FULL-CYCLE ASSESSMENT OF ALTERNATIVE FUELS FOR LIGHT-DUTY ROAD VEHICLES IN AUSTRALIA

First Published September 2004, Updated April 2005

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SUMMARY: This paper presents a well-to-wheels comparison of alternative fuels for Australian light-duty road vehicles. The relative performance of alternative fuel pathways is presented in terms of full-cycle energy consumption and greenhouse gas emissions. The study concludes that the best use of any energy feedstock is via the most direct well-to-wheels pathway, avoiding unnecessary conversion steps. On this basis, natural gas appears to be a promising transitional energy feedstock for automotive fuels. Ultimately, well-to-wheel pathways based upon renewable electricity generation offer the best prospects for low energy consumption and near-zero greenhouse gas emissions.

1. INTRODUCTION

The Australian light-duty vehicle sector is mostly fuelled by liquid hydrocarbon fuels derived from crude oil. However, growing concern over the environmental impacts and oil-dependence associated with widespread automobile use has prompted the investigation of alternative fuels for motor vehicles. Therefore a variety of candidate alternative fuels and powertrain technologies are being considered for their ability to reduce emissions of greenhouse gases and regulated air pollutants, at the same time promoting energy independence through the displacement of oil imports.

Candidate fuels include unleaded petrol (ULP), diesel, liquefied petroleum gas (LPG), compressed natural gas (CNG), liquefied natural gas (LNG), compressed hydrogen (GH_2), liquefied hydrogen (LH_2), electricity, methanol (MeOH), ethanol (EtOH) and biodiesel. The candidate powertrains include advanced internal combustion engine vehicles (ICVs), fuel cell-electric vehicles (FCEVs), hybrid-electric vehicles (HEVs) and battery-electric vehicles (BEVs). These alternative transport energy pathways have unique characteristics in terms of their potential for emissions reduction and promotion of energy independence. However, for a proper comparison the energy consumption and emissions must be assessed over the full fuel cycle, or 'well-to-wheels' chain (IEA, 1999).

Several previous studies have performed well-to-wheel comparisons of various alternative transport fuels. The Australian Greenhouse Office (Beer et al, 2001) has compared a variety of alternative fuels for Australia, but focused on the heavy duty vehicle sector (trucks, buses, etc) in which vehicle designs are markedly different from the light-duty sector. More recently, General Motors (2001), L-B-Systemtechnik (2002) and the EU Joint Research Commission (2003) have performed comparisons of light-duty vehicle alternative fuels and powertrains for the North-American and European markets. However the results of these studies cannot necessarily be extrapolated to the Australian context. To complement these previous studies, this paper presents a well-to-wheels comparison of fuels and powertrain technologies for Australian light-duty vehicles.

2. METHODOLOGY FOR WELL-TO-WHEELS COMPARISON

The well-to-wheel (WTW) chain is considered in two stages – well-to-tank (WTT) and tank-to-wheel (TTW) – with fuel storage onboard the vehicle being the intermediary point. The relative performance of alternative fuel pathways is determined in terms of full-cycle energy consumption in mega-joules per kilometre (MJ_{WTW}/km) and greenhouse gas emissions in grams of carbon-dioxide equivalent per kilometre (gCO_{2WTW}/km). Emissions of regulated pollutants (such as carbon monoxide, non-methane organic compounds, nitrogen oxides, sulfur oxides and particulate matter) have not been assessed.

2.1 Well-to-Tank Stage

The Well-to-Tank (WTT) stage accounts for all energy inputs and greenhouse emissions throughout energy feedstock production and transportation, fuel processing and distribution and finally, fuel storage in the tank of a vehicle. The key outputs from the WTT modelling stage are the embodied energy (MJ_{WTW}/MJ_{TTW}) and upstream greenhouse gas emissions (gCO_{2WTT}/MJ_{TTW}) per mega-joule of fuel stored onboard the vehicle. Therefore, it is important to define not only how each fuel is produced but also how the fuel is stored onboard the vehicle. For example, normally gaseous fuels such as hydrogen and natural gas may be stored as a compressed gas or a cryogenic liquid and the energy requirements of compression vs. liquefaction differ substantially. For this reason, compressed hydrogen and compressed natural gas are considered to be different "fuels" from their liquid counterparts in this study.

The WTT stage is modelled with data from Beer et al (2001), which has been revised by the author following cross-referencing against data from the General Motors (2001) and L-B-Systemtechnik studies (2002). WTT data for the alternative fuels pathways is presented in Section 3.

2.2 Tank-to-Wheel Stage

The Tank-to-Wheel (TTW) stage accounts for the energy consumption and tailpipe greenhouse emissions of the vehicle during realistic driving conditions. The key output from the TTW modelling stage is the energy consumption of the vehicle in mega-joules per kilometre of travel (MJ_{TTW}/km). Each fuel is also assumed to produce a constant amount of tailpipe greenhouse gas emissions, in grams of carbon-dioxide-equivalent per mega-joule of fuel used (gCO_{2TTW}/MJ_{TTW}) based upon the carbon content of each fuel.

During driving, the energy consumption of a vehicle depends heavily upon the nature of the driving pattern (relative amounts of low/high speed driving and stop/start acceleration), the physical attributes of the vehicle platform (mass, drag and accessory loads) and the overall operating efficiency of its powertrain. Furthermore, the total vehicle mass and powertrain efficiency depend upon the size (in terms of power rating and mass) and efficiency of each powertrain component. Therefore, in modelling the energy consumption of a vehicle for the purposes of a well-to-wheels assessment, the following are of particular importance:

- The vehicle performance specifications which translate directly into power/energy storage ratings for components in the powertrain
- The mass-specific power density (W/kg) and energy density (Wh/kg) of the powertrain component technologies, which, in conjunction with the power/energy storage ratings, determine the mass of each component.

The TTW component is modelled with a parametric vehicle modelling tool developed by the author (Simpson and Walker, 2003). This tool utilises mass-coupled parametric expressions that predict powertrain component sizes, total vehicle mass (including mass compounding effects) and net-system efficiency, based upon parametric inputs to describe the vehicle platform, performance specifications, component technologies and driving pattern.

Sections 4 and 5 present input data for modelling of the TTW stages. To limit uncertainty in the analysis, all of the alternative fuel/powertrain vehicles are based on the same vehicle platform, with identical performance specifications, and are modelled in operation over the same driving pattern.

2.3 Refining the Number of Well-to-Wheel Pathways

Table I presents the number of well-to-wheel pathways considered for each fuel. If all WTT-TTW combinations were examined, there would be a total of 73 WTW pathways to analyse and compare. However, it is possible to reduce the total number of WTW pathways without compromising the utility of the comparison.

Table II presents the 24 alternative WTT fuel pathways considered in this study. For some of the fuels, there is more than one WTT pathway for the production of the fuel from the same feedstock. Therefore, a pre-screening exercise was undertaken to identify obviously sub-optimal WTW pathways and remove them from the set of alternatives considered. For example, gaseous hydrogen may be produced from natural gas via WTT pathways (10) and (12). Clearly, it is less efficient to convert natural gas to electricity for the purposes of electrolysis (12) compared to direct thermo-chemical reforming of natural gas into hydrogen (10).

Table VI below presents the powertrain technologies considered in this study. For some fuels, there are multiple powertrains that may be used (e.g. 4 for gaseous hydrogen). The approach adopted in this study is to choose the most efficient powertrain for each fuel (judged by the vehicle with lowest TTW energy consumption), such that there is only one powertrain technology to consider for each fuel. With these refinements, the number of WTW pathways to compare can be reduced to 21.

Table I: Number of WTW pathways considered in the study

Fuel	No. of WTT pathways	No. of TTW powertrains	Total no. of WTW pathways	Refined no. of WTW pathways
Petrol	1	4	4	2
Diesel	2	2	4	2
LPG	1	2	2	1
CNG	1	2	2	1
LNG	1	2	2	1
Methanol – M100	1	2	2	1
Methanol – M85	1	2	2	1
Gaseous H2	5	4	20	3
Liquid H2	5	4	20	3
Electricity	3	3	9	3
Ethanol – E95	1	2	2	1
Ethanol – E10	1	2	2	1
Biodiesel	1	2	2	1
		Totals	**73**	**21**

Table II: Well-to-Tank data for alternative fuel pathways considered in this study

No.	Fuel	Feedstock	WTW Energy (MJ/MJ)	TTW GHG (gCO_2/MJ)	WTT GHG (gCO_2/MJ)	WTW GHG (gCO_2/MJ)
1 [a]	ULP	Crude oil	1.14	71.1	17.7	88.8
2 [a]	Diesel	Crude oil	1.27	69.7	22.2	91.9
3 [a]		Natural gas	1.78	69.7	33.6	103.3
4 [a]	LPG	LPG	1.06	58.4	17.0	76.4
5 [a]	CNG (3600psi)	Natural gas	1.09	54.8	11.7	66.5
6 [a]	LNG	Natural gas	1.11	54.7	11.6	66.3
7 [c]	MeOH	Natural gas	1.63	68.6	25.0	93.6
8 *	M85 (85% MeOH, 15% ULP)	Natural gas & Crude Oil	1.56	69.0	23.9	92.9
9 [d*]	GH$_2$ (5000psi)	Coal	2.75	0.0	252.5	252.5
10 [a*]		Natural gas	1.63	0.0	104.2	104.2
11 [ce*]		Grid electricity	4.86	0.0	486.2	486.2
12 [c*]		Natural gas-fired electricity	3.45	0.0	186.6	186.6
13 [c*]		Renewable electricity	1.76	0.0	0.0	0.0
14 [d*]	LH$_2$	Coal	3.46	0.0	324.0	324.0
15 [c*]		Natural gas	2.49	0.0	190.1	190.1
16 [ce*]		Grid electricity	5.64	0.0	564.2	564.2
17 [c*]		Natural gas-fired electricity	4.02	0.0	218.2	218.2
18 [c*]		Renewable electricity	2.07	0.0	3.0	3.0
19 [e*]	Electricity	Grid electricity	2.97	0.0	297.0	297.0
20 [*]		Natural gas-fired electricity	2.11	0.0	114.2	114.2
21 [b]		Renewable electricity	1.08	0.0	0.0	0.0
n/a [a*]	EtOH	Molasses	1.56	71.3	-16.9	54.4
22 *	E10 (10% EtOH, 90% ULP)	Molasses & Crude Oil	1.18	71.1	14.2	85.4
23 [*]	E85 (85% EtOH, 15% ULP)	Molasses & Crude Oil	1.45	71.3	-11.8	59.5
24 [c]	BioDiesel	Rapeseed	1.43	76.7	-29.9	46.8

Notes:

a) From Beer et al (2001)
b) From General Motors (2001)
c) From L-B-Systemtechnik (2002)
d) From Gregoire Padro (2003)
e) From ESAA (2000)
* Reference data amended by author. For fuel blends, values are calculated in proportion to the constituent fuels.

2.4 Calculating Well-to-Wheel (WTW) Results

Using WTT and TTW data, the calculation of WTW results is relatively straightforward.

Well-to-wheel energy consumption: $$\frac{MJ_{WTW}}{km} = \frac{MJ_{WTW}}{MJ_{TTW}} \times \frac{MJ_{TTW}}{km}$$

Well-to-wheel greenhouse gas emissions: $$\frac{gCO_{2WTW}}{km} = \left(\frac{gCO_{2WTT}}{MJ_{TTW}} + \frac{gCO_{2TTW}}{MJ_{TTW}} \right) \times \frac{MJ_{TTW}}{km}$$

3. ALTERNATIVE FUELS & WELL-TO-TANK RESULTS

Table II presents the 24 alternative fuel pathways considered in this study. These pathways include: (1) unleaded petrol refined from crude oil; (2) conventional diesel refined from crude oil; (3) Fischer-Tropsch (FT) diesel synthesised from natural gas; (4) conventional liquefied petroleum gas (LPG); (5) compressed natural gas (CNG); (6) liquefied natural gas (LNG); (7) methanol synthesised from natural gas; (8) M85 – an 85%/15% blend of methanol/unleaded petrol; (9) compressed gaseous hydrogen (GH_2) from gasified coal; (10) compressed gaseous hydrogen (GH_2) reformed from natural gas; (11) compressed gaseous hydrogen (GH_2) from electrolysis with grid electricity; (12) compressed gaseous hydrogen (GH_2) from electrolysis with natural gas-fired combined-cycle-gas-turbine (CCGT) electricity; (13) compressed gaseous hydrogen (GH_2) from electrolysis with renewable electricity; (14) liquefied hydrogen (LH_2) from gasified coal; (15) liquefied hydrogen (LH_2) reformed from natural gas; (16) liquefied hydrogen (LH_2) from electrolysis with grid electricity; (17) liquefied hydrogen (LH_2) from electrolysis with natural gas-fired combined-cycle-gas-turbine (CCGT) electricity; (18) liquefied hydrogen (LH_2) from electrolysis with renewable electricity; (19) grid electricity; (20) natural gas-fired combined-cycle-gas-turbine (CCGT) electricity; (21) renewable electricity; ethanol from fermentation/distillation of molasses; (22) E10 – a 90%/10% blend of unleaded petrol/ethanol; (23) E85 – an 85%/15% blend of ethanol/unleaded petrol; (24) biodiesel produced from rapeseed.

The alcohol-dominant fuel blends (M85 and E85) are included in this study since these blends are better-suited for use in combustion engine vehicles (ICVs and HEVs) than pure alcohol fuels (IEA, 1999). The 10% ethanol blend is included due to its current political relevance in Australia.

Unleaded petrol from crude oil (1) is used as the reference fuel pathway. To reduce the number of WTT pathways that are included in the WTW analysis, pathways (11), (12), (16) and (17) were excluded through the pre-screening exercise discussed in Section 2.3.

4. POWERTRAIN TECHNOLOGIES & TANK-TO-WHEEL RESULTS

4.1 Powertrain Architectures

The powertrain architectures included in this study include internal-combustion-engine vehicles (ICVs), internal-combustion-engine parallel hybrid-electric vehicles (HEVs), fuel cell electric vehicles (FCEVs), fuel cell hybrid-electric vehicles (FCHEVs) and battery electric vehicles (BEVs).

The parametric modelling tool (Simpson and Walker, 2003) utilises a generic approach to modelling various powertrain architectures which allows technologies to be compared in a consistent fashion. Transmission, electric motor and HEV battery technologies are kept consistent for each powertrain architecture, and the relevant technical parameters for these powertrain components are presented in Table III. These technical parameters are derived from previous modelling conducted by the author using the ADVISOR dynamic vehicle simulation software (Wipke et al, 2001). All EVs and HEVs are assumed to have 60% regenerative braking.

4.2 Vehicle Platform

The 2003 Holden VY Commodore sedan (Holden, 2003) was chosen as a representative Australian passenger car for this study. Table IV presents relevant physical data for this platform.

Table III: Transmission, electric motor and HEV battery technologies for the various powertrain architectures considered in the study

Component	Powertrain Architecture	Specific Power (W/kg)	Efficiency
Transmission	ICVs and HEVs (5 speed)	1300	87%
	FCEVs, FCHEVs and BEVs (1 speed)	1625	86%
Electric Motor	ICVs	n/a	n/a
	HEVs	1400	85%
	FCEVs, FCHEVs and BEVs	1027	86%
HEV Battery	ICVs, FCEVs and BEVs	n/a	n/a
	HEVs	444	96%
	FCHEVs	444	94%

Table IV: Physical parameters for the 2003 Holden VY Commodore sedan platform

Curb mass	1550kg
Glider mass (estimated)	1090kg
Aerodynamic drag coefficient	0.32
Frontal area	2.5m^2
Rolling resistance coefficient	0.01
Wheel radius	320mm
Accessory load	1000W

4.3 Driving Pattern

The driving pattern assumed for the tank-to-wheel modelling is the New European Driving Cycle (NEDC) from test procedures specified in United Nations Economic Commission for Europe Regulation 83. From January 2003, these test procedures have been used to measure fuel consumption and emissions for the purposes of labelling production vehicles for the Australian market (Australian Greenhouse Office, 2003).

4.4 Performance Specifications

All vehicles compared in this study are intended to have *identical performance capabilities*, in accordance with the specifications for acceleration, gradability, top speed and driving range presented in Table V. This approach distinguishes this study from previous work, in which certain performance constraints have often been relaxed for particular vehicle technologies. There are, however, two exceptions in this study. The NiMH and VRLA BEVs have reduced driving ranges since the achievement of 500km driving range is not technically feasible for these technologies.

4.5 Fuel/Powertrain Technologies and Tank-to-Wheel Results

Table VI presents the 33 powertrain technologies considered in this study. The data represents predictions of technical specifications for the 2010 timeframe. The technologies include:

- Spark-ignition ICVs for ULP (A), LPG (B), CNG (C), LNG (D), GH_2 (E), LH_2 (F), M85 (G), E85 (H) and E10 (I)
- Compression-ignition ICVs for diesel (J) and biodiesel (K)
- Spark-ignition HEVs for ULP (L), LPG (M), CNG (N), LNG (O), GH_2 (P), LH_2 (Q), M85 (R), E85 (S) and E10 (T)
- Compression-ignition HEVs diesel (U) and biodiesel (V)
- Fuel cell/reformer EVs for ULP (W) and MeOH (X)
- Fuel cell EVs for GH_2 (Y) and LH_2 (Z)
- Fuel cell/reformer HEVs for ULP (Aa) and MeOH (Bb)
- Fuel cell HEVs for GH_2 (Cc) and LH_2 (Dd)
- BEVs with lithium-ion (Li-Ion) (Ee), nickel-metal hydride (NiMH) (Ff) and valve-regulated lead-acid (VRLA) batteries (Gg)

Table V: Performance constraints for the vehicles in this study

Top speed	220 km/h
Acceleration	0-100 kph in 9.0s
Gradability	6.5% at 100 kph
Driving range	500km

Table VI: Tank-to-wheel results for powertrain technologies considered in this study

No.	Fuel	Powertrain	Fuel specific energy (MJ/kg)	Engine / Fuel Cell / Battery specific power (W/kg)	Engine / Fuel Cell / Battery efficiency (%)	Curb Mass (kg)	TTW Efficiency (%)	TTW Energy Consumption (MJ/km)
A	ULP	ICV	37.3[1]	642[7]	22.5[8]	1537	10.4	3.25
B	LPG	ICV	20.7[1]	642[7]	23.7[8,9]	1574	10.9	3.13
C	CNG	ICV	15.6[1]	531[7]	25.8[8]	1656	11.8	2.95
D	LNG	ICV	26.6[1]	531[7]	25.8[8]	1609	11.8	2.91
E	GH2	ICV	12.7[2]	642[7]	27.7[8]	1611	12.7	2.71
F	LH2	ICV	9.5[2]	642[7]	27.7[8]	1655	12.7	2.75
G	M85	ICV	22.2[3]	642[7]	24.5[8,9]	1565	11.2	3.02
H	E85	ICV	24.8[3]	642[7]	23.9[8,9]	1558	11.0	3.08
I	E10	ICV	35.8[3]	642[7]	22.5[8]	1539	10.4	3.25
J	Diesel	ICV	37.3[1]	510[7]	28.5[8]	1600	13.1	2.62
K	BioD	ICV	31.9[1]	510[7]	28.5[8]	1607	13.1	2.62
L	ULP	HEV	37.3[1]	642[7]	30.5[8]	1798	14.7	2.47
M	LPG	HEV	20.7[1]	642[7]	32.1[8,9]	1827	15.4	2.37
N	CNG	HEV	15.6[1]	531[7]	33.0[8]	1907	15.8	2.36
O	LNG	HEV	26.6[1]	531[7]	33.0[8]	1869	15.8	2.33
P	GH2	HEV	12.7[2]	642[7]	37.7[8]	1854	18.1	2.03
Q	LH2	HEV	9.5[2]	642[7]	37.7[8]	1887	18.1	2.05
R	M85	HEV	22.2[3]	642[7]	33.2[8,9]	1820	15.9	2.29
S	E85	HEV	24.8[3]	642[7]	32.4[8,9]	1815	15.6	2.33
T	E10	HEV	35.8[3]	642[7]	30.5[8]	1800	14.7	2.47
U	Diesel	HEV	37.3[1]	510[7]	34.8[8]	1866	16.7	2.21
V	BioD	HEV	31.9[1]	510[7]	34.8[8]	1872	16.7	2.21
W	ULP	FCEV	37.3[1]	259[7]	37.8[8]	2234	14.7	2.75
X	MeOH	FCEV	19.5[1]	259[7]	41.5[8]	2293	16.2	2.55
Y	GH2	FCEV	12.7[2]	375[7]	56.6[8]	1889	22.4	1.66
Z	LH2	FCEV	9.5[2]	375[7]	56.6[8]	1925	22.4	1.67
Aa	ULP	FCHEV	37.3[1]	259[7]	39.2[8]	2162	16.8	2.37
Bb	MeOH	FCHEV	19.5[1]	259[7]	42.6[8]	2204	18.2	2.21
Cc	GH2	FCHEV	12.7[2]	375[7]	55.6[8]	1884	24.0	1.55
Dd	LH2	FCHEV	9.5[2]	375[7]	55.6[8]	1914	24.0	1.56
Ee	Li-Ion	BEV	0.50[4]	420[4]	95.0[4]	2654	39.2	1.14
Ff	NiMH	BEV	0.26[5]	393[5]	92.0[5]	2748	37.5	1.22
Gg	VRLA	BEV	0.13[6]	300[6]	90.0[6]	2817	36.4	1.27

Notes:

1. From International Energy Agency (1999)
2. From TIAX (2002)
3. For fuel blends, values are calculated in proportion to the constituent fuels.
4. Based on 140Wh/kg and 420W/kg lithium-ion (Li-Ion) batteries (SAFT, 2003)
5. Based on 70Wh/kg and 220W/kg nickel-metal-hydride (NiMH) batteries (Ovonic, 2000)
6. Based on 35Wh/kg and 300W/kg valve-regulated lead-acid (VRLA) batteries (JSB, 2000)
7. From European Commision Joint Research Centre (2003)
8. From L-B-Systemtechnik (2002)
9. Efficiency adjusted for octane rating of fuel based on data in International Energy Agency (1999)

The results of the tank-to-wheel modelling are presented in Table VI in terms of curb mass, TTW efficiency and TTW energy consumption. Powertrain (A) is chosen as the reference powertrain technology for the comparison.

The curb masses of the ICVs are quite similar, with some minor variations due to differences in the specific energy of fuels and specific power of engines. The HEVs are heavier (+250kg) than their ICV counterparts, which reflects the lower specific power of HEVs' motor plus battery combination relative to engines. The FCEVs are FCHEVs are all quite heavy (~2000kg) due to the low specific power of fuel cell systems (particularly reformers), although the FCHEVs are slightly less heavy due to the higher specific power of batteries relative to fuel cell systems. The BEVs are all extremely heavy (>2650kg) due to the high driving range requirements (Li-Ion: 500km, NiMH: 250km, VRLA: 125km).

The TTW efficiency correlates closely with engine/fuel cell efficiency, although the non-hybridised ICVs and FCEVs do have the additional efficiency penalty of no regenerative braking. On average, the HEVs are approximately 40% more efficient than their ICV counterparts. The reformer-based, non-hybrid FCEVs show little efficiency advantage over HEVs using the same fuels, whereas the H_2-fuelled FCEVs are approximately 25% more efficient than H_2-fuelled HEVs. FCHEVs with reformers are approximately 15% more efficient than their FCEV counterparts, whereas the H_2-fuelled FCHEVs are only slightly more efficient than non-hybrid variants. The battery EVs' high TTW efficiency must be considered in light of the fact that no fuel conversion occurs onboard the vehicle (instead occurring during the WTT stage).

However, the TTW energy consumption (which combines the effects of curb mass and powertrain efficiency) is the most-important comparison. Relative to ICVs, the higher efficiency of reformer FCEVs is largely eroded by their much-higher mass, whereas the H_2 FCEVs offer a 40% reduction in energy consumption from their ICV counterparts. The higher efficiency of HEVs relative to ICVs is only slightly impacted by their greater mass, with a decrease in energy consumption of approximately 25%. In contrast, the hybridisation of FCEVs offers both efficiency and mass-reduction benefits – the reformer FCHEVs and H_2 FCHEVs offer 14% and 7% less energy consumption, respectively, than their non-hybrid FCEV counterparts.

From these TTW results it seems clear that improvements in vehicle energy consumption are primarily due to greater powertrain efficiency, although large increases in curb mass can substantially detract from efficiency gains. Furthermore, the energy consumption of non-hybrid ICVs and FCEVs shows a heightened sensitivity to curb mass due to their lack of regenerative braking.

The equivalent TTW fuel consumption of the various powertrain options is presented in Figure I. As discussed in Section 2.3, the following powertrains were excluded from the WTW comparison due to their inferior energy consumption,:

- ICVs for LPG (B), CNG (C), LNG (D), GH_2 (E), LH_2 (F), M85 (G), E85 (H), E10 (I), diesel (J) and biodiesel (K). The ULP ICV (A) is retained as the reference vehicle.
- HEVs for GH_2 (P) and LH_2 (Q).
- FCEVs for ULP (W), MeOH (X), GH_2 (Y) and LH_2 (Z).
- FCHEV for ULP (Aa).
- BEVs with nickel-metal hydride (NiMH) (Ff) and valve-regulated lead-acid (VRLA) batteries (Gg). These BEVs could also be excluded because of their inability to achieve the driving range target.

7. WELL-TO-WHEEL RESULTS

Figure II presents the results of the well-to-wheel comparison, for which the values have been normalised against the reference fuel/vehicle – the ULP ICV (1A). The following observations can be made from these results:

- Coal-based pathways have very high WTW energy consumption and emissions due to coal's high carbon intensity and the inefficiency of converting coal into more useful fuels.
- Relative to the reference fuel/vehicle, grid-charged electric vehicles have nearly the same WTW energy consumption. However, their WTW greenhouse emissions are substantially higher due to the prevalence of greenhouse-gas-intense coal-fired power generation in Australia.
- Natural gas is a promising energy feedstock for automotive fuels in terms of WTW energy consumption and greenhouse emissions, however, it should be utilised directly (without conversion into another fuel such as hydrogen or methanol) to maximise these benefits.
- Battery electric vehicles charged with natural gas-fired electricity demonstrate substantial reductions in WTW greenhouse gas emissions relative to the reference fuel. Therefore, as Australia's power generation transitions towards a larger natural gas-fired generating capacity, the environmental merits of EVs will improve considerably.
- Renewable biofuel pathways (ethanol and biodiesel) do offer reductions in full-cycle greenhouse gases, although the degree of emissions reduction is quite dependent on the production methods used to produce these fuels. However, the energy intensity of biofuel pathways is substantially higher than other alternatives for reducing greenhouse emission (such as CNG HEVs). The environmental benefits of low-biofuel-fraction blends such as E10 are marginal at best.
- The most-efficient use of renewable electricity is to charge electric vehicles. Conversion of renewable electricity into hydrogen via electrolysis incurs substantial energy losses – so much so that these pathways are nearly as energy intense as the reference fuel/vehicle. All pathways based upon renewable electricity have near-zero greenhouse gas emissions.

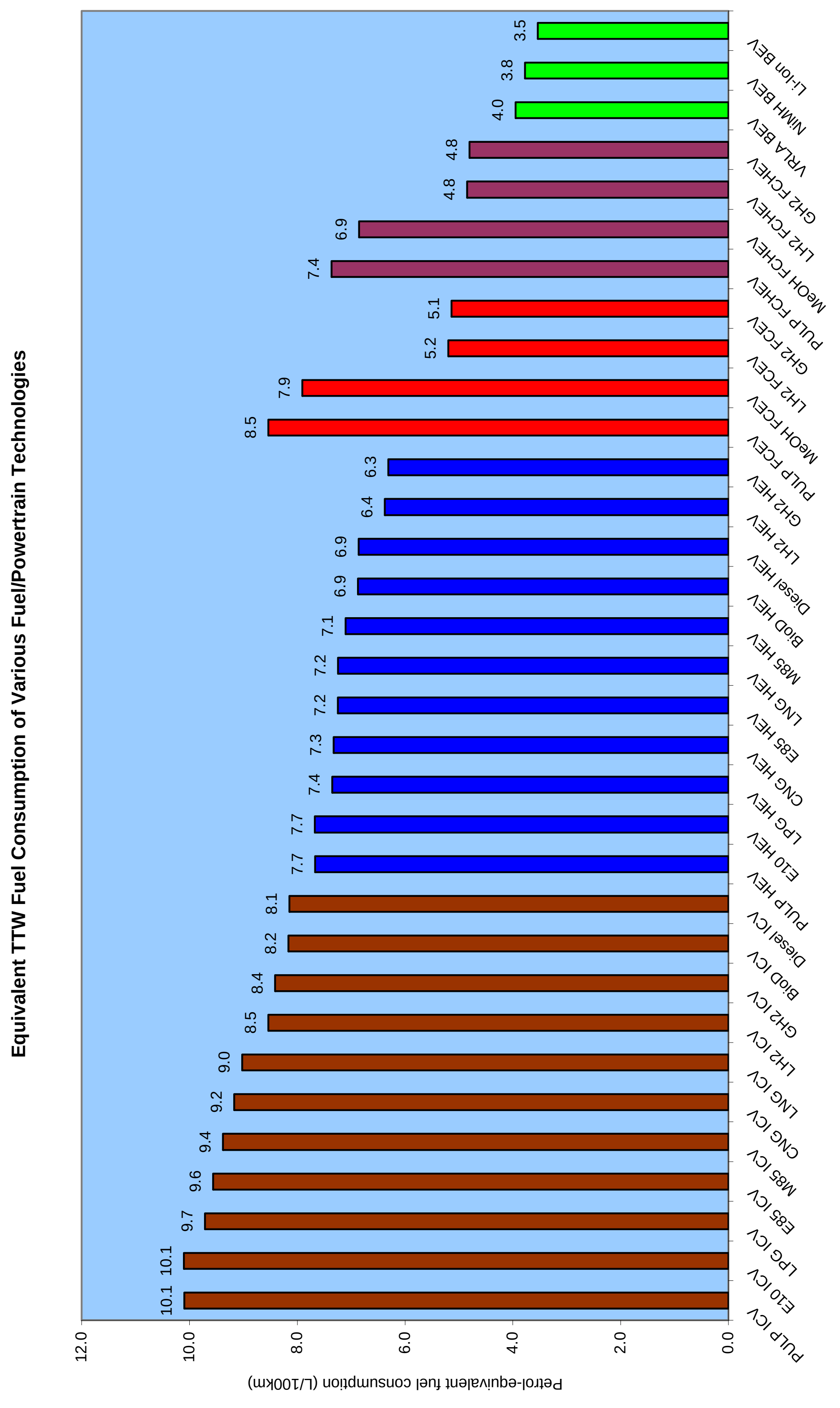

Figure I: Equivalent tank-to-wheel fuel consumption for the various fuel/powertrain options

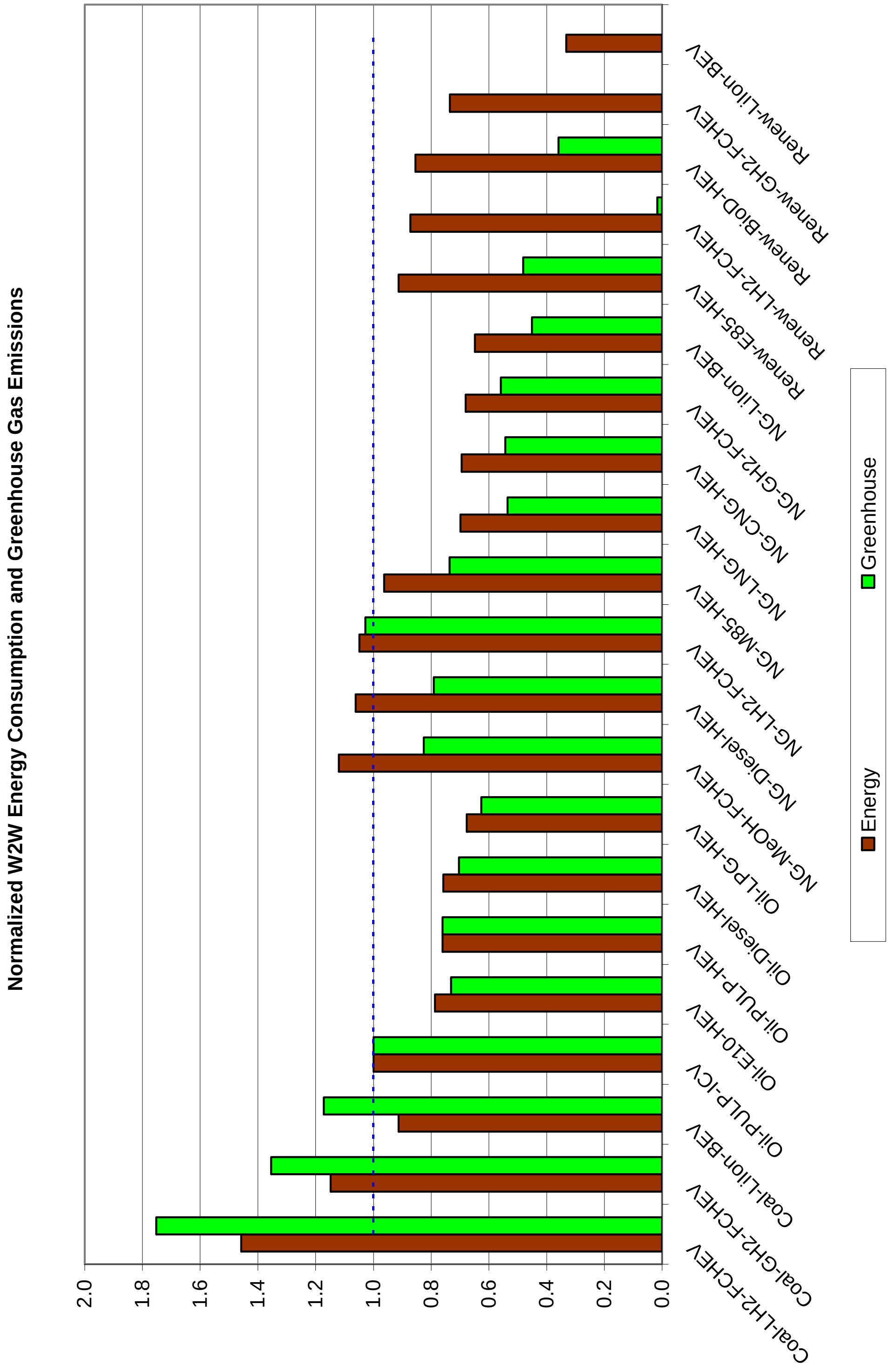

Figure II: Relative well-to-wheel results for energy consumption and greenhouse emissions

8. CONCLUSION

From the results of this well-to-wheels study, a number of important conclusions can be made:

1. The best way to utilise an energy feedstock is via as direct a pathway as possible, avoiding unnecessary energy conversions. This is an important conclusion in regard to synthetic fuels such as hydrogen. For the pathways considered in this study, it is preferable not to use hydrogen since the energy losses and emissions incurred in the production of hydrogen typically outweigh the higher efficiency of fuel cell-based powertrains.

2. Use of coal as a feedstock for production of vehicle fuels will result in extremely high levels of full-cycle energy consumption and greenhouse emissions.

3. HEVs using conventional fuels (petrol or diesel) offer significant near-term reductions in energy intensity and greenhouse gas emissions from the light-duty vehicle sector.

4. Natural gas appears to be a promising transitional energy feedstock for automotive fuels. HEVs fuelled with CNG or LNG offer even greater reductions in energy intensity and greenhouse emissions than HEVs using conventional fuels. Natural gas-fired electricity can also be used to charge electric vehicles resulting in the lowest greenhouse emissions of any natural-gas pathway.

5. Based on their energy intensity, biofuels may not be the most practical method for reducing greenhouse gas emissions from the light-duty vehicle sector.

6. Well-to-wheel pathways based upon renewable electricity generation offer near-zero greenhouse gas emissions. However, renewable electricity should be utilised directly in an electric vehicle to avoid the energy intensity of converting it into other fuels (i.e. hydrogen).

Overall, this study demonstrates the importance of well-to-wheels analysis as a methodology for exploring the true relative performance of alternative vehicle fuels and powertrain technologies.

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