis indicate that the present generation of CNG buses are far more fuel efficient, emitting 595 g CO₂/km, which corresponds to a fuel efficiency of 10.9 MJ/km.

8.2.2 Upstream emissions

As CNG is assumed to be produced from high pressure gas supplies in major cities, standard gas production and transmission processes are used for the upstream emissions of Natural Gas. Added to this are compression processes based on either a gas engine driven CNG compressor, or an electrically driven CNG compressor.

Data on natural gas production have been derived from the National Greenhouse Gas Inventory for 1998 (NGGIC, 2000). This data is presented in Table 8.6.

Table 8.6
Energy use data for oil and gas production and refinery processing

	Fuel	Energy Use Production 1998		Energy use to energy production ratio GJ/PJ produced
		PJ	PJ	
Oil and gas production and field processing	Petroleum	0.9	2528.6	0.36
	Gas	141.1	2528.6	55.80
Natural gas transmission	Gas	8.6	688.5	12.49
Gas production and distribution	Gas	2.4	371.5	6.46

The compression process involves a simple model with natural gas as energy as the main inputs, and CNG as the main output. The energy use is usually quoted in terms of its efficiency compared with the energy value of the gas being compressed. Data on compression are taken from Wang (1999) and are listed in Table 8.7. The emission data for natural gas combustion for compression is taken from standard natural gas combustion data for industrial boilers presented in NGGIC (2000) for greenhouse emissions and in Environment Australia (1999) for air toxics. This data is presented in Table 8.8. The data for electricity combustion are from the same sources for emissions while fuel usage and grid mix are taken from Electricity Supply Association of Australia (2000). Full fuel cycle inputs are presented in Table 8.9 and FFC emissions are presented in Table 8.10 for an average Australian grid mix.

Table 8.7
Energy use in natural gas compression for two fuel scenarios

Fuel	Efficiency	Value in MJ	Comment
Energy from Natural Gas	91.70%	4643	90.5 MJ per 1000MJ Gas (51.3MJ/kg) compressed
Australian Electricity	96.60%	1550	30.2 MJ per 1000MJ Gas (51.3MJ/kg) compressed

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Table 8.8
Air emissions from combustion of 1 MJ of natural gas for process energy

Emissions	Value	Unit	Source
CO ₂	51.19	g	NGGIC, 1997 Standard data Table 1
methane	10.41	mg	NGGIC, 1997 Standard data Table 1
N ₂ O	0.12	mg	NGGIC, 1997 Standard data Table 1
NO _x	220.59	mg	NGGIC, 1997 Standard data Table 1
CO	42.32	mg	NGGIC, 1997 Standard data Table 1
non methane VOC	3.48	mg	NGGIC, 1997 Standard data Table 1
SO _x	0.053	mg	(Environment Australia 1999)
particles	3.078	mg	(Environment Australia 1999)
benzene	0.86	µg	(Environment Australia 1999)
formaldehyde	30.38	µg	(Environment Australia 1999)
n-Hexane	734.18	µg	(Environment Australia 1999)
toluene	1.37	µg	(Environment Australia 1999)
PAHs	0.28	µg	(Environment Australia 1999)
As	0.08	µg	(Environment Australia 1999)
Be	0	µg	(Environment Australia 1999)
Cd	0.46	µg	(Environment Australia 1999)
Chromium	0.56	µg	(Environment Australia 1999)
cobalt	0.03	µg	(Environment Australia 1999)
Copper	0.35	µg	(Environment Australia 1999)
Lead	0.2	µg	(Environment Australia 1999)
manganese	0.15	µg	(Environment Australia 1999)
mercury	0.11	µg	(Environment Australia 1999)
Nickel	0.86	µg	(Environment Australia 1999)
Selenium	0.01	µg	(Environment Australia 1999)
Zn	11.65	µg	(Environment Australia 1999)

Note: these figures are not for a full fuel cycle – energy input to supply gas for combustion are shown in Table 8.6.

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Table 8.9
Fuel inputs for 1 MJ of average Australian electricity

Resources (Inputs from Nature)	
coal 19.5MJ/kg	7.22 g
coal 22.1MJ/kg	28 g
coal 22.6MJ/kg	40 g
crude oil	210 mg
lignite 14.4MJ/kg	4.81 g
lignite 8.2MJ/kg	108 g
natural gas	40.9 mg
pot. energy hydropower	114 kJ

Source: Grant, unpublished data from Life Cycle Inventory Databases

8.2.3 Fugitive emissions

Natural gas can contain significant quantities of naturally occurring CO₂, which in the past has often been vented to the atmosphere at the well-head. Le Cornu (1989) pointed to Cooper Basin gas as having up to 35 per cent by weight (12.7 per cent by volume) of naturally occurring CO₂. On a state by state basis, vented CO₂ accounts for between 3 and 15 per cent of full fuel-cycle CO₂ emissions from natural gas combustion (Wilkenfeld, 1991). In some instances CO₂ recovered from natural gas could be compressed and used in enhanced oil recovery.

Fugitive emissions of methane occur at the wellhead (production), processing, transmission and end user distribution. Our analysis indicates that average emissions at production stage in Australia amount to 2.17 kg per tonne of gas, while processing contributes 5.74 kg per tonne of gas.

Australian long distance high pressure (up to 15 MPa) transmission pipelines are relatively modern (the oldest dates back to 1969) and built to high standards. They are well maintained and accidental leaks are a rarity. It is estimated that at transmission stage fugitive emissions are 0.005% of the total network throughput.

Most gas losses from the distribution systems are by way of leakage from the low pressure network (7 kPa). This includes both the reticulation network and appliances operated by end users. Losses from the distribution network are difficult to estimate as they may occur both upstream and downstream from the meters. It is estimated that emissions from the distribution network, called unaccounted gas, i.e. the difference between the gas issued by the utilities and the gas sold to customers may be as high as 7.5% (NGGIC, 1996). We consider this to be an upper bound to likely fugitive emissions.

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Table 8.10
Air emissions for 1 MJ of average Australian electricity

Emission	Value	Unit	Emission	Value	Unit
acetaldehyde	54.4	µg	Manganese	82.2	pg
antimony	1.69	µg	Methane	332	mg
As	39.4	µg	Methane(sea)	45.7	µg
B	6.47	µg	methyl ethyl ketone	37.5	µg
Ba	115	Ng	Methyl isobutyl ketone	15	µg
Be	2.06	µg	Methyl methacrylate	1.87	µg
benzene	125	µg	Mg	617	µg
benzene sea	69.7	Pg	Mn	47	µg
benzo(a)pyrene	683	Pg	Mo	152	ng
Bi	985	Pg	N ₂ O	2.77	mg
Carbon disulfide	12.2	µg	naphthalene	267	ng
Cd	4.87	µg	n-Hexane	933	ng
Chloroform	5.62	µg	n-hexane (sea)	59	ng
CO	60.4	Mg	Ni	26.3	µg
CO (sea)	5.75	µg	Nickel	1.07	ng
CO ₂	253	G	non methane VOC	7.49	mg
cobalt	16.5	Pg	Non methane VOC (sea)	17.5	µg
Copper	255	Pg	NOx	678	mg
Cr (III)	24.4	µg	NOx (sea)	18.4	µg
Cr (VI)	4.49	µg	o-xylene	9.98	pg
Cu	69.2	Ng	o-xylene (sea)	0.182	pg
cumene	506	Ng	PAH	2.01	µg
CxHy sulfur	4.31	Ng	PAH (sea)	24.7	pg
Cyanide	487	µg	Pb	39.7	µg
cyclohexane	17.2	Ng	pentane	3.13	µg
DEHP	6.94	µg	phenol	1.5	µg
Dibutyl phthalate	5.25	µg	PM10	15.4	mg
Dioxin & Furans	165	Pg	PM10 (sea)	83.1	pg
dust	18.5	Mg	Se	73	µg
ethylbenzene	10.2	µg	Selenium	68.6	pg
ethylbenzene (sea)	0.104	Pg	Soot	57.4	µg
F	14.4	Mg	SOx	1.26	g
formaldehyde	32.5	µg	styrene	2.44	µg
formaldehyde (sea)	2.5	Ng	tetrachloroethylene	4.12	µg
H ₂ S	39.4	Ng	toluene	29.9	µg
HCl	113	Mg	toluene (sea)	122	pg
hexane	6.37	µg	Trichloroethylene	5.81	µg
Hg	4.73	µg	V	902	ng
Lead	316	Pg	xylenes	3.6	µg
Li	65.5	Pg	Zn	123	ng

The values for fugitive emissions used in this study are based on data on fugitive emission from natural gas production and also from the NGGI for 1998. The values are presented in Table 8.11.

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Table 8.11
Fugitive greenhouse emission data for oil and gas production and refinery processing

		Fuel Quantity	CO ₂	CH ₄	N ₂ O	NO _x	CO	NM VOC
		(PJ)	(Gg)	(Gg)	(Gg)	(Gg)	(Gg)	(Gg)
Oil	Exploration (for both oil and gas)	1257	14.8	0.2				0.1
Gas	Production and processing	1272		1.6				1
	Transmission	689		4.9				0.1
	Distribution	372	10.4	171.7				25.5
Venting and flaring for Oil and Gas Production	Venting at Gas processing plant	1272	2814	119.6				42.3
	Distributed Venting	860	749					
	Flaring	2646	2188	26.6	0.1	1.1	6.6	11.4

Source: Fugitive Emissions from Fuels 1B-2 (sheet 1): Oil and Natural Gas

A process tree for CNG production is shown in Figure 8.2 with the methane emission shown in grams as the lower value in each process box. The largest fugitive emission is in the assumed loss in fuel distribution, which is discussed in more detail below.

Methane emissions from vehicles

Methane, the principal component of natural gas, has a greenhouse radiative forcing (GWP) of 21 over a 100-year period. It is therefore important that tailpipe losses of unburnt fuel and fugitive/evaporative losses are minimised.

As methane is a non-reactive hydrocarbon, tailpipe emissions of methane are not as well controlled by catalytic converters. According to Nylund and Lawson (2000: p.46) the sulfur based odorant used in natural gas at very low concentration levels can have a very detrimental effect on the conversion efficiency of oxidation catalysts, bringing their methane conversion down to 30%. When catalysts are optimised for methane, then conversion efficiencies can be as high as 85-90%.

Methane fugitive losses in distribution

Fugitive losses would have the potential to reduce substantially any advantages that natural gas may have in terms of emissions. Gas supply authorities considered that fugitive losses would be less than 2 per cent, and concentrated entirely on the old town-gas reticulation systems. Refuelling depots or retail gas reticulation systems would be serviced by new medium or high pressure lines, and fugitive losses from this form of distribution might be expected to be very low. BTCE (1994) point out that fugitive losses may be exaggerated through a lack of understanding of the term 'unaccounted for gas,' which is the overall accounting error including metering over a vast distribution network.

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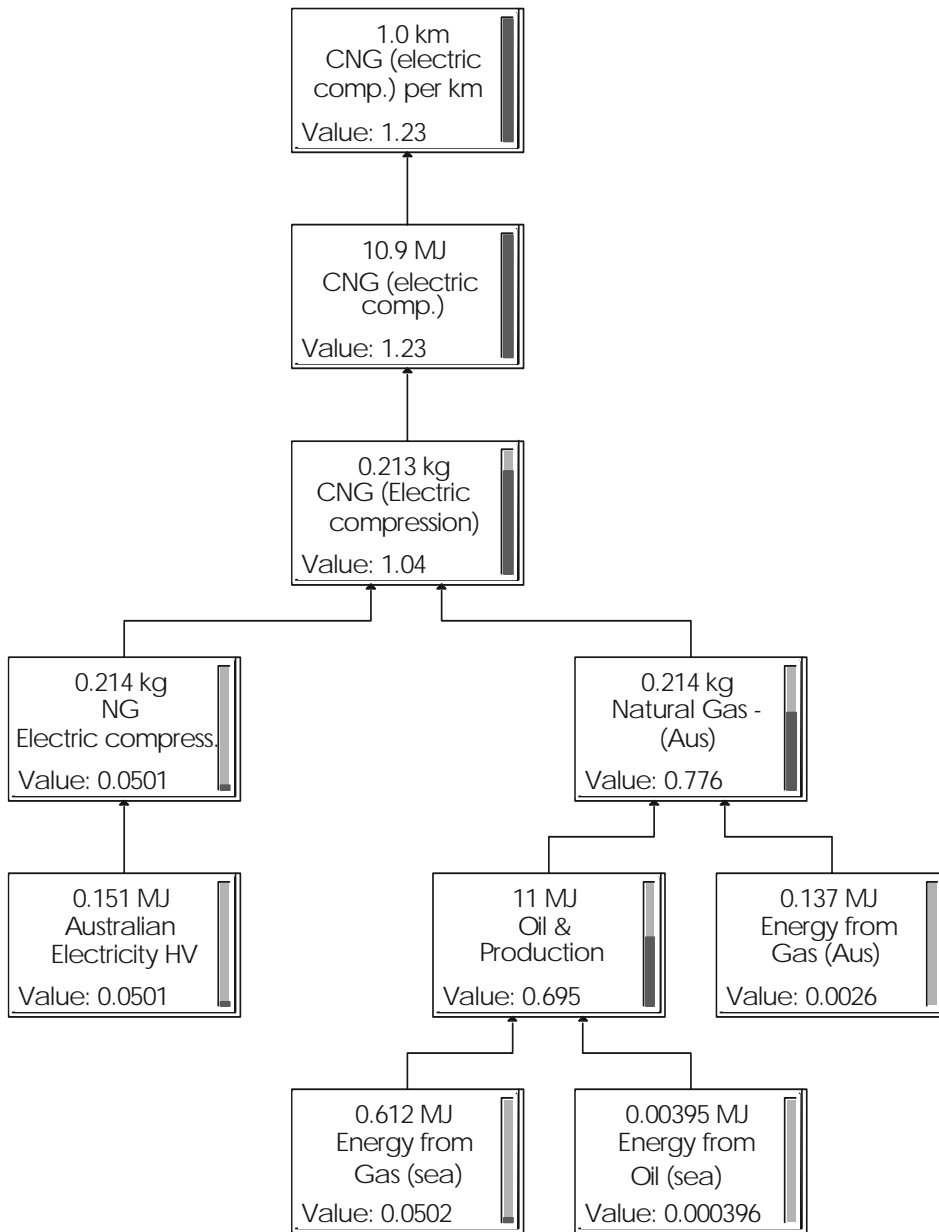


Figure 8.2
Methane emission in grams across CNG life cycle per km truck transport

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(Kadam, 1999) assumes emissions from gas processing plants are 0.1% while the 1998 NGGI claims total distribution losses for low pressure gas supply are 0.25%. In the final modelling, a figure of 0.1% has been used for fugitive emission of methane from CNG facilities – including all operations from the point of gas supply to the facility, up to, but not including, the combustion of the gas on board the vehicle. A sensitivity analysis showing the effect of different levels of fugitive emissions is presented in Figure 8.3. It shows that up to 1% emission the greenhouse gas emission results are still lower than the baseline diesel fuel, though at 10% the full fuel cycle emission is substantially above the diesel baseline. The embodied emissions and the baseline are the same at approximately 4% fugitive emissions.

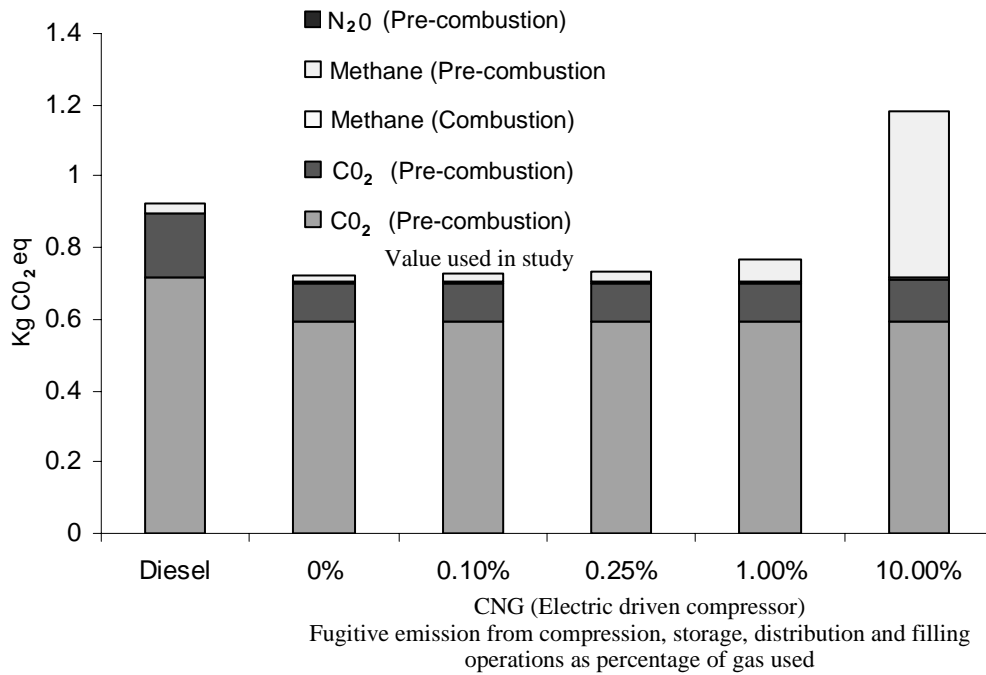


Figure 8.3
Effect of different fugitive emission assumption of full fuel cycle greenhouse emission per km of truck travelled

Two modes of compression were examined: compression using natural gas and compression using electricity.

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8.3 Results

8.3.1 Emission per unit energy

Table 8.12
Urban and rural life cycle emissions calculated for diesel and CNG

Full Lifecycle	Units (per MJ)	LS diesel	CNG (Elec.comp)	CNG (NG comp)
Greenhouse	kg CO ₂	0.0858	0.0665	0.0683
NMHC total	g HC	0.140	0.027	0.029
NMHC urban	g HC	0.111	0.003	0.003
NOx total	g NOx	1.044	0.140	0.152
NOx urban	g NOx	0.987	0.126	0.137
CO total	g CO	0.253	0.011	0.014
CO urban	g CO	0.242	0.005	0.008
PM10 total	mg PM10	40.7	1.1	1.2
PM10 urban	mg PM10	39.3	0.9	1.0
Energy Embodied	MJ LHV	1.18	1.09	1.15

Table 8.13
Urban and rural precombustion emissions per MJ for CNG

Precombustion	Units	LS diesel	CNG (Elec.comp)	CNG (NG comp)
Greenhouse	kg CO ₂	0.0191	0.0117	0.0135
NMHC total	g HC	0.0565	0.0248	0.0273
NMHC urban	g HC	0.027	0.001	0.001
NOx total	g NOx	0.100	0.026	0.038
NOx urban	g NOx	0.043	0.013	0.023
CO total	g CO	0.023	0.007	0.011
CO urban	g CO	0.012	0.001	0.004
PM10 total	Mg PM10	5.42	0.439	0.526
PM10 urban	Mg PM10	4	0.257	0.327
Energy Embodied	MJ LHV	1.18	1.09	1.15

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Table 8.14
Urban and rural combustion emissions per MJ for CNG

Combustion	Units	LS diesel	CNG (Elec.comp)	CNG (NG comp)
Greenhouse	kg CO ₂	0.067	0.054	0.054
NMHC total	g HC	0.084	0.019	0.019
NMHC urban	g HC	0.084	0.019	0.019
NOx total	g Nox	0.944	0.114	0.114
NOx urban	g Nox	0.944	0.114	0.114
CO total	g CO	0.230	0.003	0.003
CO urban	g CO	0.230	0.003	0.003
PM10 total	mg PM10	35.26	0.7	0.7
PM10 urban	mg PM10	35.26	0.7	0.7
Energy Embodied	MJ LHV	0	0	0

Table 8.15
Summary of life cycle emissions per MJ from CNG

		LS diesel	CNG (Elec.comp)	CNG (NG comp)
Greenhouse	Precombustion	0.0191	0.0117	0.0135
Greenhouse	Combustion	0.0667	0.0548	0.0548
NMHC total	Precombustion	0.0565	0.0248	0.0273
NMHC total	Combustion	0.0835	0.0019	0.0019
NMHC urban	Precombustion	0.0271	0.0007	0.0010
NMHC urban	Combustion	0.0835	0.0019	0.0019
NOx total	Precombustion	0.1000	0.0262	0.0384
NOx total	Combustion	0.944	0.114	0.114
NOx urban	Precombustion	0.043	0.013	0.023
NOx urban	Combustion	0.944	0.114	0.114
CO total	Precombustion	0.0225	0.0072	0.0108
CO total	Combustion	0.2301	0.0034	0.0034
CO urban	Precombustion	0.0123	0.0014	0.0045
CO urban	Combustion	0.2301	0.0034	0.0034
PM10 total	Precombustion	5.42	0.44	0.53
PM10 total	Combustion	35.26	0.66	0.66
PM10 urban	Precombustion	4.00	0.26	0.33
PM10 urban	Combustion	35.26	0.66	0.66
Energy Embodied	Precombustion	1.18	1.09	1.15

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8.3.2 Emissions per unit distance

Table 8.16
Urban and rural life cycle emissions per km calculated for diesel, CNG

Full Lifecycle	Units (per km)	LS diesel	CNG (Elec.comp)	CNG (NG comp)
Greenhouse	kg CO ₂	0.9250	0.7284	0.7474
NMHC total	g HC	1.509	0.293	0.320
NMHC urban	g HC	1.192	0.028	0.032
NOx total	g NOx	11.250	1.533	1.666
NOx urban	g NOx	10.638	1.383	1.502
CO total	g CO	2.723	0.116	0.155
CO urban	g CO	2.612	0.052	0.086
PM10 total	mg PM10	438.4	12.0	12.9
PM10 urban	mg PM10	423.1	10.0	10.7
Energy Embodied	MJ LHV	12.7	11.90	12.50

Table 8.17
Urban and rural precombustion emissions per km for diesel and CNG

Precombustion	Units (per km)	LS diesel	CNG (Elec.comp)	CNG (NG comp)
Greenhouse	kg CO ₂	0.2060	0.1290	0.1480
NMHC total	g HC	0.609	0.272	0.299
NMHC urban	g HC	0.292	0.007	0.011
NOx total	g NOx	1.080	0.287	0.420
NOx urban	g NOx	0.468	0.137	0.256
CO total	g CO	0.243	0.079	0.118
CO urban	g CO	0.132	0.015	0.049
PM10 total	mg PM10	58.4	4.81	5.76
PM10 urban	mg PM10	43.1	2.81	3.58
Energy Embodied	MJ LHV	12.7	11.9	12.5

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Table 8.18
Urban and rural combustion emissions per km for diesel, CNG

Combustion	Units	LS diesel	CNG (Elec.comp)	CNG (NG comp)
Greenhouse	kg CO ₂	0.719	0.595	0.595
NMHC total	g HC	0.900	0.212	0.212
NMHC urban	g HC	0.900	0.212	0.212
NOx total	g NOx	10.177	1.246	1.246
NOx urban	g NOx	10.177	1.246	1.246
CO total	g CO	2.480	0.037	0.037
CO urban	g CO	2.480	0.037	0.037
PM10 total	mg PM10	380.00	7.2	7.2
PM10 urban	mg PM10	380.00	7.2	7.2
Energy Embodied	MJ LHV	0	0	0

Table 8.19
Summary of life cycle emissions per km for diesel, CNG

		LS diesel	CNG (Elec.comp)	CNG (NG comp)
Greenhouse	Precombustion	0.2060	0.1290	0.1480
Greenhouse	Combustion	0.7190	0.5994	0.5994
NMHC total	Precombustion	0.6090	0.2720	0.2990
NMHC total	Combustion	0.9000	0.0212	0.0212
NMHC urban	Precombustion	0.2920	0.0072	0.0108
NMHC urban	Combustion	0.9000	0.0212	0.0212
NOx total	Precombustion	1.0800	0.2870	0.4200
NOx total	Combustion	10.170	1.246	1.246
NOx urban	Precombustion	0.468	0.137	0.256
NOx urban	Combustion	10.170	1.246	1.246
CO total	Precombustion	0.2430	0.0788	0.1180
CO total	Combustion	2.4800	0.0368	0.0368
CO urban	Precombustion	0.1320	0.0154	0.0488
CO urban	Combustion	2.4800	0.0368	0.0368
PM10 total	Precombustion	58.40	4.81	5.76
PM10 total	Combustion	380.00	7.17	7.17
PM10 urban	Precombustion	43.10	2.81	3.58
PM10 urban	Combustion	380.00	7.17	7.17
Energy Embodied	Precombustion	12.70	11.90	12.50

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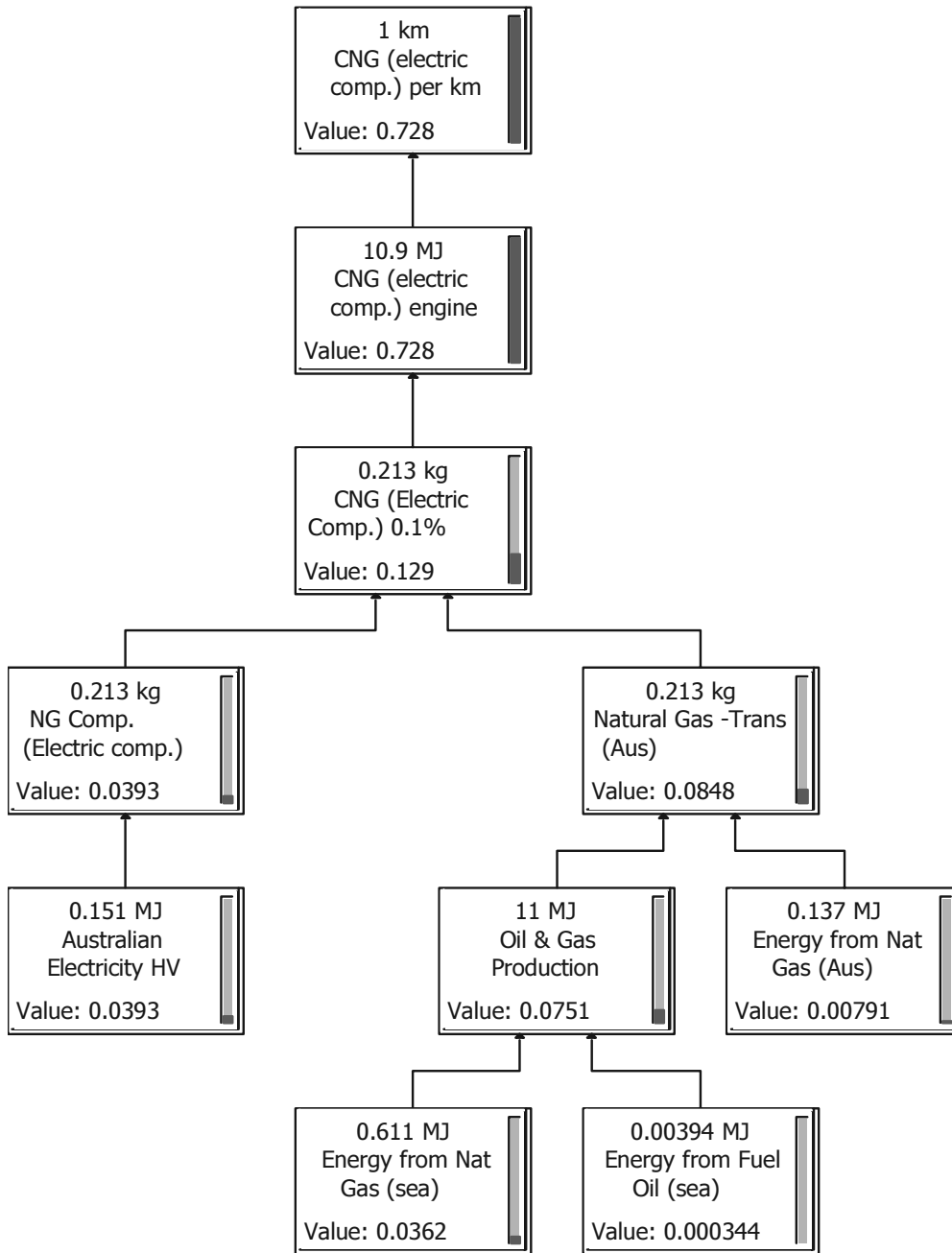


Figure 8.4
Embodied greenhouse gases from CNG production and use with electrical compression

Part 2 Details of Fuels

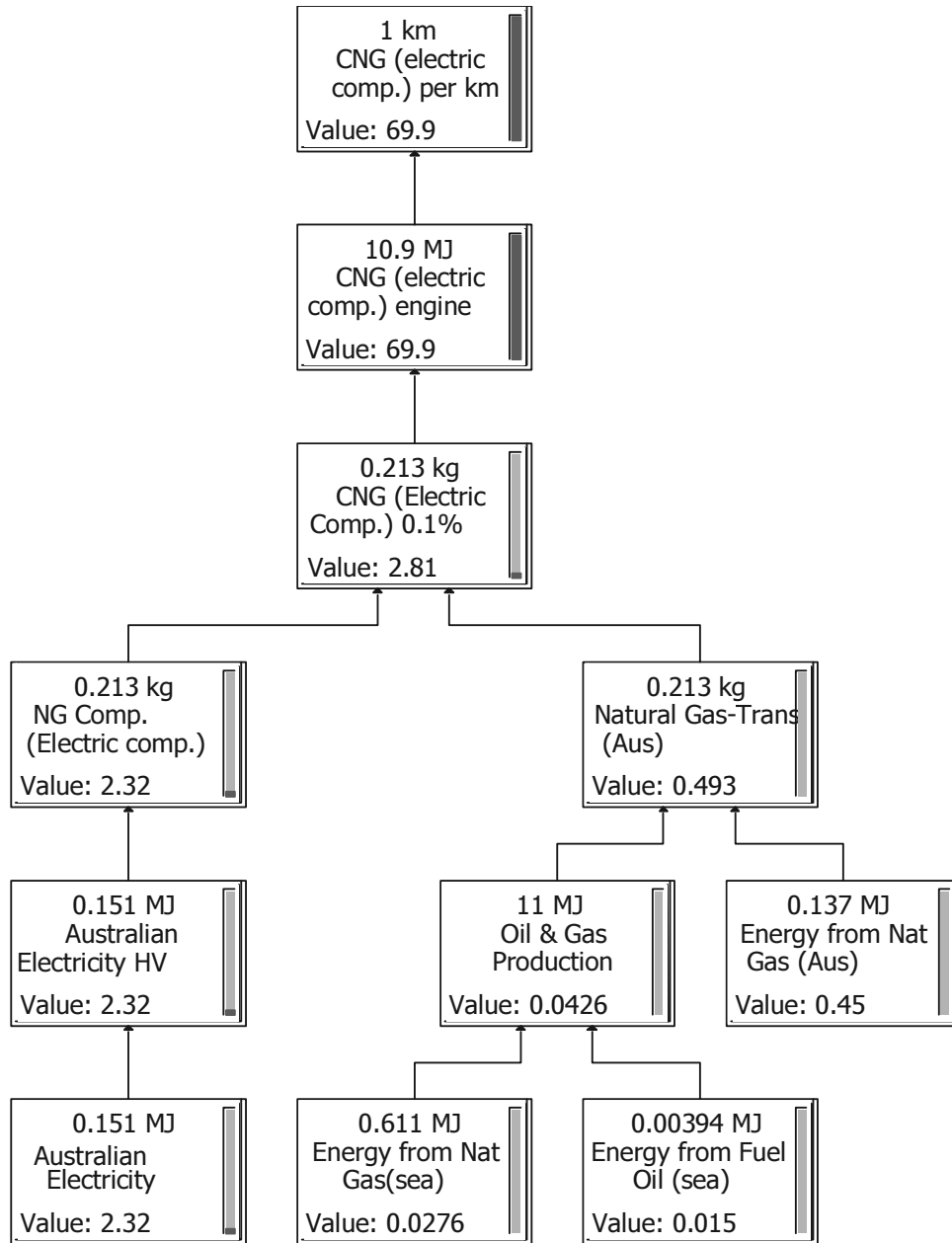


Figure 8.5
Embodied particulate matter from CNG production and use with electrical compression

Part 2 Details of Fuels

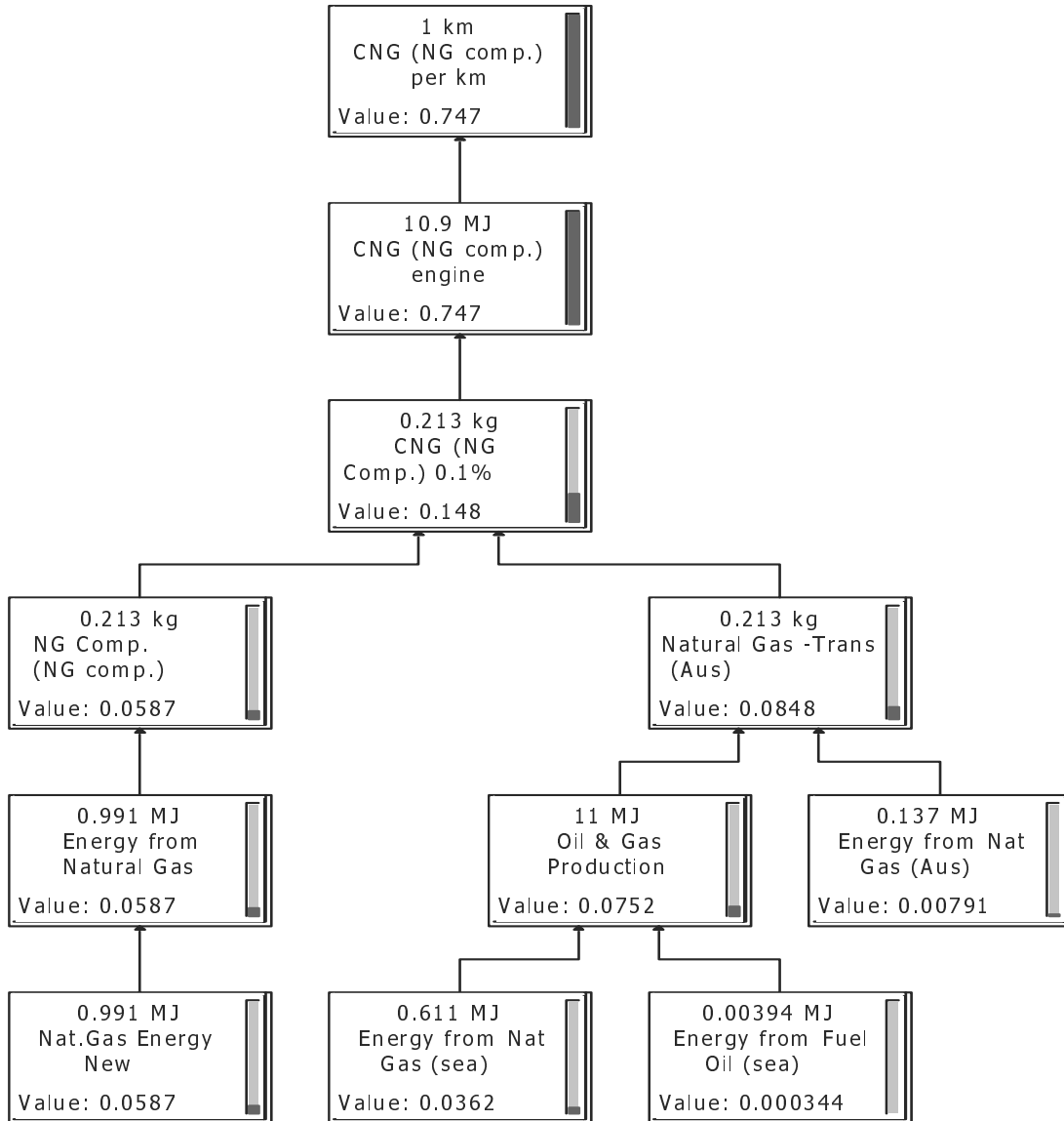


Figure 8.6
Embodied greenhouse gases from CNG production and use with natural gas compression

Part 2 Details of Fuels

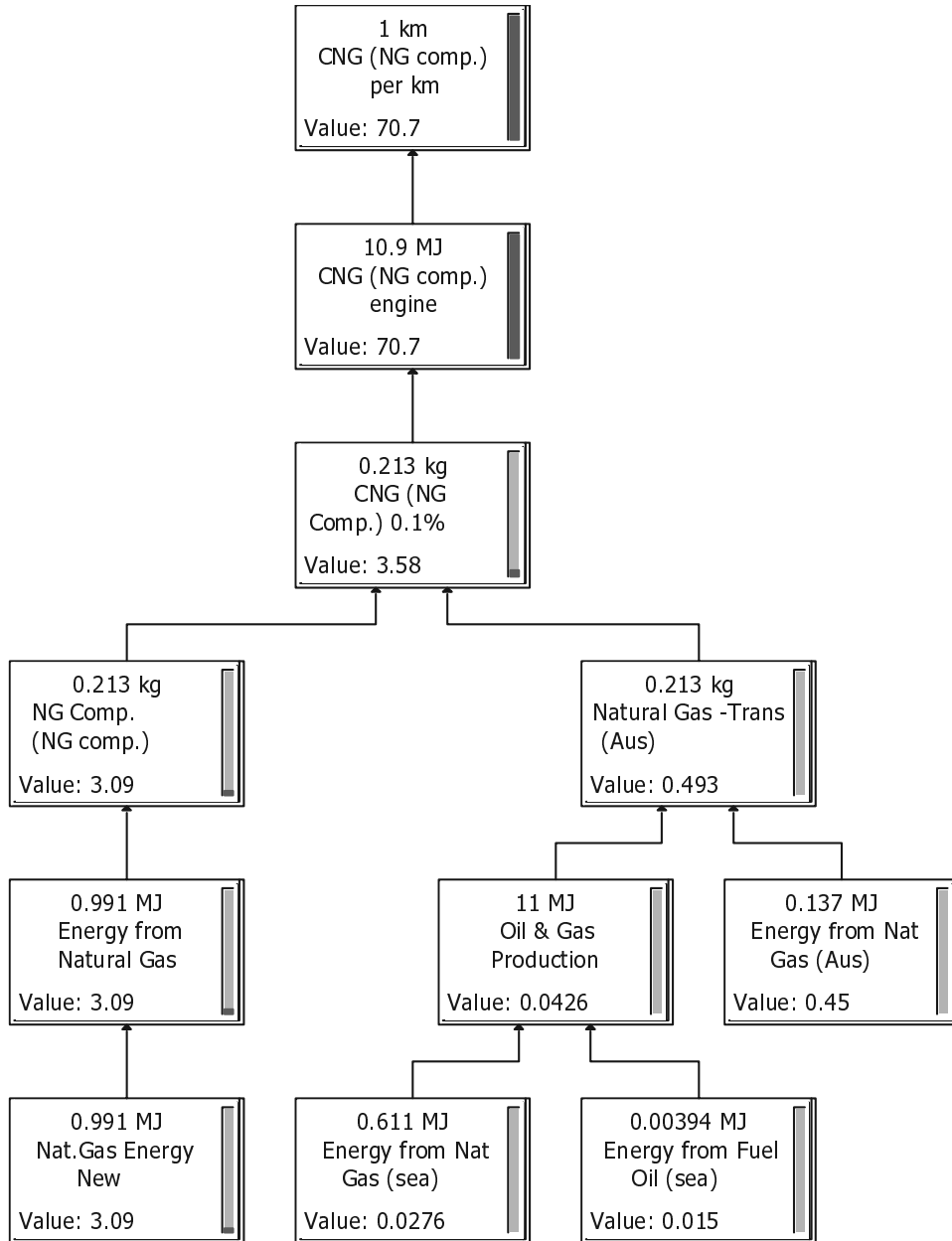


Figure 8.7

Embodied particulate matter from CNG production and use with natural gas compression

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8.3.3 Uncertainties

We use the uncertainty estimates given by Beer et al. (2000) on the basis of the tailpipe emissions to estimate the uncertainties associated with the above results to be as given in Table 8.20.

Table 8.20
Estimated one standard deviation uncertainties (in percent) for CNG emissions

	g/MJ	g/t-km	g/p-km
CO ₂	10	2	12
NMHC	135	135	135
NOx	50	29	72
CO	15	11	22
PM10	60	17	108

8.3.4 Discussion

Our results indicate lower greenhouse gas emissions both from tailpipe emissions and from upstream emissions. Earlier studies, such as those reported in the IPCC Second Assessment Report (Watson et al., 1996), the Expert Reference Group (1998) report, or those mentioned at <http://www.hsph.harvard.edu/Organizations/hcra/diesel/diesel.pdf> obtain different results. There are two reasons for this – changes in vehicle technologies, and the expected fugitive emissions.

Changes in vehicle technologies

The lower vehicle emissions arise from the improved performance of the present series of dedicated CNG engines that are optimised for the use of CNG. Earlier studies were based on a previous generation of CNG engines. This is evident when the history of the Western Australian experience is examined. The Expert Reference Group (1998) report examined issues associated with diesel and natural gas fuels and decided that diesel was the preferred fuel. The ANGVC (2000) responded with a review of the report and discussed what it believed to be the inadequacies of the report.

Following the Western Australian election, the decision to purchase diesel buses was reversed and natural gas buses were ordered. The firm Advanced Engine Components Ltd. was contracted to install its multipoint sequential electronic fuel injection natural gas vehicle system on Daimler-Chrysler M447G engines. The system was tested in June 2001 at the Swiss Federal Laboratories for Materials Testing and Research (EMPA) in Zurich under the official European Transient Cycle. The engine was certified as being compliant with the Euro4 standard. The results of the tests done in June 2001, shown in Table 8.21, demonstrate that the present generation of NGV vehicles perform at Euro4 specifications.

Table 8.21
Emissions (g/kWh) from Daimler-Chrysler M447G engines

Technology	CO	THC	CH ₄	NMHC	NOx	PM	CO ₂	Specific Fuel Consumption
G20 Fuel Gas ²	0.131	0.167	0.156	0.011	3.09	0.006	626	185-216
G25 Fuel Gas	0.134	0.479	0.459	0.02	2.88	0.007	637	185-216
Euro3 standard	5.45	2.38	1.6	0.78	5.0	0.16		
Euro4 standard	4.0	1.65	1.1	0.55	3.5	0.03		

² EU reference fuel: G20 is 100% methane, G25 is 86% methane.

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Fugitive emissions

The reduction in upstream emissions occurs because we assumed for Australia, on the basis of the advice received from stakeholders, that fugitive emissions are 0.1% of supply. This leads to the results, tabulated above, that embodied emissions of greenhouse gases are less than that of diesel. Earlier studies and overseas studies, based on assumptions of higher fugitive emissions, produce opposite results in relation to greenhouse gases. We undertook a sensitivity study, as depicted in Figure 8.3, that indicates that if fugitive emissions exceed 4 % of supply then embodied emissions of greenhouse gases exceed those of low sulfur diesel.

8.4 Viability and functionality

8.4.1 Safety

According to the IANGV web site (www.iangv.org/sources/ga.html) natural gas vehicles (NGV) have an excellent safety record (especially when compared to petrol driven vehicles). They cite two fundamental reasons for this: the structural integrity of the NGV fuel system and the physical qualities of natural gas as a fuel.

The fuel storage cylinders used in NGVs are much stronger than petrol tanks. The design of NGV cylinders are subjected to a number of specified “severe abuse” tests, such as heat and pressure extremes, gunfire, collisions and fires.

Though fuel storage cylinders are stronger than petrol tanks, when composite material used to encase the tanks, the materials are fundamentally more susceptible to physical damage than metals under abusive conditions. For this reason, composite materials on NGV cylinders must always be properly handled and protected. Incidents involving natural gas cylinder ruptures revealed that some form of chemical attack or physical damage to the composite overwrap on the cylinder was involved. This has been addressed in new cylinder standards by prescribing a standard acid exposure test.

NGV fuel systems are “sealed”, which prevent any spills or evaporative losses. Even if a leak were to occur in an NGV fuel system, the natural gas would dissipate into the atmosphere because it is lighter than air.

Natural gas has a high ignition temperature, about 650°C, compared with about 350°C for gasoline. It also has a narrow range of flammability; that is, in concentrations in air below about 5 percent and above about 15 percent by volume, natural gas will not burn. The high ignition temperature and limited flammability range make accidental ignition or combustion of natural gas unlikely.

8.4.2 Warranty

There are many dedicated natural gas vehicles available. These, are provided with standard manufacturers’ warranties. In the case of aftermarket conversions, third party warranties are also available to cover gas related components. As an example, the Cummins warranty for both ISC (Diesel) and C8.3G+ (Natural Gas) engines is identical.

8.4.3 Functionality

The knock resistance of methane is high, which is advantageous for engine performance. The Research Octane Number of methane is about 120, enabling compression ratios of up to 13:1 to be achieved in some OEM engines. Though the maximum efficiency of a spark-ignition gas engine is estimated to be 10-15% lower than the efficiency of a diesel engine (Nyland and

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Lawson, 2000), the data that were used in our analysis (based on engine dynamometer information) indicate that CNG is only 1.5% less efficient than low sulfur diesel.

CNG buses appear to display a large discrepancy between their theoretical or engine dynamometer performance, and their on-road performance. According to Bates et al. (2001) in the current French NGV programme, natural gas buses have 28% to 62% worse fuel consumption than diesel buses under real-life driving conditions.

Examination of the literature in relation to the use of CNG as a fuel for bus fleets (Watt, 2000; SRI International, 1996; Los Angeles County Metropolitan Transportation Authority, 1999) reveals that in general, CNG buses require greater maintenance. Stage Coach New Zealand reports that fires have been caused by backfiring problems as a result of faulty maintenance, including a failure to re-install flash arresters. Bell Street Buses in Melbourne report similar problems (Watt, 2000). The ANGVC believes that current generation technology, if properly fitted and maintained, should not give rise to incidents such as these.

The Los Angeles County Metropolitan Transportation Authority (LACMTA) notes that due to chronic problems with the engine and fuel system components, CNG buses have had a significantly greater defect rate than diesel buses. A fleet of Orion V CNG buses in operation in New York with NYCTA consistently had twice the road failures as the same model of diesel bus. Engine and fuel system road calls for the CNG buses were also twice as high as the road calls for diesel engines and fuel systems. In Los Angeles, the LACMTA vehicles' engines and fuel system road calls accounted for approximately 48.5 percent of total road calls for the fleet, while engine and fuel system road calls for a fleet of older diesel buses only accounted for 34 percent of total road calls.

Until there is large-scale experience with CNG bus maintenance, reliability problems and the likelihood of faulty maintenance as a result of unfamiliarity with the equipment will be greater with CNG buses than with diesel buses. Fleet operators in Australia often report that a change in maintenance procedures results in improved reliability. Due to the small size and varying ages of CNG fleets in Australia, it is difficult to make an accurate statistical evaluation of vehicle reliability. Adjustments to maintenance procedures and adjustments to driving style may both result in improved reliability.

The performance of CNG engine and fuel system components are expected to improve as the technology matures. The performance of natural gas engine and fuel system components have improved considerably in recent years and are expected to improve further as the technology matures. In the past this has been hampered by low demand for natural gas engines but increasing demand for low emissions engines is likely to accelerate technology improvements and reduce price differentials between natural gas and diesel engines.

8.4.4 Operating range

We have noted that a typical range for a CNG truck is 560 km, which can be increased to over 640 km by increasing the number of cylinders on board the vehicle or by increasing the CNG pressure within the tanks at the time of fill. In the case of dual-fuel operations, diesel capacity may also allow for additional range.

CNG buses are heavier than the corresponding diesel vehicle as a result of the weight of the tanks. The Sydney Bus fleet menu on the web provides technical details on the Sydney Bus fleet at <http://www.sydneybuses.nsw.gov.au/sb.fleet.html>. According to the information provided there, a Scania L113CRB CNG bus has an unladen weight of 11,240 kg and can carry 72 passengers. The equivalent Scania L113CRL diesel bus has an unladen weight of 11,040 kg and can carry 69 passengers. These Scania CNG buses have a range of 250 km. The newer Sydney Bus CNG buses are Mercedes Benz 0405H buses with a range of 400 km. Developments in cylinder technology in recent years have increased the capacity for on board storage. Older model

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Scania buses, for example, carried around 530 kg of cylinders (excluding mounting hardware) to deliver a driving range of only 250 km, whereas current Scania's can deliver over 450 kms with only 550 kg of cylinders (including mounting hardware) on board.

8.4.5 *Re-fuelling*

Sydney Buses describe their refuelling system as follows:

The refuelling station at State Transit Authority's Kingsgrove bus depot has two 500 m³/hr compressors, eight 250 bar storage cylinders and the associated dispensers and reclaiming units. Each depot will have three compressors operating at a rate of 3000 cubic metres per hour at 34 MPa. The storage cascade has a total capacity of 3500 cubic metres. The buses will be able to be filled from empty to 20 MPa in three and a half minutes, with up to 40 buses being filled within two hours. The process is automatic with connection and disconnection of the coupling the only manual requirement.

Currently there are limited public CNG refuelling facilities (total 13) but over 30 public sites are expected to be operational by the end of 2002. In addition the demand for depot-based sites is increasing and it is expected that a similar number of additional depot based stations will be developed over this time. NGVs can also be fuelled from a small dispenser directly connected to a home or business natural gas line. This is commonly known as a Vehicle Refuelling Appliance (VRA). A small electrically driven compressor operates the dispenser.

8.4.6 *Availability*

Natural gas is abundant in Australia thus, in principle, there are no problems with fuel availability. In practice, natural gas is vulnerable to disruption in the gas supply. This was most evident with the Longford incident in 1998 when gas supplies to Melbourne, and much of the rest of Victoria were halted following the disaster at the Longford plant. New pipelines are under construction to ensure alternate gas supply routes to Sydney and Melbourne.

8.5 *CNG conversions*

The majority of CNG vehicles in Australia were sourced as new vehicles. However, there has been growing interest in the conversion of conventionally fuelled vehicles to CNG through after-market conversions.

The emissions performance of converted Australian CNG vehicles is unclear due to a lack of comprehensive industry-wide data. The only results available were from one system that was used in a small number of vehicles. That system is currently being upgraded and is no longer sold in the previous configuration. Some tailpipe emissions from the previous configuration were much higher than those for OEM vehicles. It is possible that the difference in emission levels between converted vehicles and OEMs may decrease as the heavy-duty vehicles conversion industry becomes more firmly established.

8.6 *Health Issues*

NGVs have the potential to effect a significant reduction in local air pollutants such as CO, NMHCs, SO_x, particles, smoke and odour. The effects of traces of formaldehyde in NGV exhausts (though less than from alcohol fuels) have yet to be determined.

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8.5.1 Production and transport

Particulate Matter

The LCA estimate for CNG urban precombustion (truck) PM10 emissions of 3 to 4 mg/km is substantially less than the LSD estimate of 43 mg/km.

Air Toxics

The LCA estimate for CNG urban precombustion (truck) NMHC emissions of 0.007 to 0.011 g/km is substantially less than the LSD estimate of 0.292 g/km.

The public health effects of air toxics will be mainly associated with combustion emissions in large urban centres. An accompanying disk to this report provides details of air toxic emissions from upstream activities.

8.5.2 Use

Anyon (1998) points out that LPG, like CNG, has much lower emissions than diesel, and LPG has low particle levels, which make it an attractive fuel for urban buses and delivery vehicles. However, as diesel particle emissions reduce to Euro4 levels this advantage may be lost.

Exhaust emissions of methane, which is a greenhouse gas, are relatively high.

Particulate Matter

Research consistently shows that CNG (and gaseous fuels in general) with its simple chemistry and very low sulfur content, emit extremely low levels of particles. (Anyon, 1998)

Emissions of particulate matter are almost eliminated with natural gas use as shown in the earlier results tables. The IANGV (1990) noted that the NGV engine's lubricating oil appeared to be the source of remaining particle emissions.

The LCA estimate for CNG combustion (truck) PM10 emissions of 7.2 mg/km is substantially less than the LSD estimate of 380 mg/km.

Air Toxics

CNG produces much lower emissions of the main air toxics such as benzene, 1,3 butadiene, formaldehyde and acetaldehyde, compared with diesel (Anyon, 1998)

CNG contains no benzene, so refuelling and running losses of this toxic would be zero. (USEPA, 1993)

The LCA estimate for CNG combustion (truck) NMHC emissions of 0.212 g/km is less than the LSD estimate of 0.900 g/km.

Summary

CNG upstream emissions of both particles and air toxics are substantially less than LSD. CNG tailpipe emissions of particles are substantially less than LSD. CNG tailpipe emission of benzene, 1,3 butadiene, formaldehyde and acetaldehyde are less than LSD.

No comparative emissions data for CNG and LSD has been identified for:

- polycyclic aromatic hydrocarbons (PAH);
- toluene; and
- xylene

8.7 OHS Issues

Australian long distance high pressure (up to 15 MPa) transmission pipelines are relatively modern (the oldest dates back to 1969) and built to high standards. They are well maintained and accidental leaks are a rarity. Refuelling CNG is considered to be the 'least-safe' moment of its use. CNG is much lighter than air and thus it is safer than spilled diesel. In the case of CNG leak, because of the gaseous nature of the fuel, the gas will issue as a very high velocity jet into surroundings aiding greatly in the rapid dispersion of the fuel.

The OHS issues in the lifecycle of CNG are covered by a range of State and Commonwealth occupational health and safety provisions. While there will be different OHS issues involved in the production process associated with CNG compared with LSD, no OHS issues unique to the production and distribution of CNG have been identified.

8.8 Vapour Pressure Issues

Most gas losses from the distribution systems are by way of leakage from the low pressure network (7 kPa). This includes both the reticulation network and appliances operated by end users. Losses from the distribution network are difficult to estimate as they may occur both upstream and downstream from the meters. It is estimated that emissions from the distribution network, called unaccounted gas, i.e. the difference between the gas issued by the utilities and the gas sold to customers are as high as 7.5% (NGGIC, 1996).

Since the use of CNG as a fuel requires a closed delivery system, evaporative emissions from a dedicated CNG vehicle are assumed to be zero. (USEPA, 1993). Different views are held on evaporative emissions. One is that CNG vehicles do not have any, due to their sealed pressurised fuel system. BTCE (1994), on the other hand, refers to 'frequent leaks' as a technical problem to be solved for NGVs.

8.9 Environmental Impact and Benefit

Noise levels from natural gas buses are less than those of diesel buses. Kadayifci and Bryett (1997) measured a decrease of 2 to 5 dBA during drive-by tests, and 2 to 3 dBA during stationary noise tests. Tests in France on identical diesel and CNG buses found up to 8 dBA reductions in noise outside the bus. Passengers experienced about 4dBA less noise (MVV InnoTec GmbH, 2000).

The operational experience is salutary. Perception problems about poor driveability of CNG buses were put to rest with comparison trials with diesel buses. The conclusion was that lack of noise from the CNG buses gave the drivers the impression of a lack of acceleration (Watt, 2000:p.66)

NGVs have the potential to effect a significant reduction in local air pollutants such as CO, NMHCs, SO_x, particles, smoke and odour. The situation with regard to NO_x is less clear cut, and the effects of traces of formaldehyde in NGV exhausts (though less than from alcohol fuels) have yet to be determined.

The potential for water and soil pollution is effectively eliminated by the use of natural gas.

With respect to sustainability, known world reserves of natural gas now constitute over 95% of equivalent oil reserves. In Australia this ratio is more than three times the oil reserve. Proven Australian resources of natural gas currently stand at 109,051 PJ, at existing production levels, this will last 91 years compared to domestic oil reserves which are estimated to last 39 years. Natural Gas is an indigenous fuel that, if broadly adopted by the transport industry, could result in the order of an additional 100PJ per annum of gas being consumed rather than imported and more expensive crude oil (ANGVC 2001).

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CNG can also be a renewable fuel for vehicles because it can be purified from the biogas extracted from waste treatment facilities.

8.10 Expected Future Emissions

Arcoumanis (2000) developed a model that examines a given alternative fuel relative to the reference diesel engine (Euro2) in terms of a specific regulated pollutant. A value of 1 implies identical performance to the low sulfur diesel/Euro2 combination. A value greater than 1 implies inferior performance, whereas a value less than 1 indicates superior performance.

Table 8.22 lists the estimated emissions factors for CNG. The columns in bold represent the standards relative to the Euro2 standard. The adjacent column gives the expected performance of CNG. The estimates of Arcoumanis (2000) indicate that CNG can be expected to meet all future Australian Design Rules for all pollutants.

Table 8.22
Estimated emission factors for CNG under future technologies (PM is unregulated)

Technology	CO	CO	THC	THC	NOx	NOx	PM	PM	CO ₂	LCA CO ₂
Euro2	1.0	0.3	1.0	0.9	1.0	0.2	1.0	0.1	1.0	0.9
Euro3	0.53	0.2	0.6	0.6	0.71	0.1	0.67	0.1	1.0	0.9
Euro4	0.38	0.1	0.42	0.4	0.5	0.1	0.2	0.05	1.0	0.8

8.11 Summary

8.11.1 Advantages

- CNG has very low particle emissions because of its low carbon to hydrogen ratio.
- There are negligible evaporative emissions, requiring no relevant control.
- Due to its low carbon-to-hydrogen ratio, it produces less carbon dioxide per GJ of fuel than diesel.
- It has low cold-start emissions due to its gaseous state.
- It has extended flammability limits, allowing stable combustion at leaner mixtures.
- It has a lower adiabatic flame temperature than diesel, leading to lower NOx emissions.
- It has a much higher ignition temperature than diesel, making it more difficult to auto-ignite, thus safer.
- It contains non-toxic components.
- It is much lighter than air and thus it is safer than spilled diesel.
- Methane is not a volatile organic compound (VOC).
- Engines fuelled with natural gas in heavy-duty vehicles offer more quiet operation than equivalent diesel engines, making them more attractive for use in urban areas.
- It has nearly zero sulfur levels and, thus, negligible sulfate emissions.
- Natural gas is distributed via underground pipe networks, removing the need for hazardous transportation and transfer processes.
- Because of the pipeline delivery, retailers or fleet operators are not required to store large quantities of fuel, usually prepaid, on site.
- Natural gas use does not give rise to issues with groundwater contamination such as those experienced through diesel/petrol spillage or leakage from underwater storage.

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- Natural gas pricing is stable and predictable, removing uncertainty to business caused by fuel price fluctuations.

8.11.2 Disadvantages

- CNG on board a vehicle takes 3 to 4.5 times more volume for storage than diesel, thus storage needs may be reduced.
- It requires dedicated catalysts with high loading of active catalytic components to maximise methane oxidation.
- The composition may vary depending on the CNG source, which affects stoichiometric air/fuel ratios. This has not been a problem in Australia to date.
- It requires special refuelling stations that necessitate new infrastructure.
- The energy required to compress natural gas leads to increased greenhouse gas emissions.
- The extra weight of the fuel tank leads to higher fuel consumption or loss of payload.
- Exhaust emissions of methane, which is a greenhouse gas, are relatively high compared with low sulfur diesel.
- It can give rise to backfire in the inlet manifold if the ignition system is faulty or fails in use.
- Relatively small fugitive emissions of methane can have a significant effect on the embodied greenhouse gas emissions.