Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

Description of individual processes and detailed input data

All WTT data was stored in LBST's E^3 database and that software was used to calculate the energy and GHG balances of the pathways. This appendix provides full detail of the input data. It consists in two elements:

- A series of tables giving input data to each process,
- A textual description and justification of each process.

The information has been split into logical sections each incorporating the processes involved in a number of related pathways. The process that are new to this version are highlighted in <mark>yellow</mark>.

Both energy and GHG figures are shown per unit energy content of the output of the particular process (MJ), NOT of the output of the total pathway (e.g. the energy required for wheat farming is shown per MJ of wheat grain, rather than MJ of ethanol).

The energy figures are expressed as net total energy expended (MJ_{xt}) in each process (i.e. excluding the energy transferred to the final fuel) per unit energy content of the output of the process (MJ). Where intermediate energy is involved (e.g. electricity) the relation between primary and intermediate energy is expressed in efficiency terms and in terms of total primary energy (MJ_p) per unit energy actually expended in the process (MJ_x).

Example:
- If a process requires 0.1 MJ of electricity per MJ final fuel, the expended energy is expressed as 0.1 MJ_x/MJ.
- If electricity is generated with a 33% efficiency, the primary energy associated to 1 MJ of electricity is 3 MJ_p.
- The total primary energy associated to the process is then 3 x 0.1 = 0.3 MJ_p/MJ.

All energy is accounted for regardless of the primary energy source, i.e. including renewable energy. This is necessary to estimate the energy efficiency of each process and each pathway. The share of fossil energy in each complete pathway is shown in the overall pathway energy balance (*see **WTT Appendix 2***).

The CO_2 figures represent the actual emissions occurring during each process. When CO_2 emissions stem from biomass sources only the net emissions are counted. The figures exclude the CO_2 emissions associated with the combustion of the final fuel when it is of fossil origin. For carbon-containing fuels of renewable origin, however, a credit is given for an amount of CO_2 equivalent to that released during combustion. In the TTW section of the study, all fuels can then be treated in the same way and allocated CO_2 emissions corresponding to their carbon content regardless of its origin.

The figures used in this study and described in this appendix are generally based on literature references as given. In a number of cases, particularly with regards to oil-based pathways, we have used figures considered as typical in the industry and generally representing the combined views of a number of experts. Where no specific reference is given, the figures are the result of standard physical calculations based on typical parameters. This is the case for instance for CNG or hydrogen compression energy.

Most processes include a line labelled "Primary energy consumption and emissions": this is an approximate and simplified calculation intended for the reader's guidance. The full calculation has been carried out by LBST's E^3 database resulting in the figures in ***WTT Appendix 2***.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

Where appropriate we have specified a range of variability associated to a probability distribution either normal (Gaussian), double-triangle for asymmetrical distribution or equal (all values in the range equally probable). The equal distribution has been used when representing situations where a range of technologies or local circumstances may apply, all being equally plausible. For the complete pathway, a variability range is estimated by combining the individual ranges and probability distributions with the Monte-Carlo method.

__Corrections from version 2b of May 2006__
Minor errors and inconsistencies have been corrected. The bio-diesel esterification pathway has been slightly altered to include glycerine purification. The following sections have been changed:

3	*Z5*
9	*RF*
11	*SC2*
13.4	*RO/SO5 RO/SO6*
13.5	*C9 (removed) C10*
13.6	*SY3 SYML*
14.3	*W3k*

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

Table of contents

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

1 Useful conversion factors and calculation methods

1.1 General

1 kWh = 3.6 MJ = 3412 Btu
1 Mtoe = 42.6 GJ
1 MW = 1 MJ/s = 28.8 PJ/a (8000 h)

1 t crude oil ~ 7.4 bbl
1 Nm^3 of EU-mix NG ~ 0.8 kg ~ 40 MJ
(i.e. 1 Nm^3 of NG has approximately the same energy content as 1 kg of crude oil)

1.2 Factors for individual fuels

Gases

NG EU-mix	MW	GJ/d	PJ/a	kg/h	kg/d	t/a	Nm$_3$/h
MW (MJ/s)		86.4	28.8	80.4	1929	643	102
GJ/d	0.012		0.333	0.930	22.3	7.4	1.18
PJ/a (8000 h)	0.035	3		2.79	67.0	22.3	3.53
kg/h	0.012	1.07	0.36		24	8	1.27
kg/d		0.04	0.01			0.33	0.05
t/a (8000 h)		0.13	0.04	0.13	3		0.16
Nm$_3$/h		0.85	0.28	0.79	19.0	6.3	

Methane	MW	GJ/d	PJ/a	kg/h	kg/d	t/a	Nm$_3$/h
MW (MJ/s)		86.4	28.8	72.0	1728	576	101
GJ/d	0.012		0.333	0.833	20.0	6.7	1.17
PJ/a (8000 h)	0.035	3		2.50	60.0	20.0	3.50
kg/h	0.014	1.20	0.40		24	8	1.40
kg/d		0.05	0.02			0.33	0.06
t/a (8000 h)		0.15	0.05	0.13	3		0.18
Nm$_3$/h		0.86	0.29	0.71	17.1	5.7	

Hydrogen	MW	GJ/d	PJ/a	kg/h	kg/d	t/a	Nm$_3$/h
MW (MJ/s)		86.4	28.8	30.0	719	240	336
GJ/d	0.012		0.333	0.347	8.3	2.8	3.89
PJ/a (8000 h)	0.035	3		1.04	25.0	8.3	11.66
kg/h	0.033	2.88	0.96		24	8	11.20
kg/d		0.12	0.04			0.33	0.47
t/a (8000 h)		0.36	0.12	0.13	3		1.40
Nm$_3$/h		0.26	0.09	0.09	2.1	0.7	

WTT APPENDIX 1

Liquids

Gasoline

Gasoline	MW	GJ/d	PJ/a	kg/h	kg/d	t/a	m₃/d
MW (MJ/s)		86.4	28.8	83.1	1995	665	2.68
GJ/d	0.01		0.33	0.96	23.1	7.70	0.03
PJ/a (8000 h)	0.03	3		2.89	69.3	23.1	0.09
kg/h	0.01	1.04	0.35		24	8	0.03
kg/d		0.04	0.01			0.333	
t/a (8000 h)		0.13	0.04	0.13	3		
m₃/d		32.3	10.8	31.0	745	248	

FT diesel

FT diesel	MW	GJ/d	PJ/a	kg/h	kg/d	t/a	m₃/d
MW (MJ/s)		86.4	28.8	81.8	1964	655	2.52
GJ/d	0.01		0.33	0.95	22.7	7.58	0.03
PJ/a (8000 h)	0.03	3		2.84	68.2	22.7	0.09
kg/h	0.01	1.06	0.35		24	8	0.03
kg/d		0.04	0.01			0.333	
t/a (8000 h)		0.13	0.04	0.13	3		
m₃/d		34.3	11.4	32.5	780	260	

Diesel

Diesel	MW	GJ/d	PJ/a	kg/h	kg/d	t/a	m₃/d
MW (MJ/s)		86.4	28.8	83.5	2005	668	2.41
GJ/d	0.01		0.33	0.97	23.2	7.73	0.03
PJ/a (8000 h)	0.03	3		2.90	69.6	23.2	0.08
kg/h	0.01	1.03	0.34		24	8	0.03
kg/d		0.04	0.01			0.333	
t/a (8000 h)		0.13	0.04	0.13	3		
m₃/d		35.9	12.0	34.7	832	277	

DME

DME	MW	GJ/d	PJ/a	kg/h	kg/d	t/a	m₃/d
MW (MJ/s)		86.4	28.8	126.6	3039	1013	4.54
GJ/d	0.01		0.33	1.47	35.2	11.72	0.05
PJ/a (8000 h)	0.03	3		4.40	105.5	35.2	0.16
kg/h	0.01	0.68	0.23		24	8	0.04
kg/d		0.03	0.01			0.333	
t/a (8000 h)		0.09	0.03	0.13	3		
m₃/d		19.0	6.3	27.9	670	223	

Methanol

Methanol	MW	GJ/d	PJ/a	kg/h	kg/d	t/a	m₃/d
MW (MJ/s)		86.4	28.8	180.9	4342	1447	5.48
GJ/d	0.01		0.33	2.09	50.3	16.75	0.06
PJ/a (8000 h)	0.03	3		6.28	150.8	50.3	0.19
kg/h	0.01	0.48	0.16		24	8	0.03
kg/d		0.02	0.01			0.333	
t/a (8000 h)		0.06	0.02	0.13	3		
m₃/d		15.8	5.3	33.0	793	264	

Ethanol

Ethanol	MW	GJ/d	PJ/a	kg/h	kg/d	t/a	m₃/d
MW (MJ/s)		86.4	28.8	134.3	3224	1075	4.06
GJ/d	0.01		0.33	1.55	37.3	12.44	0.05
PJ/a (8000 h)	0.03	3		4.66	111.9	37.3	0.14
kg/h	0.01	0.64	0.21		24	8	0.03
kg/d		0.03	0.01			0.333	
t/a (8000 h)		0.08	0.03	0.13	3		
m₃/d		21.3	7.1	33.1	794	265	

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

Solids

Hard Coal	MW	GJ/d	PJ/a	kg/h	kg/d	t/a
MW (MJ/s)		86.4	28.8	135.8	3260	1087
GJ/d	0.01		0.33	1.57	37.7	12.58
PJ/a (8000 h)	0.03	3		4.72	113.2	37.7
kg/h	0.01	0.64	0.21		24	8
kg/d		0.03	0.01			0.333
t/a (8000 h)		0.08	0.03	0.13	3	

Wood	MW	GJ/d	PJ/a	kg/h	kg/d	t/a
MW (MJ/s)		86.4	28.8	200.0	4800	1600
GJ/d	0.01		0.33	2.31	55.6	18.52
PJ/a (8000 h)	0.03	3		6.94	166.7	55.6
kg/h	0.01	0.43	0.14		24	8
kg/d		0.02	0.01			0.333
t/a (8000 h)		0.05	0.02	0.13	3	

1.3   GHG calculations

CO$_2$-equivalence coefficients

Methane   23
Nitrous oxide   296

CO$_2$ emissions from combustion (assuming total combustion)

1 kg of a fuel with C% carbon emits:

$1 \times C\% / 100 / 12 \times 44 = (0.0367 \times C\%)$ kg of CO_2

1 MJ of a fuel with λ MJ/kg (LHV) and C% carbon emits:

$1 / \lambda \times C\% / 100 / 12 \times 44 = (0.0367 / \lambda \times C\%)$ kg of CO_2

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

2   Fuels properties

2.1   Standard properties of fuels

Gases

		NG EU-mix	NG (Rus)	Methane		Hydrogen	LPG
LHV	MJ/kg	45.1	49.2	50.0		120.1	46.0
	kg/kWh	0.080	0.073	0.072		0.030	0.078
	kWh/kg	12.53	13.67	13.89		33.36	12.78
	MM, g/mol	17.7	16.3	16.0		2.0	50.0
	kWh/Nm^3	9.90	9.94	9.92		2.98	28.52
C content	% m	69.4%	73.9%	75.0%		0.0%	82.4%
CO_2 emission factor (assuming total combustion)							
	g CO_2/MJ	56.4	55.1	55.0			
	kg CO_2/kg	2.54	2.71	2.75			
	kg CO_2/Nm^3	3.22	3.72	3.85			

Liquids

		Crude	Gasoline	Diesel	Naphtha	HFO	Syn diesel	Methanol	DME	Ethanol	RME	REE	MTBE	ETBE
Density	kg/m^3	820	745	832	700	970	780	793	670	794	890	890	745	750
LHV	MJ/kg	42.0	43.2	43.1	44.0	40.5	44.0	19.9	28.4	26.8	37.2	37.9	35.1	36.3
	kg/kWh	0.086	0.083	0.084	0.082	0.089	0.082	0.181	0.127	0.134	0.097	0.095	0.103	0.099
	kWh/kg	11.67	12.00	11.97	12.22	11.25	12.22	5.53	7.90	7.44	10.33	10.53	9.75	10.07
C content	% m	86.5%	86.4%	86.1%	85.0%	89.0%	85.0%	37.5%	52.2%	52.2%	76.5%	76.5%	68.2%	70.6%
CO_2 emission factor (assuming total combustion)														
	g CO_2/MJ	75.5	73.3	73.2	70.8	80.6	70.8	69.1	67.3	71.4	75.4	74.0	71.2	71.4
	kg CO_2/kg	3.17	3.17	3.16	3.12	3.26	3.12	1.38	1.91	1.91	2.81	2.81	2.50	2.59

Solids

		Hard Coal	Wood	Wheat	S beet	Rapeseed	SunFseed	SB pulp	SB slops	Wheat straw	DDGS	Sugar cane
Moisture content			0.3	0.16	0.765	0.1	0.1	0.09	0.09	0.16	0.1	73%
LHV (dry matter)	MJ/kg	29.4	18.0	17.0	16.3	26.4	26.4	15.6	15.6	17.2	16.0	19.6
	kg/kWh	0.122	0.200	0.212	0.221	0.136	0.136	0.231	0.231	0.209	0.225	0.184
	kWh/kg	8.2	5.0	4.7	4.5	7.3	7.3	4.3	4.3	4.8	4.4	5.4
C content	% m	77.2%	50.0%									
CO_2 emission factor (assuming total combustion)												
	g CO_2/MJ	96.3	101.9									
	kg CO_2/kg	2.83	1.83									

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

2.2   Detailed composition of natural gas per source

Origin	CIS	NL	UK	Norway	Algeria	EU-mix	
						%mol	%m
Share in EU-mix	21.4%	22.0%	30.4%	11.8%	14.4%		
H_2	0.0%	0.0%	0.5%	0.5%	0.8%	0.3%	0.0%
C1	98.4%	81.5%	86.0%	86.0%	92.1%	88.5%	79.9%
C2	0.4%	2.8%	8.8%	8.8%	1.0%	4.6%	7.7%
C3	0.2%	0.4%	2.3%	2.3%	0.0%	1.1%	2.7%
C4	0.1%	0.1%	0.1%	0.1%	0.0%	0.1%	0.3%
C5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
C6	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
C7	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CO_2	0.1%	1.0%	1.5%	1.5%	0.0%	0.9%	2.2%
N_2	0.8%	14.2%	0.8%	0.8%	6.1%	4.5%	7.1%
	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
MM (g/mol)	16.3	18.5	18.4	18.4	16.8	17.7	
Density (kg/Nm3)	0.727	0.827	0.820	0.820	0.750	0.791	
LHV (MJ/Nm3)	35.7	31.4	38.6	38.6	33.7	35.7	
LHV (GJ/t)	49.2	38.0	47.1	47.1	44.9	45.1	
MON (CARB)	138.2	132.9	122.3	122.3	138.0	129.2	
Methane number (CARB)	105.3	96.8	79.6	79.6	105.0	90.7	
Methane number (DK)	96.6	93.3	75.7	75.7	98.3	84.1	

Source: GEMIS

MON and Methane number methods references:

'Algorithm for methane number determination for natural gasses' (sic) by Paw Andersen, Danish gas Technology Centre, Report R9907, June 1999
http://uk.dgc.dk/publications/algotitme.htm

CARB: http://www.arb.ca.gov/regact/cng-lpg/cng-lpg.htm

The EU-mix is the gas that is deemed to be available to the vehicle as CNG.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

2.3 Deemed composition of LPG

Component	% m/m	% v/v	MM	LHV (GJ/t)	C (%m/m)	H (%m/m)
C1	0.1	0.3	16	50.1	75.0	25.0
C2	2.4	4.0	30	47.5	80.0	20.0
C2=	0.5	0.9	28	47.2	85.7	14.3
C3	40.0	45.4	44	46.4	81.8	18.2
C3=	1.0	1.2	42	45.8	85.7	14.3
nC4	30.0	25.8	58	45.8	82.8	17.2
iC4	22.0	19.0	58	45.7	82.8	17.2
C4=	1.5	1.3	56	45.3	85.7	14.3
iC4=	1.5	1.3	56	45.1	85.7	14.3
nC5	1.0	0.7	72	45.4	83.3	16.7
Total	**100.0**	**100.0**	**50**	**46.0**	**82.4**	**17.6**
Total						
C2-	3.0					
C3	41.0					
C4	55.0		**CO2 emission factor**			
C5+	1.0		3.02 t CO2 / t			
Olefins	4.5		65.7 kg CO2 / GJ			

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

3   Common processes

Code	Process	Assoc. process	MJex/ MJ	g CO2/ MJ	g CH4/ MJ	g N2O/ MJ	g CO2 eq/ MJ	Eff	MJp/ MJex	g CO2/ MJex	g CH4/ MJex	g N2O/ MJex	MJex/ t.km	Min	Max	Probability distribution	Reference
	Transport fuels simplified production processes (used for auxiliary transport fuel requirements)																
Z1	**Diesel production** Crude oil		0.1600	14.30													CONCAWE
Z2	**Road tanker** Diesel									73.25			0.936				LBST
Z3	**HFO production** Crude oil		0.0880	6.65													TFE 2001
Z4	**Product carrier 50 kt** Energy (ship's fuel) as HFO)									gCO2/tkm 9.99			0.124	0.112	0.136	Dble tri	Oko inventar
Z5	**Rail transport** Electricity (EU-mix, MV) *Primary energy consumption and emissions*	Z7a	MJex/ t.km *0.5949*	g CO2/ t.km *25.05*	g CH4/ t.km *0.06*	g N2O/ t.km *0.00*	g CO2 eq/ t.km *26.79*						0.210				Okoinventar
Z6	**Marginal NG for general use (4000 km piped)**								1.1306	63.12	0.20	0.00					

As electricity is used as an intermediate rather than final energy source, the figures below are shown in total primary energy (MJp) to produce one unit of electricity (MJe)

Code	Process	Assoc. process	MJp/ MJe	g CO2/ MJe	g CH4/ MJe	g N2O/ MJe	g CO2 eq/ MJe	Eff		Reference
Z7	**Electricity (EU-mix)** Production									GEMIS 4.07
	Biomass		0.0074							
	Coal brown		0.1956							
	Coal hard		0.5512							
	Geothermal		0.0016							
	Hydro		0.1239							
	Oil		0.2397							
	NG		0.3440							
	Nuclear		1.1354							
	Waste		0.1838							
	Wind		0.0044							
			2.7868					35.9%		
Z71	HV+MV losses		0.0172							
Z72	LV losses		0.0120							
Z7a	Electricity (EU-mix, MV)		2.8347	119.36	0.2911	0.0054	127.65	35.3%		GEMIS 3.03
Z7b	Electricity (EU-mix, LV)		2.8687	120.79	0.2946	0.0055	129.18	34.9%		GEMIS 3.03

Z1   Diesel production

This process is used to compute the energy associated to the consumption of diesel fuel for transportation purposes in a given pathway. The figures stem from the Diesel provision pathway COD.

Z2   Road tanker

This process represents the diesel fuel consumption and CO_2 emissions of a standard diesel-powered road tanker per t.km transported, including the return trip of the empty vehicle.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

When calculating the total energy and emissions associated to road transport, the figures corresponding to diesel production are added.

Z3   Heavy Fuel Oil (HFO) production

This process is used to compute the energy associated to the consumption of HFO for transportation purposes (essentially shipping) in a given pathway. Evaluating the energy associated to HFO production is a difficult issue. It can be argued that increasing HFO demand would "rebalance the barrel", resulting in decreased requirement for conversion of residue into distillates; this could even result in an energy saving in the refineries. Conversely, decreasing HFO demand would increase the need for conversion and increase energy requirements. In our pathways, HFO is essentially used for long-distance shipping of fossil-based fuels and the share of the HFO production energy in the total for the pathway is very small. For simplicity we have opted for a single value showing a net energy consumption.

Z4   Product carrier (50 kt)

This process represents the energy and CO_2 emissions associated with long-distance sea transport of a number of liquid products such as FT diesel or methanol (per t.km and including the return trip of the empty ship) [*ESU 1996*]. This does not concern crude oil which is generally transported in larger ships). The variability range represents the diversity of ships available for such transport.

Z5   Rail transport

This process represents the energy and CO_2 emissions associated to transport of liquid products by rail (per t.km), assuming the use of EU-mix electricity as energy source [*GEMIS 2002*].

Z6   Marginal use of natural gas

This process represents the energy and CO_2 emissions associated with use of marginal natural gas (assumed to be Russian gas quality transported to Europe over 4000 km by pipeline.

Z7   Electricity (EU-mix)

Unless the process produces its own electricity, the electrical energy used in processes deemed to take place within the EU is assumed to have been generated by the EU electrical mix in 2010. There are several sources of information for this a/o the IEA, Eurelectric and the EU Commission's "Poles" model. All sources report slightly different figures for the past years and of course show different forecasts. There is, however, a general agreement to show a decrease of nuclear, solid fuels and heavy fuel oil compensated mainly by natural gas. Renewables, although progressing fast in absolute terms, do not achieve a significant increase in relative terms because of the sharp increase in electricity demand. As a result, although the primary energy composition of the 2010 "kWh" is different from that of 2000, the resulting CO_2 emissions are not very different.

We have opted for the figures compiled in the German GEMIS database for the year 1999 [*GEMIS 2002*]. A correction is applied to account for typical transmission losses to the medium and low voltage levels.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

4 Crude oil – based fuels provision

4.1 Crude oil, diesel fuel

Code	Process	Assoc. processes	Expended energy and emissions per MJ of main product of the process					Transport distance	Transport energy	Transport requirement	Range		Probability distribution	Reference
			MJex/ MJ	g CO2/ MJ	g CH4/ MJ	g N2O/ MJ	g CO2eq/ MJ	km or Nm	MJex/ t.km	t.km/ MJ	Min	Max		
CO1	**Crude oil production**													
	Energy as crude oil		0.0250	1.89			1.89				0.010	0.040	Normal	Oil companies average value
	CO2 eq emissions			1.45			1.45							
	Total CO2 eq			3.33			3.33							
CO2	**Crude oil transportation**													Shell 2001
	Energy as HFO	Z3	0.0101	0.81			0.81				0.0096	0.0106	Normal	
CD1	**Crude oil refining, marginal diesel**													CONCAWE
	Crude oil		0.1000	8.60			8.60				0.0800	0.1200	Normal	
CD2	**Diesel transport**													Total
	Barge, 9000 t (33%)													
	Energy as Diesel	Z1	0.0011	0.08			0.08							
	Energy as HFO		0.0052	0.39			0.39							
	Total CO2			0.48			0.48							
	Primary energy consumption and emissions		*0.0070*	*0.53*			*0.53*							
	Rail, 250 km (33%)													
	Distance	Z5						250		0.0058				
	Primary energy consumption and emissions		*0.0035*	*0.15*	*0.0004*	*0.0000*	*0.16*							
	Pipeline (33%)													
	Electricity (EU-mix, LV)	Z7b	0.0002											
	Primary energy consumption and emissions		*0.0006*	*0.02*	*0.0001*	*0.0000*	*0.03*							
	Total Primary energy consumption and emissions		*0.0037*	*0.23*	*0.0001*	*0.0000*	*0.24*							
CD3	**Diesel depot**													
	Electricity (EU-mix, LV)	Z7b	0.0008											Total
	Primary energy consumption and emissions		*0.0024*	*0.10*	*0.0002*	*0.0000*	*0.11*							
CD4	**Diesel distribution and dispensing**													
	Tanker load and distance	Z2, Z1						150		0.0037				
	Diesel consumption and emissions		0.0035	0.31			0.31							
	Retail, Electricity (EU-mix, LV)	Z7b	0.0034											Total
	Primary energy consumption and emissions		*0.0138*	*0.72*	*0.0010*	*0.0000*	*0.75*							

CO1   Crude oil production

These figures include all the energy and GHG emissions associated with crude oil production and conditioning at or near the wellhead (such as dewatering and associated gas separation). The total CO_2eq figure includes emissions of GHGs other than combustion CO_2.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

Production conditions vary considerably between producing regions, fields and even between individual wells and it is only meaningful to give typical or average energy consumption and GHG emission figures for the range of crudes under consideration, hence the wide variability range indicated. These figures are best estimates for the basket of crude oils available to Europe [*Source: CONCAWE*].

CO2 Crude oil transportation

Crude oil is mostly transported by ship. The type of ship used depends on the distance to be covered. The bulk of the Arab Gulf crude is shipped in large ships (VLCC or even ULCC Very/Ultra Large Crude Carrier) that can carry between 200 and 500 kt and travel via the Cape of Good Hope to destinations in Western Europe and America or directly to the Far East. North Sea or African crudes travel shorter distances for which smaller ships (100 kt typically) are used.

Pipelines are also extensively used from the production fields to a shipping terminal. Some Middle Eastern crudes are piped to a Mediterranean port. The developing regions of the Caspian basin will rely on one or several new pipelines to be built to the Black Sea. Crude from central Russia is piped to the Black Sea as well as directly to Eastern European refineries through an extensive pipeline network.

Although the majority of refineries tend to be at coastal locations, a number of them are inland. Within Western Europe, there are several inland pipelines from the Mediterranean to North Eastern France and Germany as well as from the Rotterdam area to Germany.

Here again, there is a wide diversity of practical situations. The figures used here are typical for marginal crude originating from the Middle East. The energy is supplied in the form of HFO, the normal ship's fuel [*Source: Shell*]. Note that North Sea or North African crudes or again pipeline transport would command somewhat smaller figures.

CD1 Crude oil refining, marginal diesel

This represents the energy and GHG emissions that can be saved, in the form of crude oil, by not producing a marginal amount of diesel in Europe, starting from a 2010 "business-as-usual" base case [*Source: CONCAWE*, see **WTT Appendix 3** for details].

CD2 Diesel transport

Road fuels are transported from refineries to depots via a number of transport modes. We have included water (inland waterway or coastal), rail and pipeline (1/3 each). The energy consumption and distance figures are typical averages for EU.

Barges and coastal tankers are deemed to use a mixture of marine diesel and HFO. Rail transport consumes electricity. The consumption figures are typical [*Source: Total*]. The road tanker figures pertain to a notional 40 t truck transporting 26 t of diesel in a 2 t tank (see also process Z2).

CD3 Diesel depot

A small amount of energy is consumed in the depots mainly in the form of electricity for pumping operations [*Source: Total*].

CD4 Diesel distribution

From the depots, road fuels are normally trucked to the retail stations where additional energy is required, essentially as electricity, for lighting, pumping etc. This process includes the energy required for the truck as well as the operation of the retail station [*Source: Total*].

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

4.2   Gasoline

Code	Process	Assoc. processes	Expended energy and emissions per MJ of main product of the process					Transport distance	Transport energy	Transport requirement	Range		Probability distribution	Reference
			MJex/ MJ	g CO2/ MJ	g CH4/ MJ	g N2O/ MJ	g CO2eq/ MJ	km or Nm	MJex/ t.km	t.km/ MJ	Min	Max		
CG1	**Crude oil refining, marginal gasoline** Crude oil		0.0800	6.50			6.50				0.0600	0.1000	Normal	CONCAWE
CG2	**Gasoline transport**													Total
	Barge, 9000 t (33%)													
	Energy as Diesel	Z1	0.0011	0.08			0.08							
	Energy as HFO	Z3	0.0052	0.39			0.39							
	Evaporation losses		0.0000											
	Total CO2			0.47			0.47							
	Primary energy consumption and emissions		*0.0070*	*0.53*			*0.53*							
	Rail, 250 km (33%)													
	Distance	Z5						250		0.0058				
	Primary energy consumption and emissions		*0.0034*	*0.14*	*0.0004*	*0.0000*	*0.16*							
	Evaporation losses		0.0004											
	Pipeline (33%)													
	Electricity (EU-mix, LV)	Z7b	0.0002											
	Primary energy consumption and emissions		*0.0006*	*0.02*	*0.0001*	*0.0000*	*0.03*							
	Total Primary energy consumption and emissions		*0.0037*	*0.23*	*0.0001*	*0.0000*	*0.01*							
CG3	**Gasoline depot**													Total
	Electricity (EU-mix, LV)	Z7b	0.0008											
	Primary energy consumption and emissions		*0.0024*	*0.10*	*0.0002*	*0.0000*	*0.11*							
	Evaporation losses		0.0000											
CG4	**Gasoline distribution and dispensing**													
	Tanker load and distance	Z2, Z1						150		0.0037				
	Diesel consumption and emissions		0.0035	0.31										
	Filling station, Electricity (EU-mix, LV)	Z7b	0.0034											Total
	Primary energy consumption and emissions		*0.0138*	*0.72*	*0.0010*	*0.0000*	*0.75*							
	Evaporation losses		0.0008											

CG1/4   Gasoline

These processes are essentially the same as for diesel with some specific adjustments for the gasoline case, mostly in terms of evaporation losses.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

4.3   Naphtha

Code	Process	Assoc. processes	Expended energy and emissions per MJ of main product of the process					Transport distance	Transport energy	Transport requirement	Range		Probability distribution	Reference
			MJex/ MJ	g CO2/ MJ	g CH4/ MJ	g N2O/ MJ	g CO2eq/ MJ	km or Nm	MJex/ t.km	t.km/ MJ	Min	Max		
CN1	**Crude oil refining, marginal naphtha**													
	Crude oil		0.0510	4.36			4.36				0.0450	0.0550	Normal	CONCAWE
CN2	**Naphtha transport**													Total
	Barge, 9000 t (33%)													
	Energy as Diesel	Z1	0.0011	0.08			0.08							
	Energy as HFO	Z71	0.0051	0.00			0.00							
	Evaporation losses		0.0000	0.00										
	Total CO2			0.08			0.08							
	Primary energy consumption and emissions		*0.0069*	*0.13*			*0.13*							
	Rail, 250 km (33%)													
	Distance	Z5						250		0.0057				
	Primary energy consumption and emissions		*0.0075*	*0.14*	*0.0003*	*0.0000*	*0.15*							
	Evaporation losses		0.0004											
	Pipeline (33%)													
	Electricity (EU-mix, LV)	Z7b	0.0002											
	Primary energy consumption and emissions		*0.0006*	*0.02*	*0.0001*	*0.0000*	*0.03*							
	Total Primary energy consumption and emissions		*0.0050*	*0.10*	*0.0001*	*0.0000*	*0.01*							
CN3	**Naphtha depot**													
	Electricity (EU-mix, LV)	Z7b	0.0008											Total
	Primary energy consumption and emissions		*0.0024*	*0.10*	*0.0002*	*0.0000*	*0.11*							
	Evaporation losses		0.0000											
CN4	**Naphtha distribution and dispensing**													
	Tanker load and distance	Z2, Z1						150		0.0037				
	Diesel consumption and emissions		0.0028	0.00										
	Filling station, Electricity (EU-mix, LV)	Z7b	0.0034											Total
	Primary energy consumption and emissions		*0.0000*	*0.41*	*0.0010*	*0.0000*	*0.44*							
	Evaporation losses		0.0008											

CN1/4   Naphtha

These processes are essentially the same as for diesel with some specific adjustments for the naphtha case, mostly in terms of evaporation losses.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

5 Natural gas (NG) provision (including CNG)

5.1 Natural gas extraction and processing

Code	Process	Assoc. processes	Expended energy	GHG emissions				Efficiency	Total energy and emissions per MJ of expendable energy				Transport requirement			Range		Probability distribution	Reference
			MJx/ MJ prod.	g CO$_2$/ MJ prod.	g CH$_4$/ MJ prod.	g N$_2$O/ MJ prod.	g CO$_2$eq/ MJ prod.		MJ/ MJx	g CO$_2$/ MJx	g CH$_4$/ MJx	g N$_2$O/ MJx	km or N m	MJx/ t.km	MJx/MJ /100km	Min	Max		
GG1	**NG Extraction & Processing**																		Shell
	Energy as NG		0.0200	1.13			1.13									0.0100	0.0400	Dble tri	
	CO2 venting			0.55															
	Methane losses		0.0042		0.0833		1.92												
	Primary energy consumption and emissions		*0.0242*	*1.68*	*0.0833*		*3.59*												
GG2	**Electricity generation from NG (CCGT)**																		GEMIS 3.03
	Energy efficiency							55.0%	1.8178							52.3%	57.8%		LBST
	CO2 emissions									100.11									
	Methane losses								0.0004		0.0075								
	N2O emissions											0.0047							
	Total NG input to power plant								1.8182							1.7300	1.9100		
GG2C	**Electricity generation from NG (CCGT) with CC&S**																		Rubin 2004
	Energy efficiency							47.1%	2.1228							44.8%	49.5%		
	CO2 emissions									11.94									
	Methane losses								0.0004		0.0075								
	N2O emissions											0.0000							
	Total NG input to power plant								2.1231							2.0202	2.2304	Normal	

GG1   NG extraction & processing

This process includes all energy and GHG emissions associated with the production and processing of the gas at or near the wellhead. Beside the extraction process itself, gas processing is required to separate heavier hydrocarbons, eliminate contaminants such as H$_2$S as well as separate inert gases, particularly CO$_2$ when they are present in large quantities.

The associated energy and GHG figures are extremely variable depending a/o on the location, climatic conditions and quality of the gas. The figures used here are reasonable averages, the large variability being reflected in the wide range [*Source: Shell*]. We have not accounted for any credit or debit for the associated heavier hydrocarbons, postulating that their production and use would be globally energy and GHG neutral compared to alternative sources. The figure of 1% v/v for venting of separated CO$_2$ reflects the low CO$_2$ content of the gas sources typically available to Europe. For sources with higher CO$_2$ content, it is assumed that re-injection will be common at the 2010 and beyond horizon. 0.4% methane losses are included [*Source: Shell*].

GG2   On-site electricity generation

In all gas transformation schemes requiring significant amounts of electricity, we have assumed the latter is produced on-site by a state-of-the-art gas-fired combined cycle gas turbine (CCGT) with a typical efficiency of 55% [*GEMIS 2002*], [*TAB 1999*]. The high end of the range represents potential future improvements to the technology that are thought to be achievable in the next ten years.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

G2C   On-site electricity generation with CC&S (CO_2 capture and storage)

This process would consist in scrubbing CO_2 out of the gas turbine flue gases [*Rubin 2004*]. It has been estimated that some 88% of the CO_2 could be recovered. The energy penalty is sizeable, the overall efficiency being reduced by about 8 percentage points.

Long distance pipeline transport

Code	Process	Assoc. processes	Expended energy and emissions per MJ of main product of the process					Energy efficiency	Total energy and emissions per MJ of expendable energy				Transport distance	Transport energy		Range		Probability distribution	Reference
			MJex/MJ	g CO2/MJ	g CH4/MJ	g N2O/MJ	g CO2eq/MJ		MJp/MJex	g CO2/MJex	g CH4/MJex	g N2O/MJex	km or N m	MJex/t.km	MJex/MJ/100km	Min	Max		
GP1a	**NG long-distance pipeline** Russian quality, 7000 km												7000						
	Average specific compression energy													0.360					CONCAWE/LBST
	Compression energy (Russian gas quality)		0.0512													0.300 0.043	0.400 0.057	Square	
	Compressors powered by GT fuelled by NG																		GEMIS 4.07
	Energy efficiency							27.8%	3.6000										
	CO2 emissions									197.97									
	Methane losses								0.0015		0.0306								
	N2O emissions											0.0083							
	NG consumption and emissions		0.1844	10.14	0.0016	0.0004	10.30												
	Methane losses		0.0111		0.2210										0.016%				GEMIS 4.07
	Primary energy consumption and emissions		*0.1954*	*10.14*	*0.2226*		*15.26*												
GP1b	Average quality, 4000 km												4000						
	Average specific compression energy													0.300					
	Compression energy (Russian gas quality)		0.0244													0.020	0.027		
	NG consumption and emissions		0.0878	4.83	0.0007	0.0002	4.91												
	Methane losses		0.0063		0.1263														
	Primary energy consumption and emissions		*0.0941*	*4.83*	*0.1270*		*7.75*												
GM1	EU-mix quality, 1000 km												1000						
	Average specific compression energy													0.260					
	Compression energy (EU-mix gas quality)		0.0058													0.005	0.006	Square	
	NG consumption and emissions		0.0209	1.15	0.0002	0.0000	1.17												
	Methane losses		0.0016		0.0316														
	Primary energy consumption and emissions		*0.0225*	*1.15*	*0.0317*		*1.88*												

GP1   Long-distance pipeline

(GM1) As gas is transported through a pipeline, it needs to be compressed at the start and recompressed at regular intervals. In long-distance lines, the compression energy is normally obtained from a portion of the gas itself, e.g. with a gas-fired gas turbine and a compressor. The gas flow therefore decreases along the line so that the average specific energy tends to be higher for longer distances. The actual energy consumption is also a function of the line size, pressure, number of compressor stations and load factor. The figures used here represent the average from several sources [*LBST 1997/1*] [*LBST 1997/2*], [*GEMIS 2002*] the range used representing the spread of the data obtained. They are typical for the existing pipelines operating at around 8 MPa. For new pipelines, the use of higher pressures may result in lower figures although economics rather than energy efficiency alone will determine the design and operating conditions. This would in any case only apply to entirely new pipeline systems as retrofitting existing systems to significantly higher pressures is unlikely to be practical. In order to represent this potential for further improvement we have extended the range of uncertainty towards lower energy consumption to a figure consistent with a pressure of 12 MPa.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

The distances selected are typical of Western Siberia (7000 km) and the Near/Middle East (4000 km), being the two most likely sources of marginal gas for Europe. For the typical EU-mix the average distance has been taken as 1000 km.

Methane losses associated to long-distance pipeline transport, particularly in Russia, have often been the subject of some controversy. Evidence gathered by a joint measurement campaign by Gazprom and Ruhrgas [*LBST 1997/1*], [*LBST 1997/2*], [*GEMIS 2002*] suggested a figure in the order of 1% for 6000 km (0.16% per 1000 km). More recent data [*Wuppertal 2004*] proposes a lower figure corresponding to 0.13% for 1000 km, which is the figure that we used. Note that higher losses may still be prevalent in distribution networks inside the FSU but this does not concern the exported gas.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

5.2   LNG

Code	Process	Assoc. processes	Expended energy MJx/ MJ prod.	GHG emissions g CO₂/ MJ prod.	g CH₄/ MJ prod.	g N₂O/ MJ prod.	g CO₂eq/ MJ prod.	Efficiency	Total energy and emissions per MJ of expendable energy MJ/ MJx	g CO₂/ MJx	g CH₄/ MJx	g N₂O/ MJx	Transport requirement km or N m	MJx/ t.km	MJx/MJ /100km	Range Min	Max	Probability distribution	Reference
GR1	**NG Liquefaction**															0.034	0.038	Normal	LBST
	Electricity (on-site generation)	GG2	0.0360																Bauer 1996
	NG consumption and emissions		0.065455	3.60	0.0003	0.0002	3.66												
	Methane losses		0.0042	0.14	0.0340														
	Primary energy consumption and emissions		*0.0697*	*3.74*	*0.0343*		*4.53*												
GR1C	**NG Liquefaction with CC&S**															0.034	0.038	Normal	LBST
	Electricity (on-site generation)	GG2C	0.0360																Bauer 1996
	NG consumption and emissions		0.0764	0.43	0.0003	0.0000	0.44												
	Methane losses		0.0042	0.14	0.0340														
	Primary energy consumption and emissions		*0.0807*	*0.57*	*0.0343*		*1.36*												
GR2	**LNG terminal (loading)**																		Total
	Energy as NG		0.0100	0.55															
	Electricity (on-site generation)	GG2	0.0007																
	Primary energy consumption and emissions		*0.0113*	*0.55*	*0.0000*		*0.55*												
GR3	**LNG transport (average of two distances)**																		LBST
	Distance (nautical miles)												5500			5000	6000		Mitsubishi 2000
	NG evaporation		0.0365													0.0331	0.0400	Square	Hanjin 2000
	Methane losses		0.0000		0.0002		0.00												
	NG to ship's fuel		0.0365	2.01			2.01												Total
	HFO to ship's fuel		0.0309	2.49			2.49												
	Total ship's CO2			4.50			4.50												
	Primary energy consumption and emissions		*0.0674*	*4.50*	*0.0002*		*4.50*									*0.0613*	*0.0736*		
GR4	**LNG terminal (unloading)**																		Total
	Energy as NG		0.0100	346.50															
	Electricity (EU-mix, MV)	Z7a	0.0007																
	Primary energy consumption and emissions		*0.0120*	*2.49*	*0.0000*	*0.0000*	*2.49*												
GR5	**LNG vaporisation**																		LBST
	NG for heat		0.0194	1.07			1.07												
	Energy to LNG pump drive		0.0005																
	Pump overall efficiency of which							33.3%	3.0000	165.00									
	Methane losses								0.0006			0.0113							
	NG for energy							33.3%	2.9994	164.97									
	Pump NG consumption and emissions		0.0014	0.08	0.0000		0.08												
	Primary energy consumption and emissions		*0.0208*	*1.14*	*0.0000*		*1.14*												
GR6	**LNG distribution (road tanker)**													t.km/ MJ					
	Tanker load and distance (Road tanker Z3)	Z2, Z1											500	0.0147					
	Diesel consumption and emissions		0.0160	1.23			1.23												
GR7	**LNG to CNG (vaporisation/compression)**																		Messer 1998/1999
	Electricity (EU-mix, LV)	Z7b	0.0228																
	Primary energy consumption and emissions		0.0654	2.75	0.0067	0.0001	2.95												
	Methane losses		0.0000		0.0002		0.00												
	Primary energy consumption and emissions		*0.0654*	*2.75*	*0.0069*	*0.0001*	*2.95*												

GR1   NG liquefaction

The energy required for the liquefaction process is well documented and not subject to a large uncertainty [*FfE 1996*], [*Osaka Gas 1997*]. It is assumed here that the electrical power for the compressors is supplied by a gas fired on-site combined cycle gas fired power plant (see process GG2).

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

GR1C   Liquefaction with CO$_2$ capture

A significant amount of natural gas is used to generate the electrical energy required for liquefaction. The corresponding CO$_2$ could be captured (see process CG2C). The proximity of gas and possibly oil field where the CO$_2$ could be injected would enhanced the feasibility of such a scheme.

GR2   LNG loading terminal

A small amount of electricity is required for the operation of the terminals. In addition the evaporation losses (estimated at 1%) are flared resulting in CO$_2$ emissions [*Source: Total*]. The electricity is deemed to be produced by the on-site gas-fired power plant (process GG2).

GR3   LNG transport

LNG is transported in specially designed cryogenic carriers. Heat ingress is compensated by gas evaporation. The evaporation rate is estimated at 0.15% per day, the number of days being based on an average speed of 19.5 knots. The average distance has been taken as 5500 nautical miles (5-6000 range), typical of e.g. Arab Gulf to Western Mediterranean (via Suez canal) or Nigeria to North West Europe.

The evaporated gas is used as fuel for the ship, the balance being provided by standard marine bunker fuel (HFO). This practice is also valid for the return voyage inasmuch as the LNG tanks are never completely emptied in order to keep them at low temperature (required for metallurgical reasons). The figures include an allowance for the return trip in accordance with the "admiralty formula" (see process Z4: LNG carriers have a typical gross tonnage of 110,000 t, including a payload of 135,000 m^3 or 57,000 t [*Hanjin 2000*] [*MHI 2000*]. This results in a ratio of 0.8 between the full and empty ship).

GR4   LNG unloading terminal

The terminal electricity requirement is deemed to be the same as for the loading terminal (see process GR2). The electricity, however, is now assumed to be supplied by the EU grid. If LNG is vaporised on receipt no evaporation losses are included; if LNG is further transported as such, the same figures as for the loading terminal are used. A small additional electricity consumption (0.0007 to 0.0010 MJ/MJ of LNG) is added for the LNG terminal. The road tanker loading and unloading is carried out by a truck mounted LNG pump. The additional diesel requirement for the LNG pump is very low (approximately 0.0002 MJ/MJ of LNG).

GR5   LNG vaporisation

If it is to be used in the gas distribution grid, LNG needs to be vaporised and compressed. Although small amounts can be vaporised with heat taken from the atmosphere, this is impractical for large evaporation rates and heat at higher temperature must be supplied. The figures used here assume compression (as liquid) to 4 MPa followed by vaporisation and heating of the gas from -162 to 15°C.

GR6   LNG distribution (road tanker)

This process assumes road transport of LNG from the import terminal directly to a local storage at the refuelling station (diesel truck carrying 19 t of LNG and 9 t of steel, see also process Z2).

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

GR7   LNG to CNG (vaporisation/compression)

LNG needs to be vaporised and compressed into CNG at 25 MPa (at the refuelling station). This can be done in and energy-efficient manner by pumping the liquid to the required pressure followed by vaporisation. We have assumed that the vaporisation and reheating energy has to be provided by an auxiliary heat source (electricity) as ambient air would not provide sufficient heat flow for the rates of vaporisation required. The total electricity requirement of 0.0228 MJ/MJ includes 0.0032 for pumping [*Messer 1998*]. It is assumed that the vaporization and reheating is carried out by a water bath heat exchanger. The electricity requirement is 0.0118 MJ/MJ for vaporisation and 0.0078 MJ/MJ for reheating (100% efficiency).

5.3   Natural gas distribution, CNG dispensing

Code	Process	Assoc. processes	Expended energy MJx/MJ prod.	g CO$_2$/MJ prod.	g CH$_4$/MJ prod.	g N$_2$O/MJ prod.	g CO$_2$eq/MJ prod.	Efficiency	MJ/MJx	g CO$_2$/MJx	g CH$_4$/MJx	g N$_2$O/MJx	km or Nm	MJx/t.km	MJx/MJ/100km	Min	Max	Probability distribution	Reference
GG3	**NG trunk distribution**																		
	Distance												500						
	Average specific compression energy													0.269					LBST
	Compression energy (EU-mix gas quality)		0.0030																
	Compressors powered by GT fuelled by NG																		GEMIS 4.07
	Energy efficiency							30.0%	3.3300										
	CO2 emissions									187.64									
	Methane losses								0.0007		0.0139								
	N2O emissions											0.0083							
	NG consumption and emissions		0.0099	0.00	0.0000	0.0000	0.01												
	Methane losses		0.0000		0.0006										0.0006%				GEMIS 4.07
	Primary energy consumption and emissions		*0.0100*	*0.00*	*0.0007*	*0.0000*	*0.02*												
GG4	**NG local distribution**																		
	No energy requirement																		
	Methane losses to atmosphere		0.0000		0.0000		0.00												
GG5	**CNG dispensing (compression 0.4-25 MPa)**																		LBST
	Electricity (EU-mix, LV)	Z7b	0.0220													0.027	0.014	Triangular	
	Primary energy consumption and emissions		*0.0631*	*2.66*	*0.0065*	*0.0001*	*2.84*												

GG3   NG trunk distribution

The European gas distribution systems consist of high pressure trunk lines operating at 4 to 7 MPa and a dense network of lower pressure lines. Operation of the high pressure system is fairly similar to that of a long-distance pipeline, with recompression stations and therefore energy consumption along the way. The recompression stations are assumed to be driven by electricity generated by gas turbines using the gas itself as fuel. Here again the energy consumed depends on the relative size and throughput of the lines as well as of the distance considered. A distance of 500 km for an average energy consumption of 0.27 MJ/(t.km) are typical of European networks [*GEMIS 2002*]. Gas losses are reportedly very small.

GG4   NG local distribution

The low pressure networks are fed from the high pressure trunk lines and supply small commercial and domestic customers. No additional energy is required for these networks, the pressure energy from the trunk lines being more than adequate for the local transport.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

Various pressure levels are used in different countries and even within countries. Although some local networks are still at very low pressure (<100 mbar(g)) the modern European standard is 0.4 MPa(g) (with pressure reduction at the customer boundary). Very low pressure networks also need to be fed by higher pressure systems at regular intervals (e.g. 0.7 MPa in the UK). As a result, it is reasonable to assume that, as long as a gas network is present in the area, a supply at a few bars pressure will be available for CNG refuelling stations in the vast majority of cases. Pressures up to 2 MPa are also available in some areas and may be available to some sites, particularly fleet refuelling stations. We have assumed that the typical refuelling station will be supplied at 0.4 MPa.

Significant methane losses have been reported for these local networks. They appear, however, to be based on overall gas accounting and therefore include measurement accuracy. Some losses are associated with purging operations during network maintenance. It is difficult to believe that local networks would have sizeable continuous losses. In any case all such losses would be related to the extent of the network rather than the throughput. NG used for road transport would only represent a modest increase of the total amount transported in the network and would therefore not cause significant additional losses.

GG5   CNG dispensing (compression)

The current standard for CNG vehicle tanks is 20 MPa maximum which satisfies the range requirements of CNG vehicles. Higher pressures may be used in the future but have not been envisaged at this stage. In order to fill the tank, the compressor must deliver a higher pressure which we have set at 25 MPa.

The pressure level available to a CNG refuelling station is critical for its energy consumption as compression energy is strongly influenced by the compression ratio (changing the inlet pressure from atmospheric (0.1 MPa absolute) to 0.1 MPa gauge (= 0.2 MPa absolute) results in half the compression ratio and a 20% reduction of the compression energy). We have taken 0.4 MPa (g) as the typical figure with a range of 0.1 to 2.0. The energy figures represent 4-stage isentropic compression with 75% compressor efficiency and 90% electric driver efficiency.

It is considered that the vast majority of CNG refuelling points will be setup on existing sites for conventional fuels and therefore attract no additional marginal energy.

The methane losses have been deemed to be insignificant. After the refuelling procedure about 0.2 l of NG or 0.15 g methane is released when the refuelling nozzle is disconnected. If the amount of CNG dispensed per refuelling procedure were assumed to be 1100 MJ the methane emissions would be about 0.00014 g/MJ of NG. According to [*Greenfield 2002*] the methane emissions during NG compression can be lowered to virtually zero.

Note on CO_2 emissions from natural gas combustion:

The CO_2 emissions resulting from the combustion of natural gas vary somewhat with the composition of the gas. We have adopted the following convention
- Gas used at or near the production point is deemed to be of Russian quality
- Gas used within Europe is deemed to be of the quality of the current EU-mix

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

6   Synthetic fuels and hydrogen production from NG

6.1   Syn-diesel, Methanol, DME

Code	Process	Assoc. processes	Expended energy	GHG emissions				Efficiency	Total energy and emissions per MJ of expendable energy				Transport requirement			Range		Probability distribution	Reference
			MJx/ MJ prod.	g CO₂/ MJ prod.	g CH₄/ MJ prod.	g N₂O/ MJ prod.	g CO₂eq/ MJ prod.		MJ/ MJx	g CO₂/ MJx	g CH₄/ MJx	g N₂O/ MJx	km or N m	MJx/ t.km	MJx/MJ /100km	Min	Max		
GD1	**NG to syn-diesel (remote or central plant)** Overall efficiency							63.0%								65.0%	61.0%		Senden 1996
	Energy as NG		0.5873	16.47			16.47									0.5385	0.6393	Normal	
	Primary energy consumption and emissions		*0.587302*	*16.47*			*16.47*												
GD1C	**NG to syn-diesel (remote or central plant) with CC&S** Overall efficiency							60.0%								63.2%	57.1%		Senden 1996
	Energy as NG		0.6667	4.17			4.17									0.5834	0.7500	Square	
	Primary energy consumption and emissions		*0.6667*	*4.17*			*4.17*												
GA1	**NG to Methanol (remote or central plant)** Overall efficiency							68.2%								69.2%	67.1%		Larsen 1998 LBST
	Energy as NG		0.4668	11.69															
	Methane losses		0.0000		0.0001														
	Primary energy consumption and emissions		*0.4668*	*11.6895*	*0.0001*		*11.69*									*0.4442*	*0.4894*		
GA2	**Methanol to hydrogen (on-site reforming)**																		
GT1	**NG to DME (remote or central plant)** Energy as NG		0.4033	9.99	0.0035			71.3%								0.3752	0.4314	Equal	Haldor Topsoe 2002/2001
	Electricity (on-site generation)	GG2	0.0043													0.0042	0.0044	Equal	
	Steam	GG2	-0.0022																
	Steam plant electricity (on-site generation)	GG2								0.02 (MJe/MJex)										
	Steam plant NG							85.0%	1.1765	64.79	0.0028					1.1176	1.2353	Normal	
	Oxygen												MJe/kg	kg/MJ 0.0013		0.0045	0.0047	Equal	
	Oxygen plant	GG2											1.6999			0.1246	0.1377	Normal	
	Primary energy consumption and emissions		*0.412399*	*10.49*	*0.0035*	*0.0000*	*10.58*	70.8%											
GT1C	**NG to DME (remote or central plant) with CC&S** Energy as NG		0.4254	0.58	0.0035			70.2%								0.4000	0.5000	Equal	IEA 2004
	Electricity (on-site generation)	GG2	-0.0022																
	Steam																			
	Steam plant electricity (on-site generation)	GG2																		
	Steam plant NG																			
	Oxygen													MJe/kg	kg/MJ 0.0046					
	Oxygen plant	GG2											0.4722			0.4486	0.4958	Equal	
	Primary energy consumption and emissions		*0.4254*	*0.58*	*0.0035*		*0.66*	70.2%											

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

GD1   NG to syn-diesel plant (GTL)

This is the so-called GTL process including NG reforming or partial oxidation followed by the Fischer-Tropsch (FT) synthesis. The plant also includes hydrocracking of the FT product. Plants to be designed in the next few years will have a typical overall efficiency of 63% [*Source: Shell*], i.e. 100 MJ of NG in will deliver 63 MJ of combined product, 37 MJ being expended in the process. The selectivity of the process for a specific product can be adjusted to a large degree, notably with a hydrocracking step after the FT synthesis. The maximum practically achievable diesel yield (including the kerosene cut) is considered to be around 75% of the total product, the remainder being mainly naphtha and some LPG. In this case we assume that the plant is built for the primary purpose of producing diesel. Many future plants will not produce any specialties such as base oils and waxes as these markets will soon be saturated.

Naphtha and LPG are also potential automotive fuels. The energy required to produce them from refineries is of the same order of magnitude as diesel. The GTL process produces all these products simultaneously but, contrary to the refinery case, there is no technical argument for allocating proportionally more or less energy to one product then to the others (a yield change between e.g. naphtha and diesel would not significantly affect the overall energy balance of the process). We have therefore assumed that all products are produced independently with the same energy efficiency.

GD1C   NG to syn-diesel plant with CO_2 capture

The "chemical" CO_2 from the reforming or partial oxidation reactions as well as the CO-shift reaction (required to adjust the hydrogen/CO ratio) is separated from the syngas feed to the FT process. This CO_2 is virtually pure so that only compression and liquefaction are required for potential recovery. Most GTL plants will be built near gas or oil fields where the CO_2 can be re-injected. For FT liquids from NG there is not literature source where a NG FT plant with and without CC&S is compared. FT plants are very complex. The layout differs from licensor to licensor and this can have a large impact on the energy penalty for CC&S. [*IEA 2005*] suggests an energy efficiency penalty of 3%. We have used this figure as a basis for our calculation, starting from an overall plant efficiency of 63% in the base case. The CO_2 generated in the auxiliary power plant is not recovered in this scheme, so that the CO_2 recovery is relatively low at around 75%.

GA1   NG to methanol plant

The plant energy efficiency selected here corresponds to a current state-of-the-art installation [*Statoil 1998*]. The upper value (29.64 GJ/t of methanol) is the value guaranteed by the manufacturer, the lower value (28.74 GJ/t of methanol) is a measured value for the methanol plant located in Tjeldbergodden in Norway.

This process is applicable to both a remote plant and a large "central" plant located in Europe.

GT1   NG to DME plant

There is limited data available on DME and there are no full scale commercial plants on the ground at the moment. The data used here is from Haldor Topsoe [*Haldor Topsoe 2002*], the main proponent of this compound. This process is applicable to both a remote plant and a large "central" plant located in Europe. In both cases electricity is deemed to be produced by a dedicated gas-fired power plant (CCGT, see process GG2).

GT1C   NG to DME plant with CO_2 capture

Application of CC&S to DME synthesis. CO_2 formed during the steam reforming process is produced in nearly pure form and removed before the synthesis step. Capture is therefore relatively easy and cheap. The figures used here have been derived from [*IEA 2005*]*,* [*Haldor Topsoe 2001*], [*Haldor Topsoe 2002*]. The resulting extra energy consumption for CC&S is, however, very low and these figures should be taken with great caution.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

6.2   Natural gas to hydrogen

Code	Process	Assoc. processes	Expended energy (MJx/MJ prod.)	GHG emissions				Efficiency	Total energy and emissions per MJ of expendable energy				Transport requirement			Range		Probability distribution	Reference
				g CO₂/ MJ prod.	g CH₄/ MJ prod.	g N₂O/ MJ prod.	g CO₂eq/ MJ prod.		MJ/ MJx	g CO₂/ MJx	g CH₄/ MJx	g N₂O/ MJx	km or N m	MJx/ t.km	MJx/MJ /100km	Min	Max		
GH1a	**NG to hydrogen (reforming, on-site, 2 MW hydrogen)**																		
	NG comp. (0.4 to 1.6 MPa), electricity (EU-mix)	Z7b	0.0059																
	Energy as NG		0.4406		0.0159											0.4118	0.4694	Normal	Haldor Topsoe 1998
	CO2 emissions																		
	EU-mix quality			81.19												0.0705	0.0842	Normal	
	Russian quality			79.30															
	Electricity (EU-mix, LV)		0.0161																
	Primary energy consumption and emissions		*0.5037*													*0.4749*	*0.5325*		
	EU-mix quality			*83.85*			*84.50*												
	Russian quality			*81.95*			*82.60*												
GH1b	**NG to hydrogen (reforming, central plant, 100-300 MW hydrogen)**																		
	Energy as NG (Russian gas quality)		0.3150	72.38	0.0159		72.75	76.0%								0.289	0.341	Normal	Foster Wheeler 1996
GH1bC	**NG to hydrogen (reforming, central plant, 100-300 MW hydrogen) with CC&S**																		
	Energy as NG (Russian gas quality)		0.3650	11.86	0.0159		12.23	73.3%								0.338	0.3920	Normal	Foster Wheeler 1996

GH1a   NG to hydrogen (steam reforming, on-site, 2 MW hydrogen,)

GH1b   NG to hydrogen (steam reforming, central plant, 100-300 MW hydrogen)

The efficiency of the steam reforming proper is largely independent of the size of the plant. In a large plant, however, there are opportunities for optimisation of heat recovery. In this case we have assumed that waste heat is recovered to produce electricity, the surplus of which is exported to the grid (substituting EU-mix quality). This results in a much improved overall efficiency in the case of the central plant. The figures used here are from a conceptual plant design *[Foster Wheeler 1996]*. In the first version of this report we based the NG-to-hydrogen pathway on [*Linde 1992*]. The latter involved a larger NG input but also surplus electricity production. Taking the appropriate credit into account the net energy balance falls within 1% of the Foster Wheeler case.

GH1bC   NG to hydrogen (steam reforming, central plant, 100-300 MW hydrogen) with CO₂ capture

Steam reforming of natural gas followed by the CO-shift reaction produces a mixture of hydrogen and CO2 with some residual CO. Depending on the purity requirement of the hydrogen, the CO₂ is either separated from the hydrogen with a solvent or a PSA unit is used to produce *[Foster Wheeler 1996]*.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

7   LPG and ethers

Code	Process	Assoc. processes	Expended energy	GHG emissions				Efficiency	Total energy and emissions per MJ of expendable energy				Transport requirement			Range		Probability distribution	Reference
			MJx/ MJ prod.	g CO$_2$/ MJ prod.	g CH$_4$/ MJ prod.	g N$_2$O/ MJ prod.	g CO$_2$eq/ MJ prod.		MJ/ MJx	g CO$_2$/ MJx	g CH$_4$/ MJx	g N$_2$O/ MJx	km or N m	MJx/ t.km	MJx/MJ /100km	Min	Max		
LR1	**LPG production**															0.0500	0.0700	Equal	
	Energy as LPG		0.0529	3.47															
	Electricity	GG2	0.0028																
	Primary energy consumption and emissions		*0.0580*	*3.75*	*0.0000*	*0.0000*	*3.76*												
BU1	**n-butane to isobutene**																		CONCAWE
	Electricity	Z7a	0.0044																
	NG for steam (90% eff.)	Z6	0.1627	10.27	0.0325	0.0000	11.02												
	Hydrogen		-0.0196																
	Credit for hydrogen produced by NG steam ref.		-0.0062	-1.42	-0.0003	0.0000	-1.43												
	Primary energy consumption and emissions		*0.1690*	*9.38*	*0.0334*	*0.0000*	*10.16*												
EH1	**Isobutene + ethanol to ETBE**																		CONCAWE
	Isobutene	BU1	0.7000																
	Ethanol		0.3640																
	Electricity	Z7a	0.0010																
	NG	Z6	0.0240																
	Primary energy consumption and emissions		*0.0028*	*0.1194*	*0.0003*	*0.0000*	*0.13*												
MH1	**Isobutene + methanol to MTBE**																		CONCAWE
	Isobutene	BU1	0.8122																
	Methanol		0.1886																
	Electricity	Z7a	0.0012																
	NG	Z6	0.0290																
	Primary energy consumption and emissions		*0.0028*	*0.1194*	*0.0003*	*0.0000*	*0.13*												

LR1   LPG production

It is assumed here that LPG is produced as part of the heavier hydrocarbons (condensate) associated with natural gas. Energy is required for cleaning the gas and separating the C3 and C4 fractions. Reliable data is scarce in this area and this should only be regarded as a best estimate.

BU1   n-butane to isobutene

This process of isomerisation and dehydrogenation is required to produce isobutene, one of the building blocks of MTBE or ETBE. It is an energy-intensive process.

EH1   ETBE manufacture (large plant)

This process describes the manufacture of ETBE from isobutene and ethanol. This could occur in Europe with imported butanes (turned into isobutene with BU1) and domestically produced bio ethanol.

MH1   MTBE manufacture (large plant)

This represents a typical large scale plant, usually located near a source of natural gas, manufacturing MTBE from isobutene (from field butanes) and methanol (synthesised from natural gas).

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

8   Synthetic fuels and hydrogen production from coal

Code	Process	Assoc. processes	Expended energy MJx/ MJ prod.	g CO$_2$/ MJ prod.	g CH$_4$/ MJ prod.	g N$_2$O/ MJ prod.	g CO$_2$eq/ MJ prod.	Efficiency	Range Min	Max	Probability distribution	Reference
KB1	**Lignite (brown coal) provision**											GEMIS
	Primary energy as											
	Brown coal		0.0148									
	Oil		0.0008									
	Primary energy consumption and emissions		*0.0156*				*1.77*					
KO1	**Hard coal provision (EU-mix) (1)**											GEMIS
	Primary energy as											
	Hard coal		0.0250									
	Brown coal		0.0020									
	Oil		0.0410									
	Natural gas		0.0100									
	Hydro power		0.0030									
	Nuclear		0.0110									
	Waste		0.0020									
	Primary energy consumption and emissions		*0.0940*	*6.47*	*0.3818*	*0.0003*	*15.33*					
KH1	**Coal to hydrogen**											Foster Wheeler 1996
	Energy as hard coal (EU-mix)		0.967	189.39	0.0061			50.8%				
	Primary energy consumption and emissions		*0.9670*	*189.39*	*0.0061*	*0.0000*	*189.5256*					
KH1C	**Coal to hydrogen with CC&S**											Foster Wheeler 1996
	Energy as hard coal (EU-mix)		1.303	5.64	0.0000			43.4%				
	Primary energy consumption and emissions		*1.3030*	*5.64*	*0.0000*	*0.0000*	*5.638889*					
KA1	**Coal to methanol**											Katofsky 1993
	Energy as hard coal (EU-mix)		0.6759	92.26	0.0069		92.42	59.7%				
	Electricity (ex coal)		0.0294									
	Primary energy consumption and emissions		*0.7371*	*92.26*	*0.0069*		*92.42*					
KE1	**Coal to DME**											Katofsky 1993
	Energy as hard coal (EU-mix)		0.6759	94.07	0.0069		94.23	59.7%				
	Electricity (ex coal)		0.0294									
	Primary energy consumption and emissions		*0.7371*	*94.07*	*0.0069*		*94.23*					
KD1	**Coal to syndiesel**											Gray 2001, 2005
	Energy as hard coal (EU-mix)		1.4710	167.08				40.5%	1.3470	1.5950	Equal	
	Energy as electricity		-0.3300									
	Credit for electricity based on coal IGCC		-0.6875	-66.19	0.0000	0.0000	-66.19	48%				TAB 1999
	Primary energy consumption and emissions		*0.7835*	*100.89*	*0.0000*	*0.0000*	*100.89*	56%				
KD1C	**Coal to syndiesel with CC&S**											Winslow 2004
	Energy as hard coal (EU-mix)		1.444	14.92				40.9%	1.3220	1.5660	Equal	Gray 2001,2005
	Energy as electricity		-0.239									ENEA 2004
	Credit for electricity based on coal IGCC+CC&S		-0.5829	-5.60				41.0%	50.0%	40.0%		
	Primary energy consumption and emissions		*0.8611*	*9.31*	*0.0000*	*0.0000*	*9.31*	54%				

(1) Data calculated from composition of current EU-mix and specific energy requirements and efficiencies for each source
Coal EU-mix as follows

Source	%
Australia	12
CIS	3
Columbia	7
Germany	21
Poland	7
South Africa	16
Spain	6
UK	18
USA	10

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

KB1   Lignite/brown coal provision

This process is typical of brown coal extraction in Germany and Eastern Europe [*GEMIS 2002*]. Lignite is used as fuel for the ethanol plant in pathways WTET3a/b.

KO1   Hard coal provision (EU-mix)

These figures approximate the average primary energy associated to the production and provision of hard coal to Europe [*El Cerrejon 2002*], [*DOE 2002*], [*EUROSTAT 2001*], [*GEMIS 2002*], [*IDEAM 2001*], [*IEA Statistics 2000*].

KH1   Coal to hydrogen

This represents the total process from coal gasification through CO shift, PSA etc [*Foster Wheeler 1996*].

KH1C   Coal to hydrogen with CO_2 capture

Same as above with additional capture of CO_2. The figures with and without capture are based on a conceptual plant design [*Foster Wheeler 1996*].

KA1/E1   Coal to methanol or DME

This represents the total process from coal gasification through methanol or DME synthesis. The same reference was used for both products [*Katofsky 1993*].

KD1   Coal to synthetic diesel

This is the "CTL" route, including coal gasification and Fischer-Tropsch synthesis [*Gray 2001*]*,* [*Gray 2005*], [*TAB 1999*].

KD1C   Coal to synthetic diesel with CO_2 capture

Same as above with CO_2 capture between gasification and FT synthesis [*Winslow 2004*], [*Gray 2001*], [*Gray 2005*], [*ENEA 2004*].

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

9   Farming processes

Here we tabulate and sum the fossil energy and GHG emissions attributable to farming processes, including the upstream emissions and energy needed to make the fertilizers etc. The agrochemicals processes described later describe these upstream processes in more detail. In the first version of this report, most of the agricultural resources for growing biofuels came from land which would otherwise be used for growing export cereals, in accordance with [*DG-AGRI 2002*] agricultural outlook. This led to the conclusion that no "reference crop" was needed. However, DG-AGRI have since updated their outlook: due to changes in the agricultural subsidy regime, they now expect more set-aside and a smaller cereals surplus in EU25-2012. That means that most of the biofuel crops would now come from set-aside. The result is that there is now a reference crop representing the land cover in set-aside: we have chosen unfertilized grass. Because this has low agricultural inputs, the only significant GHG effect is in the reference nitrous oxide emissions. [*LBST 2002*]*,* which otherwise shares much of the same agricultural data with this report, has more intensive reference crops..

All figures are related to the **water-free** Lower Heating Value of the biomass products. This is necessary to avoid confusion: for example apparent increases in LHV as wood dries out during transport and storage. However, the actual water content is taken into account when calculating transport and processes. Agricultural yields are expressed at the conventional % moisture: 16% for wheat; 10% for oilseeds; 9% for DDGS by-product of wheat-ethanol, sugar beet pulp and dried slops ("solubles"); 0% for wood. This helps comparability with other studies.

Unlike with a process making fossil fuel from a fossil resource, the primary energy and emissions from diesel use in biomass processes include the LHV and the carbon (as CO_2) content of the diesel itself, because the fossil CO_2 is released at this stage.
.
Best estimate figures are shown. It is not worth including a range of energy inputs, because these are low for farming compared to the whole chain. The main source of uncertainty is in the GHG emissions, caused by the N_2O emission calculation (details below).

The processes for making fertilizers and "pesticides" (in which we include other complex agro-chemicals such as fungicides and plant hormones) are detailed in the table below.

We call seeds "seeding materials" to avoid confusion with oilseeds as a crop.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

Code	Process	Assoc. processes	Input		Expended energy		GHG emissions				N2O emissions	
			kg/ MJ prod.	MJ/ MJ prod.	Primary MJx/ kg or MJ	Primary MJx/ MJ prod.	g CO2/ MJ prod.	g CH4/ MJ prod.	g N2O/ MJ prod.	g CO2eq/ MJ prod.	Min	Max
WF1	**Wood farming and chipping**											
	N fertilizer	AC1	0.0005			0.0246	1.51	0.0041	0.0048	3.03		
	Diesel for harvest, sowing etc.	Z1		0.0060		0.0070	0.53	0.0000	0.0000	0.53		
	Land emissions								0.0034	1.01		
	Diesel for chipping			0.0040	4.18	0.0046	0.35	0.0000	0.0000	0.35		
	Primary energy consumption and emissions					*0.0362*	*2.39*	*0.0041*	*0.0082*	*4.92*		
	…including 2.5% dry-mass losses in chipping and storage					**0.0371**	**2.45**	**0.0042**	**0.0084**	**5.04**		
SB1	**Sugar Beet Farming**											
	CaO fertilizer	AC4	0.0020		2.04	0.0042	0.24	0.0006	0.0000	0.25		
	K2O fertilizer	AC3	0.0007		9.73	0.0068	0.38	0.0011	0.0000	0.41		
	P2O5 fertilizer	AC2	0.0003		15.47	0.0043	0.28	0.0004	0.0000	0.29		
	N fertilizer	AC1	0.0005		49.17	0.0253	1.55	0.0043	0.0050	3.12		
	Pesticides	AC5	0.0000		272.55	0.0018	0.11	0.0002	0.0000	0.11		
	Seeding material		0.0000		33.38	0.0010	0.06	0.0000	0.0000	0.06		
	Diesel	Z1		0.0320	4.18	0.0371	2.80	0.0000	0.0000	2.80		
	Net emissions from field							0.0001	0.0118	3.50	0.0081	0.0156
	Farm primary energy consumption and emissions					*0.0806*	*5.42*	*0.0066*	*0.0168*	*10.53*		
	…including 4.5% sugar loss during storage					**0.0842**	**5.66**	**0.0069**	**0.0175**	**11.01**		
WT1	**Wheat farming**											
	K2O fertilizer	AC3	0.0005		9.73	0.0051	0.29	0.0008	0.0000	0.31		
	P2O5 fertilizer	AC2	0.0005		15.47	0.0081	0.52	0.0007	0.0000	0.53		
	N fertilizer	AC1	0.0013		49.17	0.0646	3.97	0.0109	0.0127	7.96		
	Pesticides	AC5	0.0000		272.55	0.0069	0.42	0.0006	0.0000	0.44		
	Seeding material		0.0011		2.88	0.0030	0.17	0.0000	0.0000	0.17		
	Diesel (includes drying)	Z1		0.0369	4.18	0.0428	3.23	0.0000	0.0000	3.23		
	Net emissions from field								0.0189	5.59	0.0064	0.0314
	Sum primary energy consumption and emissions					**0.1306**	*8.60*	*0.0130*	*0.0315*	**18.24**		
SC1	**Sugar cane farming (Brazil)**											
	CaO fertilizer	AC4	0.0036		0.5669	0.0020	0.11	0.0003	0.0000	0.12		
	K2O fertilizer	AC3	0.0007		2.7023	0.0019	0.11	0.0003	0.0000	0.12		
	P2O5 fertilizer	AC2	0.0003		4.2959	0.0012	0.07	0.0001	0.0000	0.08		
	N fertilizer	AC1	0.0006		13.6591	0.0083	0.51	0.0014	0.0016	1.02		
	Pesticides	AC5	0.0000		75.7090	0.0014	0.09	0.0001	0.0000	0.09		
	Seeding material		0.0000		1.9837	0.0000	0.00	0.0000	0.0000	0.00		
	Diesel	Z1		0.0053	1.1600	0.0062	0.46	0.0000	0.0000	0.46		
	Net emissions from field						0.39	0.0531	0.0055	3.24		
	Sum primary energy consumption and emissions					*0.0211*	*1.75*	*0.0553*	*0.0071*	**5.13**		

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

WF1   Wood Farming

This represents short-rotation forestry on agricultural land. Poplar or willow are generally the best-yielding species in central and Northern Europe. Willow shoots are harvested typically every 3 years; poplar trunks after 8-15 years. After about 15-20 years the trees are uprooted and new ones planted. Inputs comprise sowing, thinning, fertilizer, but mostly harvesting. Yields for a given amount of fertilizer are better than for annual crops because roots are already established at the start of the growing season. Perennial grasses share this advantage. A neutral review of European experiments with *miscanthus* [*Scurlock 1999*] indicates a realistic yield is similar to farmed wood. Switchgrass has lower yield, but has better drought resistance, enabling it to be grown in more marginal areas. Grasses generally have a higher mineral content than wood, which can cause problems of ash sintering and corrosion if one tries to use the same conversion plant (the salt content can however be lowered by delayed harvesting or washing). For this reason, farmed wood chips command a higher price at power stations, which makes it the preferred biomass crop in EU at the moment. LCA studies show results for perennial grasses between wood and arable bio-crops. We have considered SRF because there is more data, but do not wish to exclude grasses as a possible alternative with fairly similar characteristics.

Inputs vary widely, depending on soil quality, yield and the intensiveness of the farming; [*Bauen 2000*] gives a range of 0.004 to 0.065 MJ primary energy per MJ dry wood. [*Mathews 1994*] quotes figures of 0.03 to 0.04 MJ/MJ. Our data on wood farming (short rotation forestry) are from original Oeko-Institut studies in the [*GEMIS 2002*] database, used also in [*LBST 2002*]. Inputs are low compared to other energy crops, so the uncertainty is not important when comparing pathways.

Nitrous oxide emissions for forestry cannot be calculated with the JRC soil model. Instead, we used the range of measured values for direct emissions from poplar, reported by [*Flesse 1998*]. A range for indirect emissions was estimated, using the procedure based on IPCC guidelines described in [*LBST 2002*], for the 25 kg/ha nitrogen fertilizer rate reported by [*Murach 2003*] for poplar plantation. Since this procedure assumes that nitrous oxide emissions are proportional to the nitrogen fertilizer rate, the emissions from our reference crop (unfertilized grass) are effectively already subtracted. For the nitrous oxide and farming input calculations, the yield is taken to be 10 tonnes/ha, and the LHV of dry farmed wood (poplar) chips 18 GJ/ dry tonne [*GEMIS 2002*].

Dry mass losses during chipping and storage are partly from dust and spillage, and partly from respiration, rotting and evaporation of volatiles, in line with [*Hamelinck 2002*].

SB1   Sugar Beet Farming

Sugar beet gives a high yield of easily-fermented sugar. Following [*LBST 2002*], we selected the data on farming inputs given by [*FfE 1998*], which are also close to the input data of the [*ADEME 2003*] study. The yield in [*FfE 1998*] is 51.2 t/ha/a at a water content of 76%. This is about the present average yield for EU-25 (but bear in mind that sugar beet is only grown on good farmland). Better growing conditions generally increase the optimum amount of N fertilizer together with the yield, so the exact yield considered is not very critical in terms of nitrogen input per MJ product. However, there is considerable variation in the literature on optimum nitrogen inputs even for similar yields [*LBST 2002*]. Processes for making fertilizer are detailed in the following table.

N_2O emissions from the field dominate the GHG emissions. An average for sugar beet grown in EU15 is calculated using the JRC's EU GHG emissions model, as detailed in the *WTT main report*. The reference crop is unfertilized grass. We assume that the sugar beet leaves are ploughed back into the soil after harvest, which is the usual practice.

We have included storage of sugar beet in this farming process, even though it may take place at the processing site. That is so that we can compare sugar beet results with those of wheat farming, where drying and storage is already included in our input data. In store, beet loses about 0.1% of its sugar per day by

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

respiration [*Wiltshire 2000*]. For a representative beet processing campaign of 90 days (see sugar beet to ethanol process SB3a) the average loss on storage is therefore about 4.5%.

WT1 Wheat Farming

Wheat is the highest-yielding cereals crop, but it also takes the highest inputs. This process is for 'soft wheat', which accounts for most of EU production, gives the highest yield, and has the highest fermentable content. Straw use is discussed in the main WTT report. Data on wheat farming inputs is not included in [*FfE 1998*], so we took data from [*ETSU 1996*], which includes energy for drying and storage. N_2O emissions are calculated from GREASE. There is no "reference crop" (see main *WTT report*).

SC1 Sugar cane farming (Brazil)

Figures are derived from data for "scenario 2" in the thorough LCA study by [*Macedo 2004*] which describes best-current-practice in the Centre-South region, where 85% of Brazil's sugar cane is grown, and where it is claimed there is still plenty of grazing land which could be planted to increase the supply if there is a market. It is a very long way from any rainforest. Some sugar cane is also produced in NE Brazil, near some areas of surviving Atlantic rainforest, but the conditions are much less suitable there, so that production needed subsidies, and is unlikely to increase.

There are usually 5 harvests, with an average yield of 82.4 t/ha (moist), but these take place over 6 years, so the annualized yield is 68.7 t/ha/y. Macedo gives inputs per tonne of moist cane. We converted these to figures per MJ (LHV) dry cane using 72.5%, water content of harvested sugar cane [*Kaltschmitt 2001*] and LHV heat content of 19.6 MJ per kg dry matter [*Dreier 2000*] (Macedo also describes the process per tonne of cane, so these conversion factors cancel out in the overall calculation). To keep the pathway comparable with other crops, we used our usual chemical processes to calculate the energy and emissions from producing the agricultural inputs, not the values used by Macedo.

In this best-practice scenario, the solid "filter mud cake" and liquid "vinasse" residue from the distillation process (equivalent of wet DDGS in the wheat-to-ethanol process) are sent to the closer fields to recycle the water and much of the minerals. The figures represent a weighted average of nearer and more distant fields. The average nitrogen rate over 5 years is about 75 kg/ha.

The farming emissions include CO2, methane and nitrous oxide from burning the foliage to make harvesting easier: this is still the most common practice, although it is banned near towns. We used Macedo's calculation of N_2O, CH_4 and CO_2 emissions from burning, using factors recommended in [*IPCC 2001*].

Nitrous oxide emissions were calculated from the nitrogen fertilizer additions using IPCC default coefficients. Fortunately they are low, so the related uncertainty is acceptable in this case.

Sugar cane resembles more a perennial biomass crop like miscanthus than it does an arable crop. Unlike arable crops in Europe, planting sugar cane on grazing land is believed to actually increase the soil carbon stocks. The risk of soil erosion (a major concern in Brazil) is heightened in the first year of establishment, compared to grazing land, but not in subsequent years.

WTT APPENDIX 1

Code	Process	Assoc. processes	Input		Expended energy		GHG emissions				N2O emissions	
			kg/ MJ prod.	MJ/ MJ prod.	Primary MJx/ kg or MJ	Primary MJx/ MJ prod.	g CO2/ MJ prod.	g CH4/ MJ prod.	g N2O/ MJ prod.	g CO2eq/ MJ prod.	Min	Max
RF1	**Rapeseed Farming**											
	CaO fertilizer	AC4	0.0003		2.04	0.0005	0.03	0.0001	0.0000	0.03		
	K2O fertilizer	AC3	0.0004		9.73	0.0041	0.23	0.0007	0.0000	0.24		
	P2O5 fertilizer	AC2	0.0007		15.47	0.0115	0.73	0.0010	0.0000	0.75		
	N fertilizer	AC1	0.0020		49.17	0.1001	6.16	0.0169	0.0196	12.35		
	Pesticides	AC5	0.0000		272.55	0.0047	0.29	0.0004	0.0000	0.30		
	Seeding material		0.0001		7.14	0.0006	0.02	0.0000	0.0000	0.02		
	Diesel	Z1		0.0414	4.18	0.0480	3.62	0.0000	0.0000	3.62		
	Net emissions from field							0.0001	0.0436	12.91	0.0261	0.0611
	drying (electricity EU mix LV)	Z7b		0.0028	10.33	0.0080	0.34	0.0008	0.0000	0.36		
	Sum primary energy consumption and emissions					*0.1776*	*11.42*	*0.0199*	*0.0633*	***30.60***		
SF1	**Sunflower seed Farming**											
	K2O fertilizer	AC3	0.0004		9.73	0.0037	0.21	0.0006	0.0000	0.22		
	P2O5 fertilizer	AC2	0.0005		15.47	0.0080	0.51	0.0007	0.0000	0.53		
	N fertilizer	AC1	0.0007		49.17	0.0331	2.03	0.0056	0.0065	4.08		
	Pesticides	AC5	0.0000		272.55	0.0094	0.57	0.0009	0.0000	0.60		
	Seeding material		0.0001			0.0006	0.02	0.0000	0.0000	0.02		
	Diesel	Z1		0.0510	4.18	0.0592	4.46	0.0000	0.0000	4.46		
	Net emissions from field							0.0001	0.0264	7.81	0.0186	0.0342
	drying (electricity)			0.0028	10.33	0.0080	0.33	0.0008	0.0000	0.36		
	Sum primary energy consumption and emissions					*0.1220*	*8.14*	*0.0086*	*0.0329*	***18.08***		

RF1   Rapeseed Farming

Plant oils are the closest nature gets to a liquid transport fuel, so relatively little energy is lost in the conversion process. Rape gives the highest oil yield in the Northern half of Europe. However, it still has much lower yield than cereals: it is grown as a low-input break crop, to rest the soil between more profitable cereal crops. The rape straw is invariably ploughed back into the soil, because it contains most of the nitrogen and minerals taken up by the crop, is needed to improve the organic content of the soil.

Again, N_2O emissions are calculated from the JRC's EU soil emissions model, and farming inputs are from [*FfE 1998*]. The yield from these inputs is 3 t/ha, which is also about the average EU-15 yield [*EUROSTAT 2003*]. No reference crop (see main *WTT report*).

Nitrogen fertilizer rates (and rapeseed yields) in UK are typically higher than in Germany: 180kg N/ha *[Groves 2002]* compared to 145 in our data from [*FfE 1998*]. Our diesel farming inputs are between those in [*Groves 2002*] and [*ADEME 2002*]. The dry LHV of rapeseed is 23.8 GJ/t at standard 10% moisture [*FfE 1998*].

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

SF1 Sunflower Seed Farming

Rapeseed does not grow well in the drier parts of Europe: here, sunflower is grown in rather the same way, mostly as a break-crop between cereals, although average yields are lower. Inputs are from [*FfE 1998*], and average EU-15 N_2O emissions from the rapeseed field are calculated from JRC soil model. We assume the straw is ploughed in the soil, which is the usual practice. No reference crop. We assume the same LHV for sunflower seed as for rapeseed.

We found no literature data on energy and emissions for providing seeding materials for sunflower. Farming experts told us that sunflower requires slightly less kg seed-per-MJ-crop than rapeseed; however, we know that the energy inputs for sunflower seed crop production are higher. Therefore, our best estimate is that fraction of energy input due to seeding materials is very roughly the same as for rapeseed: small compared to the other farming inputs.

Code	Process	Assoc. processes	Input kg/kg	Input MJ/ kg prod.	Expended energy MJx /MJ	Expended energy MJx/ kg prod.	GHG emissions g CO_2/ kg prod.	GHG emissions g CH_4/ kg prod.	GHG emissions g N_2O/ kg prod.	GHG emissions g CO_2eq/ kg prod.
SY1	**Soya bean farming (US) for finding animal feed credits**									
	K2O fertilizer	AC3	0.0080			0.0778	4.37	0.0125	0.0000	4.67
	P2O5 fertilizer	AC2	0.0040			0.0619	3.94	0.0052	0.0000	4.07
	N fertilizer	AC1	0.0020			0.0983	6.05	0.0165	0.0000	12.13
	Pesticides	AC5	0.0005			0.1363	8.31	0.0127	0.0001	8.63
	Diesel (US)	Z1		0.8400	1.1860	0.9962	75.19	0.0000	0.0000	75.19
	Net emissions from field								1.2530	370.89
	Sum primary energy consumption and emissions					**1.3706**	97.86	0.0470	1.2531	**475.57**

SY1 Soy Bean Farming

Soy bean meal is the main protein-rich animal feed in EU. Most is imported from the US. We need to calculate primary energies and emissions for growing it in order to find the credits to apply to by-products which would substitute it. The substitution is done on a mass basis, taking into account the protein contents of the different feeds. So we need to know the inputs per kg, not per MJ.

Fertilizer and diesel inputs for growing soy in the USA are derived from [*UBA 1999*]. We used the data for US refineries [*ANL/1 1999*] in calculating primary energy and emissions from the diesel consumed. In the absence of better data, nitrous oxide emissions are calculated from IPCC default values, using the procedure explained in [*LBST 2002*].

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

N₂O EMISSIONS CALCULATION FOR ARABLE CROPS IN EU

Nitrous oxide emissions dominate the greenhouse gas emissions from farming, and are important for all biomass-based pathways. Therefore we were careful to use the best possible estimate of EU emissions. The IPCC guidelines are highly simplified and therefore need a very wide error range. The method used by JRC to estimate average GHG emissions for the different biofuels crops is described in the main *WTT report*. This is for EU-15, but we expect the average nitrous oxide emissions per MJ crop produced to be similar for EU-25. The method could not be used for short-rotation forestry and for sugar cane farming in Brazil, because these crops are not covered in the DNDC soils model we used. Here, we were forced to use IPCC default emission factors [*IPCC 1996/1*] which estimated nitrous oxide emissions based on nitrogen fertilizer rates.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

10   Production of agro-chemicals

All data on fertilizer and fuel inputs for agro-chemicals provision come from [*Kaltschmitt 1997*]. These data include the transport of the fertilizer. In these processes, the "MJ primary energy per MJ input" of fuel inputs includes the LHV and fossil carbon (as CO2) content of the fuel itself, as well as the upstream energy/emissions to make it. However, [*Kaltschmitt 1997*] do not include upstream energies and emissions, so our figures are moderately higher, especially where a lot of electricity is used. Our primary energies are similar to those in the new [*ADEME 2003*] report.

Code	Process	Assoc. processes	Input	Expended energy			GHG emissions			
			kg/ kg prod.	As used MJ/ kg prod.	MJx/ MJ	Primary MJx/ kg prod.	g CO$_2$/ kg prod.	g CH$_4$/ kg prod.	g N$_2$O/ kg prod.	g CO$_2$eq/ kg prod.
AC1	**Nitrogen Fertilizer Provision**									
	Electricity (EU-mix, MV)	Z7a		0.6	2.83	1.78	74.8	0.18	0.0034	80.0
	Hard coal	KO1		3.9	1.09	4.32	405.8	1.51	0.0011	440.8
	Diesel	Z1		0.9	1.16	1.00	75.3	0.00	0.0000	75.3
	Heavy fuel oil	Z3		4.4	1.09	4.77	384.1	0.00	0.0000	384.1
	NG	Z6		33.0	1.13	37.31	2083.0	6.58	0.0008	2234.7
	N2O from process								*9.6300*	
	Primary energy and emissions/kg						*49.17*	*3022.9*	*8.27*	*9.6353*	***6065.3***
AC2	**P fertilizer provision**									
	Electricity (EU-mix, MV)	Z7a		1.6	2.83	4.54	191.2	0.47	0.0086	204.5
	Hard coal	KO1		0.6	1.09	0.62	58.6	0.22	0.0002	63.6
	Diesel	Z1		1.1	1.16	1.30	98.1	0.00	0.0000	98.1
	Heavy fuel oil	Z3		5.0	1.09	5.44	438.3	0.00	0.0000	438.3
	NG	Z6		3.2	1.13	3.56	198.8	0.63	0.0001	213.3
	Primary energy and emissions/kg					*15.47*	*985.0*	*1.31*	*0.0089*	***1017.8***
AC3	**K fertilizer provision**									
	Electricity (EU-mix, MV)	Z7a		0.2	2.83	0.62	26.2	0.06	0.0012	28.0
	Diesel	Z1		0.5	1.16	0.63	47.3	0.00	0.0000	47.3
	NG	Z6		7.5	1.13	8.48	473.4	1.50	0.0002	507.8
	Primary energy and emissions/kg					*9.73*	*546.9*	*1.56*	*0.0014*	***583.2***
AC4	**CaO fertilizer provision (85%CaCO3+15%CaO,Ca(OH)2)**									
	Electricity (EU-mix, MV)	Z7a		0.4	2.83	1.13	47.7	0.12	0.0022	51.0
	Coal	KO1		0.3	1.09	0.35	33.3	0.12	0.0001	36.2
	Diesel	Z1		0.2	1.16	0.21	16.2	0.00	0.0000	16.2
	NG	Z6		0.3	1.13	0.34	18.9	0.06	0.0000	20.3
	Primary energy and emissions/kg					*2.04*	*116.1*	*0.30*	*0.0023*	***123.7***
AC5	**Pesticides (etc) provision**									
	Electricity (EU-mix, MV)	Z7a		28.5	2.83	80.72	3398.9	8.29	0.1535	3635.0
	Hard coal	KO1		7.6	1.09	8.35	784.2	2.91	0.0021	851.9
	Diesel	Z1		58.1	1.16	67.40	5086.9	0.00	0.0000	5086.9
	Heavy fuel oil	Z3		32.5	1.09	35.37	2849.9	0.00	0.0000	2849.9
	NG	Z6		71.4	1.13	80.71	4505.9	14.24	0.0018	4834.0
	Primary energy and emissions/kg					*272.55*	*16625.8*	*25.45*	*0.1573*	***17257.6***

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

All inputs are quoted PER kg ACTIVE INGREDIENT. The kg/MJ input of fertilizer to the farming processes are also per kg active ingredient. The name of the process indicates what is considered the active ingredient. Thus, for example, "K2O fertilizer provision" is per kg potassium content as K_2O. The quantities of fertilizer specified in the farming pathways use the same convention. The active ingredient may actually be present in a mixture of compounds.

AC1   Nitrogen Fertilizer Provision

This is the main source of GHG emissions from agro-chemicals manufacture. Most of the GHG emissions come from NOx released from the process itself. The active ingredient is considered the nitrogen content, so the data are per kg nitrogen.

AC4   Lime (CaO+CaCO$_3$) Provision

Lime contains roughly 85 % m/m $CaCO_3$ and 15% CaO, partially hydrated to $Ca(OH)_2$. When used as a fertilizer, the CaO content neutralizes the carbonic acid produced by decaying vegetable matter. This carbonic acid would otherwise release its CO_2 to the air. Therefore the CO_2 produced by the calcining process ("process emissions" in [*Kaltschmitt 1997*]) is later effectively reabsorbed, and should be left out of GHG calculations.

Lime requirements for a particular crop vary greatly depending on soil type. Fortunately, though, it never represents a major energy input to our farming pathways, so the effect of the uncertainty is small.

AC5   Pesticides (etc.) Provision

This comprises all complex organic compounds; pesticides, fungicides, plant hormones…; used in the farming processes. The input energy and emissions data (from [*Kaltschmitt 1997*]) are necessarily a very approximate guess. [*ADEME 2003*] give range of 175-576 MJ/kg primary energy for various 'plant health products': our value of 266 MJ/kg compares with their best-estimate of 297 MJ/kg. Our emissions are considerably higher than those calculated by [*Kaltschmitt 1997*] from the same data: it looks like they forgot to add in the process emissions. The final fate of the carbon in the pesticides themselves is uncertain, but the amount of CO_2 involved is negligible. In fact, in general, the mass of pesticides in farming processes is so small that the choice of data has negligible influence on the calculations of farming emissions.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

11   Biomass transport

Code	Process	Assoc processes	one-way distance km	t.km/ MJ prod.	MJ diesel/ t.km	MJx/ t.km	gCO$_2$eq/ t.km	MJx/ MJ prod.	gCO$_2$eq/ MJ prod.	Loss MJ/MJ
Standard biomass transporters										
Z8	**Truck for dry product (round trip considered)**									
	Diesel	Z1,Z2			0.97	1.13	85.10			
Z9	**Ship for inland/coastal navigation**									
	Marine diesel	Z1			0.43	0.50	37.76			
Z10	**Ocean-going bulk carrier**									
	Fuel oil	Z3			0.20	0.22	17.77			
Solid biomass road transport										
WC2a	**Wood chips road transport, 50 km**	Z8	50	0.004	0.97	1.13	85.10	**0.0045**	**0.34**	0.000
WC2b	**Wood chips road transport, 12 km**	Z8	12	0.001	0.97	1.13	85.10	**0.0011**	**0.08**	0.000
SB2	**Sugar beet road transport**	Z8	50	0.013	0.97	1.13	85.10	**0.0147**	**1.11**	0.000
WT2a	**Wheat grain road transport**	Z8	50	0.004	0.97	1.13	85.10	**0.0039**	**0.30**	0.010
WT2b	**Wheat straw road transport**	Z8	50	0.003	0.97	1.13	85.10	**0.0039**	**0.29**	0.000
SC2	**Sugar cane road transport**	Z8	20	0.004	0.97	1.13	85.10	**0.0042**	**0.32**	0.000
RO2	**Rapeseed road transport**	Z8	50	0.002	0.97	1.13	85.10	**0.0024**	**0.18**	0.010
SO2	**Sunflower seed road transport**	Z8	50	0.002	0.97	1.13	85.10	**0.0024**	**0.18**	0.010
Solid biomass shipping										
WC2c	**Coastal/river shipping wood chips (200MW plant)**	Z8	400	0.034	0.43	0.50	37.76	**0.0171**	**1.29**	0.000
Manure transport										
BG1a	**Liquid manure transport, 10 km**	Z2	10	0.013	0.94	1.09	81.95	**0.0146**	**1.10**	
BG1b	**Dry manure transport, 10 km**	Z2	10	0.004	0.94	1.09	81.95	**0.0047**	**0.35**	
Long-distance biofuel transport			Naut. Miles							
SC4	**Sugar cane ethanol from Brazil**	Z4	5500	0.380				**0.0512**	**4.11**	
SY2	**Soya bean transport**			t.km/kg prod.						
	Truck transport of soya beans	Z8	50	0.050	0.97	1.13	85.10	**0.0564**	**4.25**	
	River transport of soya beans	Z9	250	0.250	0.43	0.50	37.76	**0.1251**	**9.44**	
	Ocean transport of soya beans	Z10	5000	5.000	0.20	0.22	17.77	**1.1085**	**88.86**	0.010
	Primary energy consumption and emissions							*1.2899*	*102.56*	

Z8   Truck for dry products

Nominal 23 t truck from [*ESU 1996*] obeying EURO IV emissions restrictions. Fuel consumption takes an empty return trip into account. The actual payload depends on the density of the material. This is taken into account when calculating effective t-km in each individual trucking process. According to [*Kaltschmitt 2001*] such a truck can actually carry up to 27 t for dense material, but usually for biomass the capacity is often limited by the maximum volume, which is 100 m^3. For rapeseed, for example, the actual payload is 22 t, close to the nominal payload. Cost is approximately 0.07EUR/t.km [*ESU 1996*].

Z9   Ship for inland/coastal navigation

For 8,800 t dry product carrier for coastal navigation (e.g. Baltic) or on inland waterways (e.g. Rhine) from [*ESU 1996*]; emissions data from [*Kaltschmitt 1997*]. Marine gasoil is the fuel: emissions are approximated to those of diesel. For discussion of transport distances, see below. Empty return trip considered.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

Z10   **Ocean-going bulk carrier**

40,000 t dry product carrier; consumption of heavy fuel oil from [*Kaltschmitt 1997*]. Calculation methodology is the same as for oil transport (see above).

BIOMASS TRANSPORT DISTANCES

FARMED WOOD
For a catchment area is shaped like our map, 50 km average transport distance gives access to about 0.6 Mha. If we assume 50% of this area is arable land, and 10% of this arable land is farmed wood, with a yield of 10 dry t/ha, then annual production from whole area is 300 dry kt.

A 10 MW plant (based on feed) requires 16.8 dry kt wood per year (at 18 GJ/t). By quadratic scaling, we need transport distance of 12 km. For a 200 MW plant we need 336 dry kt wood per year; implying a single catchment area with transport distance about 50 km.

STRAW
In the good wheat-growing areas where straw may be harvested, the straw yield from wheat is about 5 t/ha. But these are prime agricultural areas with a high % of cereals farms. If we assume 60% of the land is arable, and 70% of that grows wheat (or other suitable cereal), then the transport distance is reduced to 25 km for a 200 MW plant. Note that the projected Iogen plant is about 150 MW.

FOREST RESIDUALS
The Pietarsaari cogeneration plant in Finland collects up to 200 000 m^3 per year forest residuals, with MAX transport distance 80 km [*TEKES 2002*]. That means 90 dry kt/a for a dry-matter density of 0.4 dry t/m^3. The average transport distance would then be about 50km. These forest residuals give a total water-free-LHV energy input of 54 MW. For a 200 MW plant, for example on the Baltic coast, one would need to ship wood in from about 4 collecting points like this. Looking at a map of the Baltic that means maybe 400km average shipping distance. A central-European scenario, with barge transport on the Rhine or Danube, gives a similar results.
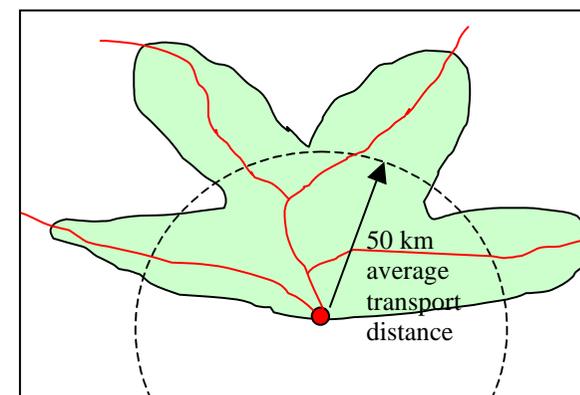
For a 10 MW plant, we get about 12 km road transport distance by quadratic scaling from the Pietarsaari example.

BIO-CROPS
In the literature one can find transport distances from the farm gate to the processing plant anything from 10 to almost 200 km. The first represents theoretical calculations of the radius needed to grow sufficient crop to feed the factory. The second represents the actual trucking distance for some existing plants: their supplies come from scattered farms which have opted to grow designated energy crops under existing rules for agricultural subsidies. Our distance represents what we think is reasonable for the medium-term future, if energy farming becomes much more common.

The calculation of t.km per MJ product takes into account the real payload of the truck, bearing in mind the volume limitation of the truck (see trucking processes). The return journey is already taken into account in the truck fuel consumption. For fine materials, 1% losses during loading and transport are considered.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

MANURE
This is used for biogas, usually at fairly small scale, hence the short transport distance taken into account.

SB2   **Soy bean transport**

This process is used in the pathway for calculating animal feed (soy meal) credits (see after 'biofuels processes'): everything in this pathway is related to mass of soy meal, since we have no LHV data on soy bean meal. The pathway represents soy bean trucking to a river-port, and than trans-shipping to a transatlantic vessel (e.g. near New Orleans). This scenario is from [*UBA 1999*].

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

12   Biogas from organic waste

Three sources of organic waste are considered namely municipal waste, "liquid" manure and dry manure. The process is described in the main *WTT report*. The anaerobic fermentation produces raw biogas that, depending on the intended use may need to be treated (to remove contaminants such as sulphur) and/or upgraded (to remove CO_2). The plant usually produces its own heat and electricity (CHP). Data for municipal waste is from [*Börjesson 2004*], [*Börjesson 2005*] and from [*Boisen 2005*] for manure. All three options include a small credit for use of the residual organic material as fertiliser. When left untreated, stored manure produces methane that is vented to the atmosphere. This is particularly so for liquid manure where the right conditions for anaerobic fermentation are met. Using manure for biogas production therefore offers a credit for avoided field methane emissions, particularly large for liquid manure.

Code	Process	Assoc. processes	Bio-feed	Expended energy			GHG emissions				Overall energy efficiency	Range		Probability distribution
			MJ bio-en/ MJ prod.	As used MJ/ MJ prod.	MJx/ MJ	Primary MJx/ MJ prod.	g CO2/ MJ prod.	g CH4/ MJ prod.	g N2O / MJ prod.	g CO2eq / MJ prod.		Min	Max	
	Raw biogas production from municipal waste													
	Municipal waste		1.4286								70%	1.2286	1.6286	
	Heat (for info, internally generated)			0.0865								0.0778	0.0952	
	Electricity (for info, internally generated)			0.0622								0.0311	0.0933	
	Methane losses							0.2000						
	Raw biogas production from liquid manure													
	Municipal waste		1.4286								70%	1.2286	1.6286	
	Heat (for info, internally generated)			0.1500								0.1400	0.1700	
	Electricity (for info, internally generated)			0.0430								0.0400	0.0500	
	Methane losses							0.2000						
	Methane field emissions credit							-2.8571				-1.4286	-4.2857	
	Raw biogas production from dry manure													
	Municipal waste		1.4286								70%	1.2286	1.6286	
	Heat (for info, internally generated)			0.1500								0.1400	0.1700	
	Electricity (for info, internally generated)			0.0430								0.0400	0.0500	
	Methane losses							0.2000						
	Methane field emissions credit							0.2857				-0.1429	-0.4286	
	Biogas treatment and upgrading													
	Raw biogas		1.0100											
	Electricity (for info, internally generated)			0.0300								0.0200	0.0400	
	Methane losses							0.2000						
	Biogas CHP plant													
	Raw biogas		1.7000									1.6200	1.7900	
	Heat generation		0.0000											
	Electricity generation		0.0000											
	Methane losses							0.0533						

Processes BG2a/b/c represent the integration of these steps to produce upgraded biogas from the different feedstocks. This gas is then suitable for use as automotive fuel or to be introduced into a natural gas grid. Processes BG3a/b/c represent direct small scale electricity production from raw biogas.

WTT APPENDIX 1

Code	Process	Assoc. processes	Bio-feed MJ bio-en/ MJ prod.	Expended energy			GHG emissions				Overall energy efficiency	Range		Probability distribution
				As used MJ/ MJ prod.	MJx/ MJ	Primary MJx/ MJ prod.	g CO2/ MJ prod.	g CH4/ MJ prod.	g N2O / MJ prod.	g CO2eq / MJ prod.		Min	Max	
BG2a	**Municipal waste to biogas (upgraded)**													
	Municipal waste		1.6916			0.6916								
	Electricity import	Z7a		0.0524	2.8347	0.1485				6.69				
	Methane losses							0.4423			g/MJ			
	N-fertiliser credit					-0.0299				-1.01	-0.18			
	Primary energy consumption and emissions					*0.8102*		*0.4423*		*15.85*				
BG2b	**Liquid manure to biogas (upgraded)**													
	Liquid manure		1.9367			0.9367								
	Electricity import	Z7a		-0.0134	2.8347	-0.0380				-1.71				
	Methane losses							0.4820		11.09				
	Methane field emissions credit							-3.8773		-89.18	g/MJ			
	N-fertiliser credit					-0.0215				-0.73	-0.13			
	Primary energy consumption and emissions					*0.8772*		*-3.3953*		*-80.53*				
BG2c	**Dry manure to biogas (upgraded)**													
	Dry manure		1.9367			0.9367								
	Electricity import	Z7a		-0.0134	2.8347	-0.0380				-1.71				
	Methane losses							0.4820		11.09				
	Methane field emissions credit							-0.3877		-8.92	g/MJ			
	N-fertiliser credit					-0.0215				-0.73	-0.13			
	Primary energy consumption and emissions					*0.8772*		*0.0943*		*-0.27*				
	Raw biogas to electricity (small scale, local)													
	Raw biogas		2.5000								*40%*	2.6316	2.3810	
	Heat generation			-1.2500										
	Electricity generation			-1.0000										
	Methane losses							0.0778						
BG3a	**Municipal waste to electricity (small scale, local)**													
	Municipal waste		4.2213			3.2213								
	Heat surplus (for info, no credit given)			-1.2241										
	Methane losses							0.2737		6.30	g/MJ			
	N-fertiliser credit					-0.0745				-9.09	-0.44			
	Primary energy consumption and emissions					*3.1468*		*0.2737*		*-2.79*				
BG3b	**Liquid manure to electricity (small scale, local)**													
	Liquid manure		3.9946			2.9946								
	Heat surplus (for info, no credit given)			-0.9809										
	Methane losses							0.3133		7.21				
	Methane field emissions credit							-7.9977		-183.95	g/MJ			
	N-fertiliser credit					-0.0443				-5.40	-0.26			
	Primary energy consumption and emissions					*2.9503*		*-7.6844*		*-182.14*				
BG3c	**Dry manure to electricity (small scale, local)**													
	Dry manure		3.9946			2.9946								
	Heat surplus (for info, no credit given)			-0.9809										
	Methane losses							0.3133		7.21				
	Methane field emissions credit							-0.7998		-18.39	g/MJ			
	N-fertiliser credit					-0.0443				-5.40	-0.26			
	Primary energy consumption and emissions					*2.9503*		*-0.4865*		*-16.59*				

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

13 Conversion processes for "conventional biofuels"

The range of energy and emissions reported by different authors for processing biomass into 'conventional biofuels' is much smaller than the uncertainty in farming emissions, especially N_2O emissions. Therefore we do not complicate by giving an error range. Where there are significantly different processes (e.g. lignocellulose-to-ethanol) we have made separate calculations for the two processes.

Large variations in the energy and emissions reported in the literature are due to different treatment of by-products, as discussed in the main body of this report.

13.1 Ethanol from sugar beet

Code	Process	Assoc. processes	Bio-feed MJ bio-en/ MJ prod.	Expended energy As used MJ/ MJ prod.	Expended energy MJx/ MJ	Expended energy Primary MJx/ MJ prod.	GHG emissions g CO2/ MJ prod.	GHG emissions g CH4/ MJ prod.	GHG emissions g N2O / MJ prod.	GHG emissions g CO2eq / MJ prod.	Overall energy efficiency	Range Min	Range Max	Probability distribution
	Sugar beet to ethanol													
SB3a	**Sugar beet to ethanol, pulp and slops to animal feed**													
	Basic process without slop or pulp credits													
	Sugar beet		1.8930			0.8930						1.7980	1.9880	
	Energy for main process													
	NG for steam at 90% eff.	Z6		0.3038	1.1306	0.3435	19.18	0.0606	0.0000	20.57		0.2886	1.1872	
	Electricity (MV)	Z7a		0.0172	2.8347	0.0488	2.05	0.0050	0.0001	2.20	kg/kg biomass	0.0163	2.9788	
	Primary energy and emissions (no by-product credits)					**1.2852**	21.23	0.0656	0.0001	**22.77**				
	Sugar beet pulp			-0.3850							0.050			
	Slops			-0.1770							0.023			
	Combined pulp and slops by-products			-0.5620							0.073			
	Pulp and slops drying													
	NG			0.2361	1.1306	0.2669	14.90	0.0471	0.0000	15.99	kWh	0.2243	1.1872	
	Electricity (MV)	Z7a		0.0182	2.8347	0.0516	2.17	0.0053	0.0001	2.32	wheat/kWh	0.0173	2.9788	
	Credit for pulp+slops replacing wheat grain (LHV basis)	WT1		-0.4665	0.1306	-0.0609	-4.01	-0.0061	-0.0147	-8.51	0.83			
	Net primary energy consumption and emissions					*1.5429*	*34.29*	*0.1120*	*-0.0145*	*32.57*				
SB3c	**Sugar beet to ethanol, pulp and slop to biogas digestor and CHP**													
	Basic process without credits		1.8930			**1.2852**	21.23	0.0656	0.0001	**22.77**		1.7980	1.9880	
	Pulp plus slops to biogas digester			-0.5620										
	Credits from biogas plant													
	NG	Z6		-0.2279	1.1306	-0.2577	-14.39	-0.0455	0.0000	-15.43				
	Electricity (MV)	Z7a		-0.0214	2.8347	-0.0607	-2.56	-0.0062	-0.0001	-2.73				
	Net primary energy consumption and emissions					*0.9668*	*4.29*	*0.0139*	*0.0000*	*4.60*				

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

SB3a   Ethanol from sugar beet; by-products used as animal feed

Sugar factories usually dry the by-product sugar beet pulp and sell it for animal feed, because it is worth more as feed than as fuel. Dried slop from the fermentation is a more valuable feed than the pulp.

Sugar factories using beet do not work all year round because of sugar loss from the beet in storage (see SB1 farming pathway). Beet processing 'campaigns' last between 60 days (Poland) and 150 days (Britain). Average for EU25 is about 90 days (also the German figure). However, it may be possible to keep the ethanol part of the plant working continuously by storing pasteurised syrup.

Following [*LBST 2002*] we choose a conventional fermentation plant, not integrated with a sugar refinery, as analysed by [*FfE 1998*]. First the process is shown without any credits for use of the pulp or slop. The size of the plant is not very important for efficiency, but has a big effect on costs. [*FfE 1998*] made a cost analysis on a hypothetical 59MW (ethanol) plant.

The main steps in the basic process are cleaning, slicing, sieving out the pulp by-product, syrup pasteurisation, fermentation, distillation, and final purification. Per MJ ethanol output, these steps use a total of 4.8KJ electricity and 0,27 MJ heat [*FfE 1998*], which we assume is supplied by a natural gas burner with 90% efficiency; i.e. 0,30 MJ natural gas. Distillation and final ethanol purification (drying with zeolite) consumes most of the energy. It takes 2.02 Kg sugar beet (at 76.5% water content) to make 1MJ ethanol.

There are two by-products: sugar beet pulp sieved from the syrup (0.050 kg/kg pulp, or 0.385 MJ/MJ ethanol), and the slop filtered from the fermented mash (0.023 dry kg/kg pulp, or 0.177 MJ/MJ ethanol). When the equivalent products from cereals fermentation are sold for animal feed, they are called "brewers' dried grains" and "solubles"; usually sold together. Both beet by-products have a dry LHV of 15MJ/kg [*FfE 1998*], contain initially 35-40% water, and have to be dried to about 9% water [*FfE 1998*], [*NRC 1998*]. The heat energy for drying and pelleting pulp is given in [*FfE 1998*] as 0.295MJ/moist kg sugar beet input: if we assume slops needs the same heat-per-dry-kg, the heat for drying both, per MJ ethanol, is 0.295*(0.05+0.023)/0.05/2.02 = 0,213 MJ/MJ ethanol. Again heat comes from a natural gas burner with 90% efficiency. In addition there is a small amount of electricity required for the blowers: 0.007 kWh/(kg moist sugar beet) for the pulp drying, or 0.018 MJ/MJ ethanol for drying both sugar beet and slop.

FODDER CREDIT CALCULATION
There is only 8.6 dry % m/m protein in dried sugar beet pulp [*NRC 1998*], but slop contains protein from the yeast: "solubles" from maize fermentation contain 26.7%m protein [; we can guess about 25 dry %m for dried slops. So the combined feed has about 13.4 dry % m/m protein, which is within the range for wheat. But wheat grain has a greater digestible energy content: according to [*NRC 1998*], pigs can digest 16.2 MJ/dry kg, compared to 13.2 MJ/dry kg for sugar beet pulp, and 13.9 MJ in "solubles". Taking into account the difference in LHV values; 17 MJ/dry kg for wheat grain [*Kaltschmitt 2001*] compared to 15.6 MJ/dry kg for pulp and slop [*FfE 1998*]; we calculate that 1 water-free MJ pulp replaces 0.83 water-free MJ wheat grain. The primary energy and emissions credits are then easily calculated from our wheat farming process WT1. The feed must be transported to the animals whatever they eat, so we assume the transport energy for the feed cancels out.

Note it costs more energy (and emissions) to dry the animal feed than you get credit for fodder saved. Nevertheless, this is the most likely destination for the by-products on economic grounds. To improve the energy balance and keep rational economics, one could make a process in which process heat comes from woody waste or straw, for example, but that applies to any process using heat.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

SB3c   **Ethanol From Sugar Beet; Pulp Added To The Biogas Fermentor**

The sieved pulp mash and is added to an anaerobic digester, which is already producing biogas from the waste-water. Furthermore, the slop is no longer filtered from the waste-water, and also makes biogas. The plant is simpler than one burning the by-products because they do not need to be dried. But the process is still probably less attractive economically than selling the by-products as animal feed.

To calculate the heat credit from the biogas burning we used the efficiency data of the biogas plant in [*FfE 1998*] (proposed for making methane for transport fuel). This plant incorporates a small gas engine for providing its own electricity, together with a small excess, which we treated as an electricity credit (you would not bother with this engine in practice but its effect on the overall energy and emissions balance is negligible). For each MJ biomass in, this plant produces 0.405 MJ biogas and 0.038 MJ electricity. We assume 1MJ biogas substitutes 1MJ natural gas.

The waste from the biomass fermentor would probably be used as fertilizer. However, the quantity is much smaller than the uncertainty in fertilizer use in the sugar beet farming process, so it is pointless to account for this.

Ethanol From Sugar Beet; By-Products Burnt For Process Heat

Animal feed is usually worth much more per MJ than biomass fuel: it would normally be cheaper to fuel the burner on some sort of waste. However, in order to allow comparison with other studies, we have included this option. The drying process for pulp and slop (taken from the SB3a) consumes about half the heat content of the by-products. The dried (9% water) by-products are burnt in a biomass boiler at 85% efficiency [*GEMIS 2002*], and replace natural gas burnt at 90% efficiency. The results of this process are almost the same as those for SB3c; pulp added to the biogas fermentor.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

13.2   Ethanol from wheat grain

Code	Process	Assoc. processes	Bio-feed MJ bio-en/ MJ prod.	Expended energy As used MJ/ MJ prod.	MJx/ MJ	Primary MJx/ MJ prod.	GHG emissions g CO2/ MJ prod.	g CH4/ MJ prod.	g N2O / MJ prod.	g CO2eq / MJ prod.	Overall energy efficiency	Range Min	Max	Probability distribution
WT3	**Wheat grain handling and drying (to dwg, 3% moisture)**													
	Wheat grain (16% moisture)		1.0000											
	Electricity (MV)			0.0026	2.8347	0.0072	0.30	0.0007	0.0000	0.33				
	Diesel			0.0400	1.1600	0.0464	0.57	0.0000	0.0000	0.57				
	Net primary energy consumption and emissions					*0.0536*	*0.88*	*0.0007*	*0.0000*	*0.90*				
WT4a	**Wheat grain to ethanol, conventional boiler**											t dw g/t EtOH		
	Dried wheat grain (dwg, 3% moisture)		1.8644			0.8644							3.03	
	Heat to process			0.3640										
	NG for steam at 90% eff.	Z6		0.4044	1.1306	0.4573	25.53	0.0807	0.0000	27.39				
	Electricity (MV)	Z7a		0.0540	2.8347	0.1531	6.45	0.0157	0.0003	6.89				
	Net primary energy consumption and emissions					*1.4747*	*31.97*	*0.0964*	*0.0003*	*34.28*				
WT4b	**Wheat grain to ethanol, NG CCGT**											t dw g/t EtOH		
	Dried wheat grain (dwg, 3% moisture)		1.8644			0.8644							3.03	
	Heat to process			0.3640										
	Electricity to process			0.0540										
	NG to CCGT			0.6794	1.1306	0.7681	42.88	0.1356	0.0000	46.00				
	Electricity net surplus			-0.1867										
	Credit for electricity surplus based on NG to state-of-the-art stand-alone CCGT			-0.3395	1.1306	-0.3839	-21.43	-0.0677	0.0000	-22.99				
	Net primary energy consumption and emissions					*1.2486*	*21.45*	*0.0678*	*0.0000*	*23.01*				
WT4c	**Wheat grain to ethanol, Lignite CHP**											t dw g/t EtOH		
	Dried wheat grain (dwg, 3% moisture)		1.8644			0.8644							3.03	
	Heat to process			0.3640										
	Electricity to process			0.0540										
	Lignite to CHP plant			0.7761	1.0156	0.7882	89.28	0.0000	0.0000	89.28				
	Electricity net surplus			-0.0775										
	Credit for electricity surplus based on lignite-fired conv. power station			-0.1937	1.0156	-0.1967	-22.15	0.0000	0.0000	-22.15				
	Net primary energy consumption and emissions					*1.4559*	*67.13*	*0.0000*	*0.0000*	*67.13*				
WT4d	**Wheat grain to ethanol, Straw CHP**											t dw g/t EtOH		
	Dried wheat grain (dwg, 3% moisture)		1.8644			0.8644							3.03	
	Heat to process			0.3640										
	Electricity to process			0.0540										
	Straw to CHP plant			0.7761	1.0165	0.7889	0.96	0.0000	0.0000	0.97				
	Debit for additional fertilisers (net)				kWh/kg						kgex/MJ EtOH			
	N				13.6591	0.0000	0.00	0.0000	0.0205	6.06	0.0000			
	P				4.2959	0.0011	0.07	0.0001	0.0000	0.07	0.0001			
	K				2.7023	0.0037	0.21	0.0006	0.0000	0.22	0.0004			
	Total					0.0047	0.27	0.0007	0.0205	6.35				
	Electricity net surplus			-0.0775										
	Credit for electricity surplus based on Straw-fired conv. power station			-0.2460	1.0165	-0.2500	-0.31	0.0000	0.0000	-0.31				
	Net primary energy consumption and emissions					*1.4080*	*0.93*	*0.0007*	*0.0205*	*7.01*				
WTDa	**Credit for DDGS as animal feed**											kg/MJ EtOH	Protein factor	
	Soya substitution	SYML				-0.3074	-4.01	-0.0115	-0.0199	-10.17		0.043	0.78	
WTDb	**Credit for DDGS as fuel**											kg/MJ EtOH		
	Electricity			-0.2042	1.1306	-0.4197	-23.43	-0.0741	0.0000	-25.14		0.043		

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

The data used here are essentially derived from [*LowCVP 2004*]. Process Wt3 describes the grain drying step to arrive at "dry wheat grain" (dwg, 3% moisture). Processes WT4a/b/c/d describe the ethanol plant proper. They all assume the same energy requirement for the plant but different utility generation schemes.

WT4a   Conventional natural gas boiler

Heat is supplied by a conventional natural gas fired boiler and electricity is imported. This can be considered as representative of the vast majority of existing installations and is also by far the cheapest solution.

WT4b   Combined cycle gas turbine

A natural gas fired gas turbine with a heat recovery steam generator (HRSG) provides both heat and electricity. As more heat than electricity is required supplementary firing is applied in the HRSG. As the heat is required only as low pressure steam, a back pressure turbo-generator is also installed behind the HRSG. The plant is assumed to be sized and operated to produce the heat required for ethanol manufacture. There is, however, a surplus of electricity which is exported into the grid, thereby generating an energy and GHG credit.

This solution is considerably more energy efficient but also significantly more complex and expensive to build and operate.

WT4c   Lignite boiler CHP

High pressure steam is produced in a lignite boiler. A back pressure turbo-generator produces electricity and low pressure steam for the process. Here again the plant is assumed to be sized and operated to produce the heat required for ethanol manufacture but it nevertheless generates an electricity surplus.

Lignite (or brown coal) is a cheap and abundant fuel in certain parts of Europe and actual plants are either operating or under construction in Eastern Germany.

WT4d   Straw boiler CHP

Wheat cultivation produces large amounts of straw. Some LCA studies have considered straw as a by-product but this is not necessarily the case. In most of the EU it should be ploughed back to maintain the water-retention properties of the soil (see also straw availability, *WTT report, section 5*). Where it may be removed from the field it is partly already used for litter and other applications. Therefore it is misleading to systematically assume that straw can be used to fuel the ethanol production process. In practice this should only be proposed where there is little water stress, a high density of cereals production and a low density of livestock. These conditions would apply to concentrated wheat-producing areas in Northern Europe excluding the Low Countries and Denmark. In any case removing straw will reduce soil nutrients, which needs to be compensated by an additional fertiliser input.

This scheme is similar to the previous case but straw in used instead of lignite. The main advantage of this scheme is to use a renewable source of energy to drive the process. It must be realised, however, that handling and burning of solids is considerably more complex and costly than with liquids or gases, particularly in the case of a low energy density material such as straw. This will therefore be the most expensive option.

WTDa   Credits for DDGS as animal feed

Ethanol production produces a by-product known as DDGS (Distiller's Dried Grain with Solubles) which is the solid residue after digestion of the carbohydrates. DDGS is a protein-rich material and is therefore a useful animal feed component. Its nearest equivalent is corn gluten feed, a by-product of maize milling the supply of which is fixed by the amount of maize milled. Wheat DDGS contains 38.5% dry matter crude protein [*Univ. Minnesota 2002*] more than DDGS from

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

maize). In the EU marginal animal feed is soy bean meal imported from the USA. The meal made from pure soy beans has a protein content of 49% [*NRC 1998*]. Since protein feeds are much more valuable than energy feeds [*DG-AGRI 2003*], farmers would use 1kg DDGS to replace 38.5/49 = 0.78 kg soy bean meal (the digestible energy ratio is anyway similar). The equivalent quantity of soy bean meal is calculated on the basis of the protein content using data from [*NRC 1998*]. The energy and emissions for the soy meal is calculated according to a scenario of soy beans grown in the US, and crushed in EU, following [*UBA 1999*] (see *section 13.6*).

WTDb   Credits for DDGS as fuel

Although animal feed is by far the most lucrative usage and therefore the most likely, DDGS may also be used as fuel, for instance in solid-burning (i.e. coal) power plants that need to meet their renewable energy obligations. The calorific energy content of DDGS is considerably greater than the energy required to produce the equivalent animal feed, so burning DDGS gives a higher energy credit.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

13.3 Ethanol from sugar cane (Brazil)

Code	Process	Assoc. processes	Bio-feed	Expended energy			GHG emissions				Overall energy efficiency	Range		Probability distribution
			MJ bio-en/ MJ prod.	As used MJ/ MJ prod.	MJx/ MJ	Primary MJx/ MJ prod.	g CO2/ MJ prod.	g CH4/ MJ prod.	g N2O / MJ prod.	g CO2eq / MJ prod.		Min	Max	
SC3	**Sugar cane to ethanol**													
	Sugar cane		2.7720			1.7720								
	Credit for surplus heat (diesel)			-0.1150	1.2609	-0.1450	-10.94			-10.94				
				kg/kWh EtOH	kWh/kg									
	H2SO4	C7		0.00047	4.0052	0.0019	0.09	0.0003	0.0000	0.10				
	CaO	C6		0.00043	4.9835	0.0021	0.46	0.0004	0.0000	0.47				
	Cyclohexane			0.00003	9.9000	0.0003	0.01			0.01				
	Primary energy consumption and emissions					***1.6313***	*-10.39*	*0.0006*	*0.0000*	***-10.37***				

Data for this process were taken from the careful life-cycle analysis by [*Macedo 2004*],adopting his "scenario 2" describing best-current-practice in the Centre-South region of Brazil, where 85% Brazilian ethanol is produced. His analysis also takes into account the energy for plant construction and some minor inputs which we neglect to be consistent with our calculations for other processes.

The data refer to the production of *anhydrous* ethanol, in Macedo's best-current-practice scenario. Cyclohexane is used in the drying process. The yield corresponds to 91.8 litres ethanol per tonne of moist cane. Inputs were converted from quantities per-tonne-of-cane to per-MJ-ethanol using the same LHV and water content for sugar cane as used in the sugar cane farming process, and standard values for ethanol (see section 1.2).

Plant capacity is 120 000 litres ethanol per day, and it operates for 180 days per year. A very important factor is that the bagasse to raise steam which provides all the process heat, and electricity via a steam turbine. In fact modern plants have a surplus of bagasse. Although this could be used to generate electricity exports, usually the surplus bagasse is simply sold as a fuel for nearby factories (e.g. for food processing), where it mostly replaces fuel oil (almost identical to diesel; used for our credit).

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

13.4 Bio-diesel from plant oil

Code	Process	Assoc. processes	Bio-feed	Expended energy			GHG emissions				Overall energy efficiency	Range		Probability distribution
			MJ bio-en/ MJ prod.	As used MJ/ MJ prod.	MJx/ MJ	Primary MJx/ MJ prod.	g CO2/ MJ prod.	g CH4/ MJ prod.	g N2O / MJ prod.	g CO2eq / MJ prod.		Min	Max	
RO3	**Rapeseed to raw oil: extraction**													
	Rapeseed		1.6326			0.6326								
	Electricity (MV)	Z7a		0.0084	2.8347	0.0238	1.00	0.0024	0.0000	1.07				
	NG for steam at 90% eff.	Z6		0.0442	1.1306	0.0500	2.79	0.0088	0.0000	2.99				
	n-hexane	see notes		0.0031	1.1600	0.0036	0.27	0.0000	0.0000	0.27	kg/MJ prod.			
	Rapeseed cake										-0.0408			
	Soya meal / rapeseed cake replacement ratio										0.80			
	Credit for rapeseed cake	SYML			0.7862	-0.1155	-8.09	-0.0020	0.0211	-1.89				
	Primary energy consumption and emissions					***0.5945***	*-4.03*	*0.0092*	*0.0212*	***2.44***				
SO3	**Sunflower seed to raw oil: extraction**													
	Sunflower seed		1.5201			0.5201								
	Electricity (MV)	Z7a		0.0078	2.8347	0.0222	0.93	0.0023	0.0000	1.00				
	NG for steam at 90% eff.	Z6		0.0412	1.1306	0.0465	2.60	0.0082	0.0000	2.79				
	n-hexane	see notes		0.0029	1.1600	0.0033	0.25	0.0000	0.0000	0.25	kg/MJ prod.			
	Sunflower seed cake										-0.0361			
	Soya meal / sunflower seed cake replacement ratio										0.61			
	Credit for sunflower cake	SYML				-0.0779	-5.46	-0.0014	0.0142	-1.43				
	Primary energy consumption and emissions					***0.5142***	*-1.67*	*0.0091*	*0.0143*	***2.60***				
RO4 /SO4	**Raw oil to refined oil**													
	Crude plant oil		1.0417			0.0417								
	Electricity, MV	Z7a		0.0006	2.8347	0.0017	0.07	0.0002	0.0000	0.08				
	NG for steam at 90% eff.	Z6		0.0091	1.1306	0.0103	0.58	0.0018	0.0000	0.62				
	Primary energy consumption and emissions					***0.0537***	*0.65*	*0.0020*	*0.0000*	***0.70***				

RO3   Rapeseed Oil Extraction

Rapeseed is crushed and the oil is extracted with the aid of n-hexane solvent and heat. Our data is from [*UBA 1999*], [*Groves 2002*] and [*ADEME 2002*] have slightly better yield, with slightly higher inputs. The hexane is a refinery product made almost entirely from crude oil: we simplified the other primary energy inputs listed in [*FfE 1997*] to crude oil equivalents. In all conversion processes, we assume process heat or steam is supplied by a NG boiler working at 90% efficiency.

Rapeseed cake is the by-product: a high-protein animal feed. Farmers decide how much of it to feed to animals on the basis of the protein content. The crude protein content of rapeseed cake (39.6% dry mass) and pure soy bean meal (49% dry mass) is given in [*NRC 1998*]. Therefore one kg rapeseed cake will replace 39.6/49 = 0.80 kg soy bean meal. The process for making 1 kg soy meal is described below. The LHV of plant oil is 36 MJ/kg [*FfE 1998*].

SO3   Sunflower Oil Extraction

A similar process to rapeseed oil extraction: data from [*UBA 1999*]: the oil yield is slightly lower than for rapeseed, so more kg of cake are produced per MJ. However, the sunflower seed cake contains less protein (30% dry matter), so the credit for replacing soy beans meal is smaller.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

RO/SO4 Plant Oil Refining

This process, from [*UBA 1999*], uses, in addition to the fossil energy inputs listed, 6 kg fullers' earth per t of plant oil for adsorbing impurities. Fullers' earth is a cheap mineral, with negligible energy input for this quantity. Data are similar to [*Groves 2002*] and [*ADEME 2002*].

Code	Process	Assoc. processes	Bio-feed	Expended energy			GHG emissions				Overall energy efficiency	Range		Probability distribution
			MJ bio-en/ MJ prod.	As used MJ/ MJ prod.	MJx/ MJ	Primary MJx/ MJ prod.	g CO2/ MJ prod.	g CH4/ MJ prod.	g N2O / MJ prod.	g CO2eq / MJ prod.		Min	Max	
RO5 /SO5	**Refined oil to FAME: esterification**													
	Refined plant oil		1.0065			0.0065								
	Electricity EU mix, MV	Z6a		0.0029	2.8347	0.0082	0.35	0.0008	0.0000	0.37				
	Methanol	GA1		0.0585	1.6584	0.0969	5.41	0.0171	0.0000	5.81		0.0556	0.0614	
	NG for steam at 90% eff.	Z6		0.0410	1.1306	0.0464	2.59	0.0082	0.0000	2.78		0.0401	0.0430	
	Various other chemicals	see notes				0.0103	0.14	0.0000	0.0000	0.14				
	Primary energy and emissions (no glycerine credit)					0.1683	8.49	0.0261	0.0000	9.09 kg/MJ prod.				
	Glycerine										-0.0028			
5a	Credit for typical chemical replaced by glycerine	C10				-0.0591	-5.95	-0.0070	-0.0002	-6.16				
	Glycerine purification			0.0388	1.1306	0.0439	2.45	0.0077	0.0000	2.63				
	Primary energy consumption and emissions					*0.1531*	*4.98*	*0.0269*	*-0.0001*	*5.56*				
5b	Credit for glycerine replacing wheat grain (LHV basis)	WT1				-0.0061	-0.40	-0.0006	-0.0014	-0.84		0.99 kg/kg dry wheat grain		
	Glycerine purification			0.0388	1.1306	0.0439	2.45	0.0077	0.0000	2.63				
	Primary energy consumption and emissions					*0.2061*	*10.54*	*0.0333*	*-0.0014*	*10.89*				
RO6 /SO6	**Refined oil to FAEE: esterification**													
	Refined plant oil		0.9509			-0.0491								
	Electricity EU mix, MV	Z6a		0.0029	2.8347	0.0082	0.35	0.0008	0.0000	0.37				
	Ethanol	GA1		0.1100	1.5318	0.1685	1.14	0.0028	0.0007	1.42		0.1045	0.1155	
	NG for steam at 90% eff.	Z6		0.0410	1.1306	0.0464	2.59	0.0082	0.0000	2.78		0.0401	0.0430	
	Various other chemicals	see notes				0.0030	0.14	0.0000	0.0000	0.14				
	Primary energy and emissions (no glycerine credit)					0.1770	4.21	0.0118	0.0008	4.71 kg/MJ prod.				
	Glycerine										-0.0026			
6a	Credit for typical chemical replaced by glycerine	C10				-0.0591	-5.95	-0.0070	-0.0002	-6.16				
	Glycerine purification			0.0388	1.1306	0.0439	2.45	0.0077	0.0000	2.63				
	Primary energy consumption and emissions					*0.1618*	*0.70*	*0.0126*	*0.0006*	*1.18*				
6b	Credit for glycerine replacing wheat grain (LHV basis)	WT1				-0.0003	-0.02	0.0000	0.0000	-0.02		0.99 kg/kg dry wheat grain		
	Glycerine purification			0.0388	1.1306	0.0439	2.45	0.0077	0.0000	2.63				
	Primary energy consumption and emissions					*0.2206*	*6.64*	*0.0196*	*0.0008*	*7.31*				
Note: in the case of FAEE methanol is replaced by bio-ethanol from pathway WTET2a. The energy used in this process is deemed to remain the same														

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

RO/SO5   Esterification (methanol)

The process is the same for rapeseed oil and sunflower seed oil. Plant oil consists of 3 fatty acid chains on a 3-carbon backbone. 3 molecules of methanol combine with the fatty acids to make 3 molecules of fatty acid methyl ester (FAME), leaving their three alcohol groups stuck on the 3-carbon backbone to form glycerine. 0.1 t methanol reacts with 1 t plant oil to make 0.1 t glycerine and 1 t FAME.

Input data are similar to [*Groves 2002*] and [*ADEME 2002*]. The LHV RME is 36.8 GJ/t, that of glycerine is 16.0 GJ/t [JRC calculation] and methanol is 19.9 GJ/t. Methanol is made mostly from natural gas. "Various other chemicals" aggregates the primary energy inputs and emissions fro a list of minor inputs (NaOH, Na_2CO_3, H_3PO_4, HCl) detailed in [*UBA 1999*] and [*GM 2002*].

Two credit calculations are made for glycerine. In RO5a/SO5a it is for a typical chemical product; we found data for propylene glycol, in [*GEMIS 2002*], which differs from glycerine only by 1 oxygen atom, and is one of many chemicals which glycerine might displace. It uses much less primary energy than synthetic glycerine according to [*GM 2002*], presumably because the data for the latter includes energy for distilling a pharmaceutical-quality product. RO5b/SO5b include a credit for glycerine replacing wheat as an animal feed credit. We know that glycerine is easily digestible, but there is no numerical data in the literature. We assume that its digestible energy content is 95% of the LHV: the same fraction as for wheat. Then glycerine replaces wheat 1:1 on an LHV basis; we can use our wheat-farming process to calculate the credit.

RO/SO6   Esterification (ethanol)

Same as RO/SO5 replacing methanol by ethanol.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

13.5 Processes to make materials needed for biomass processing and credit calculations

These processes make ingredients for biofuels. As with other biomass processes, we include the LHV and fossil C (as CO_2) content of the input fuels in our "MJ primary energy" and CO_2 emissions figures associated with fuels inputs.

Materials needed for biomass processing and credit calculations

Code	Process	Assoc. processes	Input kg/ kg prod.	Expended energy			GHG emissions			
				As used kWh/ kg prod.	kWhx/ kWh	Primary kWhx/ kg prod.	g CO_2/ kg prod.	g CH_4/ kg prod.	g N_2O/ kg prod.	g CO_2eq/ kg prod.
C6	**Pure CaO for processes**									
	Natural gas	Z6		1.13	1.1306	1.28	257.7	0.8146	0.0001	276.5
	Diesel	Z1		0.05	1.1600	0.05	16.9			16.9
	Electricity (EU-mix, MV)	Z7a		0.02	2.8347	0.05	7.4	0.0179	0.0003	7.9
	CaCO3=CaO+CO2						785.7			785.7
	Primary energy and emissions/kg					*1.38*	*1067.6*	*0.8326*	*0.0004*	*1086.9*
C7	**Sulphuric acid**									
	Electricity (EU mix-MV)	Z7a		0.21	2.8347	0.60	90.7	0.2211	0.0041	97.0
	NG	Z6		0.46	1.1306	0.51	103.4	0.3268	0.0000	110.9
	Primary energy and emissions/kg					*1.11*	*194.1*	*0.5479*	*0.0041*	*207.9*
C8	**Ammonia**									
	NG	Z6		10.9	1.1306	*12.32*	*2323.3*	*4.3077*		*2422.3*
C10	**Propylene glycol (alternative credit for esterification process)**									
	Propylene from crude oil		0.79	2.34		1.84	1500.0	0.9984	0.0263	1530.7
	Electricity (EU mix-MV)	Z7a		1.39	2.8347	3.94	597.3	1.4566	0.0270	638.8
	Primary energy and emissions/kg					*5.78*	*2097.3*	*2.4550*	*0.0533*	*2169.5*

C6   Pure CaO for Processes

Calcium oxide is used for neutralization in SSCF processes and elsewhere. A more pure grade is required than the lime used in agriculture. Another difference is that the carbon dioxide driven off from limestone in the calcining process is not reabsorbed when the product is used for neutralizing sulphuric acid, for example. So, unlike in lime-for-agriculture, the CO_2 emissions from the calcining process should be included. Data from [*GEMIS 2002*].

C7   Sulphuric Acid

Used in SSCF digestion. Data from [*ESU 1996*]. Sulphur mining is neglected

C8   Ammonia

Used in SSCF processes. Data from [*Kadam 1999*].

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

C10 **Propylene Glycol**

This is a solvent and antifreeze which could represent the sort of bulk chemical replaced by glycerol from FAME, considering that the extra supply far exceeds the amount of synthetic glycerine still produced The electricity consumption is a preliminary estimate in [*GEMIS 2002*], and this source also gives primary energies for propylene. Propylene is a refinery product: almost all the input energy is from crude oil, but there are minor credits for gas and coke by-products which we converted to crude-oil equivalents. To convert to MJ, JRC calculated the LHV of propylene; 45.9GJ/tonne, using "HSC for Windows" thermo-chemistry programme. Propylene is a chemical input here, not a fuel being processed. That means we include its LHV and fossil carbon contents (as CO_2) in its "primary energy and emissions". This saves having to add them separately when we come to calculate the credit

13.6 Soy bean meal production

Code	Process	Assoc. processes	Input kg/ kg prod.	Expended energy			GHG emissions			
				As used kWh/ kg prod.	kWhx/ kWh	Primary kWhx/ kg prod.	g CO_2/ kg prod.	g CH_4/ kg prod.	g N_2O/ kg prod.	g CO_2eq/ kg prod.
SY3	**Soya bean meal from crushing US beans, per kg bean meal (inc.transport from US)**									
	Electricity (EU mix-MV)	Z7a		0.07	2.8347	0.21	31.8	0.0774	0.0014	34.0
	NG for steam at 90% eff.	Z6		0.38	1.1306	0.43	86.4	0.2730	0.0000	92.7
	n-hexane			0.01	1.1600	0.01	3.9			3.9
	Plant oil by-product credit		-0.23			-0.58	-121.0	-0.3458	-1.0303	-433.9
	Primary energy and emissions/kg					***0.07***	*1.1*	*0.0046*	*-1.0288*	***-303.3***
SYML	**Soya bean meal supply**			kg biomass/kg meal						
	Soybeans farming/kg meal	SY1		1.23	0.3807	0.47	120.5	0.0579	0.3819	241.9
	Soyabeans transport/kg meal	SY2		1.23	0.3583	0.44	126.3			126.3
	Soyabean meal from beans crushing	SY3		1.00	0.0726	0.07	1.1	0.0046	-1.0284	-303.2
	Primary Energy and emissions per kg					***0.98***	*247.9*	*0.0625*	*-0.6465*	***65.0***

SY3 **Soy bean meal from crushing soy beans**

This is a mass-based process which is needed to calculate the credits per kg of protein-rich animal feeds. The overall process comes from [*UBA 1999*].

Hexane (solvent used to increase oil recovery) is an oil-refinery product made almost entirely from crude oil. The primary energy inputs listed in [*Kaltschmitt 1997*] were simplified by converting them to crude oil equivalents.

The soy bean oil is treated as a by-product. It attracts an energy and CO_2 credit by substituting rapeseed oil. This is how we calculated the credit: we found the energy and emissions for making 1MJ rapeseed oil starting with the energy and emissions from the oil mill (process RO3), and adding (energy and emissions from the rapeseed farming, per MJ rapeseed)*(MJ of rapeseed need to make 1 MJ oil). Then we multiplied all this by the LHV of plant oil (always around 36 MJ/kg) to find the energy and emissions per kg of oil.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

Astute readers will have noticed that, since rape oil extraction itself has a credit for rapeseed cake, which replaces soy bean meal, we have a loop here. However, this is not a problem: even Excel is sometimes capable of an iterative calculation to converge on the correct solution.

SYML   Complete soy bean meal production chain

Soy bean extraction is the last step in the production chain for soy bean meal. Soy bean farming is included with the farming processes and the transport with the transport processes. Following the scenario in [*UBA 1999*], the soy beans are imported from the USA and crushed in EU, where the oil replaces rapeseed oil: there is no transport of soy oil. So now we have all the data needed to link the three together to get the total primary energy and emissions from provision of soy meal.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

14   Synthetic fuels and hydrogen production from farmed wood and wood waste

Code	Process	Assoc. processes	Bio-feed MJ bio-en/ MJ prod.	As used MJ/ MJ prod.	MJx/ MJ	Primary MJx/ MJ prod.	g CO2/ MJ prod.	g CH4/ MJ prod.	g N2O / MJ prod.	g CO2eq / MJ prod.	Overall energy efficiency	Min	Max	Probability distribution
WW1	**Forest residuals to wood chips** Losses during chipping and storage Diesel	Z1	1.0250 0.0040	1.1600		0.0250 0.0046	0.35	0.0000	0.0000	0.35				
W3d	**Wood to hydrogen: gasification, 200MW** Wood Electricity from wood *Primary energy consumption and emissions*	W3j	1.4624 0.0820			0.4624 0.1929 *0.6553*	0.00 *0.00*	0.00 *0.0000*	0.00 *0.0000*	0.00 *0.00*	60%	1.3893	1.5355	Triangular
W3e	**Wood to hydrogen: gasification, 10MW** Wood Process emissions from gasifier Electricity (EUmix, MV) for 1. gasifier 2. syngas compression and CO shift 3. PSA , CO to gas engine for electric *Primary energy and emissions (tiny surplus electricity)*	Z7a Z7a Z7a	1.9313 0.0369 0.1025 -0.1440	2.8347 2.8347 2.8347		0.9313 0.1046 0.2906 -0.4082 *0.9183*	4.40 12.24 -17.19 *-0.55*	0.0150 0.0107 0.0298 -0.0419 *0.0136*	0.0045 0.0002 0.0006 -0.0008 *0.0044*	1.66 4.71 13.09 -18.38 *1.08*	52%	1.8339	2.0272	Triangular
W3f	**Wood to syn-diesel: gasification + FT** Wood Credit for wood-to-electricity *Primary energy consumption and emissions*	W3i	2.6384 -0.2394			1.6384 -0.5633 *1.0751*	0.00 *0.00*	0.00 *0.0000*	0.00 *0.0000*	0.00 *0.00*	48%	1.9725 0.0000	2.9600 -0.7859	Triangular
W3g	**Wood to methanol or DME: gasification + synthesis** Wood *Primary energy consumption and emissions*		1.9586			0.9586 *0.9586*	*0.00*	*0.0000*	*0.0000*	*0.00*	51%	1.7021	21.7000	Equal
W3h	**Wood cofiring in coal power station** Wood		2.6667			1.6667	0.00	0.04	0.02	8.17	*38%*	2.5000	2.8571	Normal
W3i	**Wood to electricity: BCL 25MW for calculating electricity credits in BCL-based processes** Wood (emissions unknown but very small)		2.3529			1.3529	0.00	0.00	0.00	0.00	42.5%			

WW1   Forest residuals chipping

The branches, tops and roots are stripped from the trunks in the forest: losses of forest residuals during collection and forwarding to the chipper stay in the forest, and are already taken into account in the ratio of residuals to stemwood. The losses which remain are from chip making, handling and storage, due to spillage, evaporation of volatiles, respiration and rotting. The figures (from forestry experts) are more or less in line with those in [*Hamelinck 2002*]. Diesel use by the roadside chipper is from [*Hartmann 1995*]. There are some lower values for different scenarios in the literature, but anyway this energy is insignificant for the whole pathway.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

14.1   Wood gasification to hydrogen

W3d   Large scale (200 MW)

200 MW was considered the largest scale of gasifier consistent with economic wood supply from EU-grown forest residuals or farmed wood; it is about the consumption of the largest existing power plant using forest residuals and pulp-mill waste [*TEKES 2002*]. It is impossible to scale the DM2-typoe gasifier up to 200MW because of the limit on how fast heat can be injected through the gasifier walls. For this larger scale, we used a process described in detail by [*Katofsky 1993*] and [*Mann 1997*], based on a scale-up of the Batelle-Columbus BCL indirectly-heated circulating fluidized bed gasifier.

Sand carries heat to pyrolyse the dried biomass. The cooled sand and coke left from the pyrolysis returns to a separate combustion section, where it is burnt in air. In this way the syngas from the pyrolysis section is not diluted with nitrogen. The syngas goes through conventional cold (wet) gas-cleaning and is then compressed into a 950°C reformer, to convert hydrocarbons to CO and H_2, followed by a 2-stage shift reactor to improve the H_2/CO ratio. Hydrogen is separated by PSA and the remaining CO is burnt in a combined cycle condensing electricity power-plant.

However, the process is so optimised for hydrogen production that the electricity generated by the waste gas in the CCC is not sufficient to cover all the needs of the plant. If we were to give a debit for provision of grid electricity, GHG emissions and fossil energy use appear on the bottom line. This gives an unfair impression when comparing with other processes which maybe produce much less fuel but a little more electricity. Effectively these other processes have improved their energy/GHG per MJ fuel by incorporating part of a wood-to-electricity process. To even things up, we make all processes electricity-neutral by giving electricity credits or debits using the nearest equivalent wood-to-electricity process. In the case of W3E, we chose a wood-to-electricity pathway from the literature which uses the same gasifier (BCL). It is shown at the bottom of the table as W3K. The overall result is about the same as the [*Katofsky 1993*] process de-optimized to give a little more electricity and a little less hydrogen.

In doing this, we have not departed from our principle of subtracting a "reference scenario" from a "biofuels" scenario. The nature of the process forces us to produce both hydrogen and bio-electricity in the biofuel scenario: to find the contribution only of the hydrogen production, we should produce the same quantity of bio-electricity in the reference scenario. This is the same as a bio-electricity credit.

W3e   Small scale (10MW)

This is a process intended for hydrogen production from local wood resources. It was calculated by LBST, based on the CHOREN DM2 10 MW$_{th}$ externally-heated gasifier [*Schmid 2001*]. The moist wood is pyrolysed (with a simultaneous reforming reaction) using heat from the coke by-product. It can cope with wood with up to 35% moisture, but the process efficiency is calculated for 30% moisture in the wood, when the cold gas efficiency of the gasifier is 76.4% [*Schmid 2001*]. The syngas is compressed into a catalytic shift reactor to increase the hydrogen content up to about 66% at the expense of CO. The hydrogen is separated in a Pressure-Swing-Adsorption (PSA) system. The rest of the syngas is burnt for process power and heat in a micro turbine with 24% electrical efficiency and 51% process heat recovery. The process is very nearly electricity-neutral.

14.2   Synthetic fuels from wood gasification

W3f   Synthetic Diesel from Wood

Our "best estimate" is based on the study by [*Tijmensen 2002*]. In the variant we chose, syngas from the BCL gasifier (the same as in the 200 MW$_{th}$ hydrogen process) passes cold gas cleaning, a reformer and shift-reactor as in the hydrogen process. An amine process removes the CO_2, and the rest of the syngas enters a fixed-bed Fischer-Tropsch reactor, which builds alkanes from reacting CO and hydrogen on the surface of the catalyst. The reaction conditions are

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

adjusted to maximize the direct production of liquids (gasoil, kerosene and naphtha), which are condensed from the off-gas. Co-products are unreacted gas, LPG vapour and wax. The wax is hydrocracked to make more diesel and naphtha. In our chosen variant, which maximizes diesel yield, up to 2/3 of the unreacted gas (+LPG) is recycled to pass the FT reactor again. The LPG in the recycle does not react: once the alkyl chain is terminated, it cannot be re-opened by the FT catalyst.

The off-gas that is not recycled in our variant is burnt in a condensing combined cycle for process heat and electricity. This produces an excess of electricity, for which we give a wood credit, using process W3K: electricity from BCL gasifier. This simulates an electricity-neutral process as explained above.

The process yield, efficiency and the product mix depends on the performance of the FT catalyst, which determines the chain growth probability (CGP). [*Tijmensen 2002*] took a range of likely CGP values, because the catalyst performance is difficult to predict. We took their average CGP (0.85) for our best-estimate case.

The composition of the FT liquids condensed after the reactor has to be found from figure 2 of [*Tijmensen 2002*]: about 35% m/m naphtha and 65% m/m middle distillates (= gasoil + kerosene). To this should be added the products of wax cracking. The mass of wax produced is 19% of the FT liquids, and if cracked so as to maximize gasoil, yields 15% of its mass in naphtha and 85% diesel. Bearing in mind also that naphtha has slightly higher LHV than diesel (44.5 vs. 44.0 MJ/kg) the overall product mix turns out to be 68% diesel and 32% naphtha in energy terms.

For our worst-case we took the lowest CGP (0.8) considered by [*Tijmensen 2002*]. Then we calculated the overall product mix is 57% diesel and 43% naphtha in LHV terms. There is a wood credit for electricity as before.

For our best case, no variant in [*Tijmensen 2002*] can match the yield and efficiency (51%) claimed by [*CHOREN 2003*] for a projected biogas-to-liquids process based on the DMT gasifier. The CHOREN process is electrically neutral. They project 100% diesel product. That means all the non-diesel components, which are an inevitable product of the FT reaction, have to be fed back to the gasifier (the FT reactor cannot grow chains which are already terminated). For calculations using W3f we chose a triangular probability distribution drawn between the three cases.

W3g   **Wood to methanol or DME**

DME can be thought of as dehydrated methanol: the only difference between the synthesis processes is in the final catalyst reactor so that the efficiencies are more or less the same.

Our "best-case" process is based on [*Katofsky 1993*], using the BCL indirectly-heated gasifier with wet gas cleaning and reforming of higher hydrocarbons. The rest of the process is similar to methanol synthesis from natural gas. A conventional, fixed bed methanol reactor is used. With all fuel synthesis routes, it might be possible to improve efficiency by using slurry reactors or hot gas cleaning. However, neither has been demonstrated for synthesis from bio-syngas: there are question marks about gas quality [*Tijmensen 2002*]. Furthermore, the use of conventional processes enables us to compare all routes on a fair basis.

Our "worst case" is based on oxygen-blowing the Värnamo autothermal pressurized fluidized bed gasifier, modelled by [*Atrax 1999*]. Although this is a state-of-the art gasifier, it is not as sophisticated and expensive as the BCL gasifier. The process uses the hot gas filtration demonstrated at Värnamo to allow the gas to go hot into the 950°C steam reformer, where some tar is also decomposed. However, after the shift water-gas shift reactor (to boost the H2/CO ratio), it is still necessary to use a scrubbing process to remove impurities (including HCl, H_2S…) before the gas is pure enough for synthesis. In the Altrax process the

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

purification is combined with CO_2 removal by scrubbing with methanol (Rectisol Process). The DME synthesis process (by Haldor Topsoe A/S) is similar to that in the 200 MW plant.

The efficiency is lower than the BCL-gasifier process because of the energy consumption by the oxygen separation plant, and because the H_2/CO ratio in the raw syngas is lower. Again we assume that methanol could be produced at the same efficiency as DME.

14.3   Ethanol from cellulosic biomass (farmed wood, wood waste and straw)

Code	Process	Assoc. processes	Bio-feed	Expended energy			GHG emissions				Overall energy efficiency	Range		Probability distribution
			MJ bio-en/ MJ prod.	As used MJ/ MJ prod.	MJx/ MJ	Primary MJx/ MJ prod.	g CO2/ MJ prod.	g CH4/ MJ prod.	g N2O / MJ prod.	g CO2eq / MJ prod.		Min	Max	
W3j	**Woody biomass to ethanol (SSCF)**										kgex/ MJprod.	2.7550	3.0790	Equal
	Biomass input		2.9170			1.9170								
	Credit for wood-to-electricity	W3a		-0.0995	3.125	-0.3108	0.00	-0.0026	-0.0002	-0.13				
	Diesel	Z1		0.0358	1.160	0.0415	3.13	0.0000	0.0000	3.13				
	H_2SO_4	C7			1.113	0.0142	0.69	0.0019	0.0000	0.74	0.0035			
	NH_3	C8			12.324	0.1205	6.31	0.0117	0.0000	6.58	0.0027			
	$(NH_4)_2SO_4$	C7,C8			3.983	0.0107	0.55	0.0011	0.0000	0.58	0.0007			
	Antifoam	see notes			50.000	0.0776	0.43	0.0000	0.0000	0.43	0.0004			
	Corn Steep Liquor	see notes			0.500	0.0068	0.03	0.0000	0.0000	0.03	0.0038			
	CaO	C6			1.384	0.0068	1.45	0.0011	0.0000	1.47	0.0014			
	Primary energy consumption and emissions					*1.8843*	*12.59*	*0.0133*	*-0.0002*	*12.83*	35%			
W3k	**Wheat straw to ethanol (Iogen)**													
	Straw		2.3770			1.3770					0.4891			
	Transport of straw	WT2b				0.0093	0.22	0.0000	0.0000	0.22				
	Credit for straw-to-electricity	W3a		-0.0520	3.125	-0.1651	0.00	-0.0014	-0.0001	-0.07				
	H_2SO_4	C7			1.113	0.0167	0.81	0.0023	0.0000	0.87	0.0042			
	NH_3	C8			12.324	0.0456	2.39	0.0044	0.0000	2.49	0.0010			
	$(NH_4)_2SO_4$	C7,C8			3.983	0.0040	0.21	0.0004	0.0000	0.22	0.0003			
	Antifoam	see notes			50.000	0.0292	0.16	0.0000	0.0000	0.16	0.0002			
	Corn Steep Liquor	see notes			0.500	0.0025	0.03	0.0000	0.0000	0.03	0.0014			
	CaO	C6			1.384	0.0079	1.70	0.0013	0.0000	1.73	0.0016			
	Debit for additional fertilisers													
	N				13.6591	0.0000	0.00	0.00	0.00	0.00	0.0000			
	P				4.2959	0.0049	0.31	0.00	0.00	0.32	0.0003			
	K				2.7023	0.0164	0.92	0.00	0.00	0.98	0.0017			
						0.0213	1.23	0.0030	0.0000	1.30				
	Primary energy consumption and emissions					*1.3485*	*6.75*	*0.0101*	*-0.0001*	*6.95*	43%			

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

W3j   **Ethanol from woody biomass; worst/best case**

This corresponds to the "base case" of the detailed study by NERL [*Wooley 1999*] on wood-to-ethanol via SSCF (Simultaneous Saccharification and Co-Fermentation). The base case combined the best equipment and processes which were had been demonstrated in 1999. Our "best case" is the "best of industry" case in [*Wooley 1999*], which incorporates the technical advances which could be foreseen to flow from laboratory developments known in 1999. It was not considered that NREL's more futuristic projections fitted in the time-frame of this study.

Wood consists principally of hemicellulose, cellulose and lignin. Wood chips are ground, steamed and then hydrolysed in dilute sulphuric acid to release the sugars from the hemicellulose. The product is neutralised and detoxified, and part goes to breed enzyme-producing aerobic bacteria with the aid of additional nutrients (such as corn steep liquor). The bacteria-rich stream then joins the main stream in the main fermentor, where enzymatic breakdown of cellulose (saccharification) occurs simultaneously with fermentation of the different sugars released. After several days, the "beer" is sent for distillation. The slops (including lignin) are dried and burnt to raise steam, along with biogas from the waste water treatment. Surplus steam goes to turbine to make electricity.

The NREL process has an excess of electricity. Like the other wood conversion processes, our process is made electricity-neutral by giving a wood credit for the electricity produced. Since this is not a gasifier-based process, we calculated the credit using a conventional wood-fired steam turbine condensing power station, based on LBST data from the plant at Altenstadt, Germany (see wood-to-electricity processes)..

The processes to make the input chemicals are described above (section 1.10: chemicals), with two exceptions, for which we could find no quantitative data: corn steep liquor (CSL) and antifoam. CSL is a by-product from corn syrup manufacture, used as a culture medium for bacteria, and as animal feed. Usually it is neglected in LCA studies. To check if it could be significant, we gave it a (MJ primary energy input)/ (MJ digestible energy) ratio the same as wheat. This confirmed that it could have been neglected. Antifoam is a simple silicone compound. Instead of neglecting it *a priori* we attributed a primary energy per kg typical of a process chemical, which showed it to be of no unimportant in the energy balance.

W3k   **Ethanol from straw**

Data for a 150 MW straw-to-ethanol SSCF plant was supplied to the study by Iogen corp., who operate a commercial plant for straw to ethanol in Iowa [*Iogen 2003*]. A biomass credit is given for electricity export again based on the Altenstadt wood-burning power station (the straw-burning power plant at Sanguesa in Spain has a similar efficiency). Of the chemicals inputs, Iogen only specified sulphuric acid consumption, which is lower than for the wood-to-ethanol process because of a more favourable composition. We assumed that the other chemicals (e.g. for neutralization) mentioned by [*Wooley 1999*] are also needed by the straw process, in proportion to the lower sulphuric acid requirements.

The yield calculation applied to wood gives about the wood-to-ethanol yields claimed in [*Wooley 1999*]. Furthermore, we used the same procedure for the straw-to-SSCF part of process, and came up with energy and emissions figures almost the same as for a commercial state-of-the art straw-to-ethanol process.

The distillation steps and possibly fermentation steps could be combined with the main process: however, for the sake of energy calculation the processes are kept separate. The first paragraph shows that to get 1 MJ ethanol from the combined process we need we need 0.198/(1+0.198) = 0.165 MJ from our new pulp-to SSCF process (without pulp credits), and 0.835 MJ from the conventional sugar-beet process.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

14.4   Synthetic fuels and hydrogen from waste wood via Black Liquor

Code	Process	Assoc. processes	Bio-feed	Expended energy			GHG emissions				Overall energy efficiency	Range		Probability distribution
			MJ bio-en/ MJ prod.	As used MJ/ MJ prod.	MJx/ MJ	Primary MJx/ MJ prod.	g CO2/ MJ prod.	g CH4/ MJ prod.	g N2O / MJ prod.	g CO2eq / MJ prod.		Min	Max	
BLH	**Wood waste to hydrogen via black liquor** Wood waste *Primary energy consumption and emissions*		1.2410			0.2410 ***0.2410***	*0.00*	*0.0000*	*0.0000*	***0.00***	81%	1.1790	1.3031	Equal
BLD	**Wood waste to DME via black liquor** Wood waste *Primary energy consumption and emissions*		1.4851			0.4851 ***0.4851***	*0.00*	*0.0000*	*0.0000*	***0.00***	67%	1.4108	1.5594	Equal
BLM	**Wood waste to methanol via black liquor** Wood waste *Primary energy consumption and emissions*		1.5180			0.5180 ***0.5180***	*0.00*	*0.0000*	*0.0000*	***0.00***	66%	1.4421	1.5939	Equal
BLS	**Wood waste to syn diesel via black liquor** Wood waste *Primary energy consumption and emissions*		1.8280			0.8280 ***0.8280***	*0.00*	*0.0000*	*0.0000*	***0.00***	55%	1.7366	1.9194	Equal

Wood waste to methanol or DME via black liquor gasification

Black liquor is the residue of the pulp making process: a water-based slurry, 70 to 80% of which consists of lignin and spent pulping chemicals. In conventional pulp mills it is burned in a so-called "recovery boiler" to provide process heat; boiler efficiency is limited to about 65% because of the corrosive nature of the molten salts present (mostly Na_2S and Na_2CO_3). With the addition of steam from a "hog boiler" burning bark and other wood waste produced on site, a modern pulp mill is self-sufficient in heat, and can even export some electricity.

For "black liquor gasification for motor fuels" (BLGMF), one gasifies the black liquor instead of burning it in a recovery boiler. The gasifier is oxygen-blown, so an air separation unit is needed. The syngas produced is then transformed to motor fuel. As part of the energy content of the black liquor ends up in the fuel, additional heat is needed for the pulping process. This is provided by increasing the amount of biomass fed to the hog boiler. The cheapest source of extra biomass is forest residuals (branches, tops, undersize trees and occasionally roots), which can be collected at the time of felling and brought to the pulp mill using the same transport infrastructure as the stem-wood.

Taking the original pulp mill as reference, and adjusting the new process to give the same pulp production and electricity balance, one can calculate the extra wood residuals required to produce a given amount of road-fuel. This effective efficiency turns out to be appreciably higher than that of a stand-alone gasifier conversion processes. The reason is that the additional burning of forest residuals increases the thermal capacity of the plant, whilst the stack losses are reduced because the hog-fuel boiler has higher efficiency than the replaced recovery boiler. Almost all the heat from the syngas is recovered.

Our data are from the thorough technical and commercial feasibility study of methanol and DME production via black liquor gasification carried out for DG-TREN's ALTENER programme [*Ekbom 2003*]. The study first modelled a modern reference pulp mill ("KAM2" model mill), recycling all wood wastes produced in the mill, but not importing residuals from the forest. This is self-sufficient in heat, and produces a small electricity surplus from a condensing steam turbine generator. Production capacity is 2000 dry tonnes pulp per day. Then [*Ekbom 2003*] model the BLGMF plant also self-sufficient on heat and with the same

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

pulp production and electricity export. The electricity is also produced by a condensing steam turbine, even though higher efficiencies could be obtained from an advanced combined cycle generator incorporating a gas turbine. The difference between the BLGMF model and the KAM2 reference mill showed that 272.8 MW methanol would be produced with an additional biomass consumption of 414.1 MW biomass. Thus 1 MJ methanol requires 1.518 MJ biomass, and the energy conversion efficiency is 65.9%. For the process producing DME, which differs from the methanol process only in the catalyst and conditions in the final synthesis stage, 275 MW DME are produced from 408 MW biomass, so **1 MJ methanol requires 1.485 MJ biomass, a conversion efficiency of 71**%. We added a ±5% error range to these figures.

[*Ekbom 2003*] also provides estimates of the incremental plant investment, assuming that the recovery boiler in the pulp mill was anyway due for replacement. We used their estimates of 150.3 M€ for the methanol plant and 164.2 M€ for the DME plant in our costing calculations.

Fig. 14.4 Schematic process flow diagram of the BLGMF-methanol plant, reproduced with permission from [Ekbom 2003]

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1
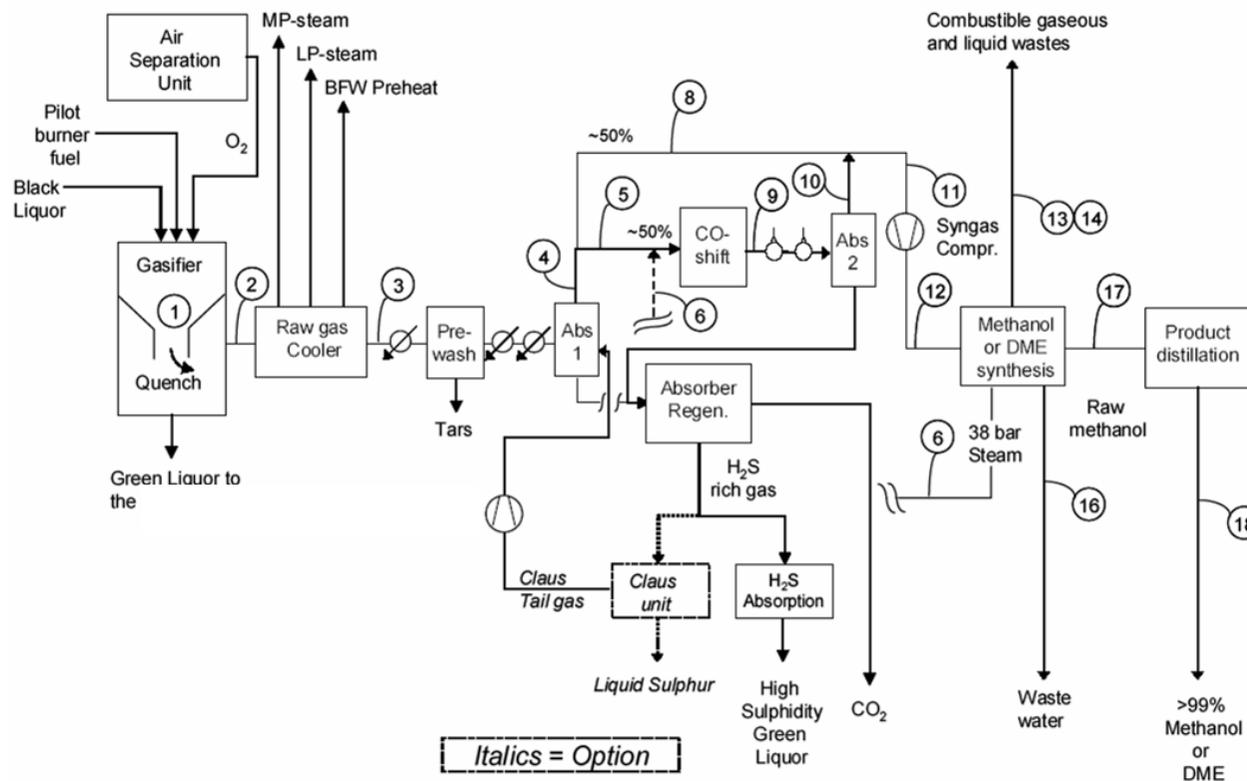
Wood waste to FT via black liquor gasification

We made a calculation of this efficiency by replacing the methanol synthesis in [*Ekbom 2003*] with the FT process described in [*Shell 1990*]. The process uses stream 11 in **Figure 14.4**. The FT process consists of an FT synthesis step in which hydrocarbons are grown on catalysts by the reaction of CO and hydrogen. To get a high diesel yield and little unreacted gas, FT synthesis is allowed to continue to produce heavy hydrocarbons, which are then cracked downstream in a hydrogen cracker. Nevertheless, a distribution of hydrocarbons is produced. [*Shell 1990*] does not specify the distribution of <C10, so this had to model it from chain growth statistics, in order to calculate the energy balance. The Shell process yields about 77 % m/m C10-C20 products (diesel+kerosene; usable in diesel engines) and 23% naphtha on either energy or mass basis. Compared to the reference pulp mill, the whole BGLF-FT process produces 194 MW C10-C20 hydrocarbons and 59.1 MW naphtha from 414 MW extra biomass. Thus 1 MJ extra biomass would produce a total of 0.47 MJ of kerosene/diesel mixture together with 0.14 MJ naphtha (<C9).

If one wishes to produce only diesel and kerosene (to compare with the claims for the Choren wood-FT process, for example), the other products must be recycled. We assumed that the naphtha is added to the hog boiler to produce electricity. To keep the electricity generation the same as the reference pulp plant, we should remove the same MJ of biomass. Therefore only 0.86 MJ biomass are needed to make 0.47 MJ kerosene/diesel by itself. Thus the **efficiency to kerosene/diesel is 55% and 1.83 MJ biomass are needed to make 1 MJ kerosene/diesel.**

Before this report was finalized, [*Ekbom 2005*] produced their own, more detailed, calculation of FT-diesel efficiency using BLGMF process, incorporating product fractionation. It is difficult to compare our model with theirs, because they calculated product mixtures from fractionation rather than simply assigning carbon numbers. Their results indicate that each 1MJ extra biomass would produce 0.43 MJ diesel-quality distillate together with 0.22 MJ naphtha. If we perform the same credit for recycling the naphtha as for our calculation above, we deduce that an extra 0.78 MJ biomass in the pulp mill would give 0.43 MJ diesel-quality distillate. That corresponds to an efficiency to diesel fuel of 55%: exactly the same as in our own calculation. Such close agreement is fortuitous, but we are happy to have independent confirmation.

The consortium estimated that the incremental cost of installing a BLGMF-FT plant in a pulp mill which needs a new recovery boiler would be about 260 M€ ±20%. Subsequently, [*Ekbom 2005*] estimated the figure to be 205 M€. Considering that this is the cost of the new plant minus 171 M€, representing the saved cost of a new recovery boiler, the difference between the two estimates of the cost of a BLGMF-FT plant is only 13%.

Wood waste to hydrogen via black liquor gasification

Neither [*Ekbom 2003*] nor [*Ekbom 2005*] considered this process. We took their detailed description of the BLGMF plant, and considered what modifications would be needed to make hydrogen instead of methanol. The methanol synthesis and distillation are not needed, but a larger CO shift reactor is required, coupled to a pressure swing absorption (PSA) to purify the hydrogen.

The hydrogen process starts from stream 4 in **Figure 14.4**. All this goes to the CO-shift instead of only half for the methanol plant. Therefore more steam is required for the CO shift reactor, but on the other hand the outlet of the CO shift contains more steam, because more is formed in the reaction. The net amount of steam compared with the methanol plant depends on whether the shift reaction is exothermic or endothermic. If we calculate this starting from steam, it is slightly exothermic, but if we include the energy for generating the steam from water, it is slightly endothermic. In practice, one could find a source of steam, but a little less heat would be recovered. Thus the difference in steam requirements is approximately zero.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

The CO_2 absorption (Abs 2) is not required because CO_2 is anyway removed downstream in the PSA. The pressure at the outlet of the CO shift reactor (2.9 MPa; [*Ekbom 2003*]) is sufficient to drive the PSA process. Hydrogen recovery is assumed to be 86%; the tail-gases can be burnt for steam and electricity.

Compared to the reference pulp mill, the BGLF-hydrogen process produces 247 MW H_2 and 108.3 MW in the other gases. Thus 1MJ extra biomass would produce 0.594 MJ hydrogen and leave 0.261 MJ in the tail-gas. If the tail gas is added to the boiler of the existing condensing steam-turbine generator, it will save the same energy input of biomass. Therefore only 0.839 MJ biomass are needed to 0.594 MJ hydrogen by itself. Thus the **efficiency to hydrogen is 81% and 1.24 MJ biomass are needed to make 1 MJ hydrogen.**

In [*Katofsky 1993*], the cost of a hydrogen plant based on the BCL wood gasifier is 27 M€ less than that of a methanol plant based on the same gasifier. The hydrogen and methanol synthesis processes are similar to the ones described here, and have roughly the same scale. Since the BLGMF-methanol plant costs 150.3 M€ in [*Ekbom 2003*] (taking into account the saving on a new recovery boiler), we expect a BLGMF hydrogen plant would cost **123 M€** on the same basis.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

15   Electricity generation

Code	Process	Expended energy	GHG emissions				Eff	Range		Probability distribution
		MJx/ MJe	g CO2/ MJe	g CH4/ MJe	g N2O/ MJe	g CO2eq/ MJe		Min	Max	
As electricity is used as an intermediate rather than final energy source, the figures below are shown in total primary energy (kWhp) to produce one unit of electricity (kWhe)										
GE	**Electricity from NG (CCGT)**	Same process as GG2								
KE1	**Electricity from Coal (conv. Boiler)** Energy as hard coal	2.3000	221.45			221.45	43.5%	2.0000	2.5000	Dble tri
KE2	**Electricity from Coal (IGCC)** Energy as hard coal	2.0833	200.58			200.58	48.0%	1.9231	2.2435	Equal
KE2C	**Electricity from Coal (IGCC) +CC&S** Energy as hard coal	2.4390	23.44			23.44	41.0%	2.2680	2.6100	Equal
W3a	**Electricity from wood steam boiler** Energy as wood	3.1250		0.0828	0.0247	9.22	32.0%	2.9700	3.2800	Normal
W3b	**Electricity from 200 MWth wood gasifier** Energy as wood	2.0747		0.0262		1.34	48.2%	2.0000	2.1739	Normal
W3c	**Electricity from 10 MWth wood gasifier** Energy as wood	2.8228		0.0356		1.83	35.4%	2.6817	2.9639	Normal
BLE	**Electricity from waste wood via black liquor** Waste wood	1.1111	0.00	0.0000	0.0000	0.0000				
DE	**Electricity from wind** Energy as wind	1.0000								
NE1	**Nuclear fuel provision** Nuclear NG Crude oil Waste Hard coal Brown coal Hydropower Total	0.1805 0.0045 0.0025 0.0018 0.0053 0.0012 0.1977	1.21	0.0029	0.0001	1.29	84.7%			
NE2	**Electricity from nuclear** Energy as diesel Energy as uranium	0.0010 3.0303	0.07				33.0%			

GE   Electricity from NG

This process represents the now standard route for efficient and cost-effective production of electric power from gas i.e. a combined cycle gas turbine complex. The overall efficiency of 55% is typical of modern state-of-the-art plants, the ± 5% range representing the range of existing and foreseeable technologies [*GEMIS 2002*], [*TAB 1999*].

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

KE1 Electricity from coal (conv. boiler)

This state-of-the-art conventional route is assumed to have a typical efficiency of 43.5%.

KE2 Electricity from coal (IGCC)

The IGCC (integrated gasification and combined cycle) alternative reaches an efficiency of 50% [*TAB 1999*].

For electricity from wood, 4 alternatives are considered, i.e. via a steam boiler plus turbine plant (W3a), wood gasification at either large or small scale (W3b/c) and finally indirectly via gasification of black liquor in a paper mill. All incorporate drying of fuel using heat from the flue gas. Forest residuals chipping is the same process as in the wood-to-hydrogen and synthetic fuels process table above. It includes dry matter losses during storage and ex-forest handling. For farmed wood, chipping is included in the farming process.

W3a Electricity from wood steam boiler

The small conventional plant is based on LBST data for the 11.5 MW fluidized-bed condensing steam-turbine power plant at Altenstadt, Germany. Fluidized bed combustors cope better with the varying quality of fuel from wood chips than conventional grate boilers.

W3b Electricity from 200 MW$_{th}$ wood gasifier

The large gasifier power station is taken from the study by [*Sydcraft 2001*] of an IGCC based on the Värnamo pressurized fluidized bed gasifier, using a state-of-the-art GTX 100 gas turbine with flue gas condensation (140 MW$_{th}$). This configuration maximizes the electrical efficiency. The lower efficiency limit is for the existing turbine at Värnamo, whilst the upper limit projects a further 2% in gas turbine efficiency by 2010. We selected this power station because the Värnamo gasifier is the only one which has been demonstrated to work with hot gas filtration, which gives a significant improvement in efficiency since the syngas enters hot into the turbine, and will surely become the norm for future IGCC power stations.

W3c Electricity from 10 MW$_{th}$ wood gasifier

Data are from the Oeko-Institut's EM generic database, which also supplies cost data. We consider 5% uncertainty in the LHV efficiency. Gasifiers give higher electrical efficiency and can cope with varying fuel quality. But the investment cost is higher: not worth it if one can use the waste heat for district heating.

BLE Electricity from waste wood via black liquor

Instead of using the output of the gasifier in a BLGMF plant for motor-fuel synthesis (section 14.4), one can burn the syngas for electricity cogeneration. Again, the heat balance of the plant is restored by burning additional biomass in the hog boiler. In the same way that [*Ekbom 2003*] analysed fuel-producing BLGMF [*Berglin 1999*] analysed different options for electricity production by replacing the black liquor recovery boiler with an oxygen-blown gasifier. The efficiency of electricity production is found by dividing the increased electricity production by the increased biomass consumption, compared to the reference mill. A little confusingly, [*Berglin 1999*] adopts a modern integrated pulp/paper mill as the reference mill, instead of the modern pulp-only-mill in [*Ekbom 2003*]. However, the changes are all in the pulp section, this should not affect the results (Berglin does this to demonstrate that the extra electricity produced could be sufficient to make the whole paper mill self-sufficient on energy, instead of consuming electricity, as at present).

The syngas is cleaned, and burnt in a combined cycle of back-pressure steam turbine, condensing steam turbine and gas turbine. Berglin discusses many different options, including three ways to remove the H_2S from the syngas. We chose the variant ("case 6", table 7 in [*Berglin 1999*]) which produces the highest electricity export, though not at the highest incremental efficiency. It removes H_2S from the syngas by reabsorbing it in the white liquor. That means it

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

uses more lime, but the lime is regenerated in a closed cycle as part of the system, so the energy implications are fully taken into account. The gas turbine assumed in this variant has an input temperature of 1430ºC, with a pressure ratio 20, and the maximum steam temperature is 530ºC. The gasifier operates at 37 bar.

The plant produces electricity from biomass (bark or forest residuals) at an incremental efficiency of 90%, because it benefits from the reduction in stack losses and increased thermal capacity in the paper mill.

DE   Electricity from wind

Contrary to biomass, wind energy is in effect inexhaustible, the limitation being in the equipment used to harness it. The notion of efficiency becomes therefore academic in this case. We have shown it as 100% efficient. The energy associated with operation and maintenance is very small.

NE1   Nuclear fuel provision

The figures used are typical of the European supply of nuclear fuel [*GEMIS 2002*].

NE2   Electricity from nuclear

The figures used here pertain to conventional nuclear reactors turning the nuclear reaction heat into steam feeding turbines. The efficiency figure is the fraction of the heat released by the nuclear reaction and transferred to the steam that is turned into electricity [*GEMIS 2002*].

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

16   Hydrogen from electrolysis

Code	Process	MJex/MJ					Eff	Min	Max	Probability distribution
YH	**Hydrogen from electrolysis** Energy as electricity	0.5385					65.0%	0.4760	0.6000	Normal

YH   Hydrogen from electrolysis

Several sources of data are available, giving figures for both small and large (alkaline) electrolysers with and without auxiliaries:

- Stuart Energy Europe (the former Hydrogen Systems) offers a 60 Nm^3/h, 2.5 MPag electrolyser (IMET technology 1000 series) with an electricity consumption of 4.8 kWh/Nm^3 or 62.5% based on hydrogen LHV. For the cell block alone (cell module without any auxiliaries) the electricity consumption is 4.2 kWh/Nm^3 or 71% efficiency. For a 800 Nm^3/h unit the electricity consumption is 4.3 kWh/Nm^3 including all auxiliaries or 69.8% efficiency [*Stuart Energy 2005*].
- Norsk Hydro indicates an electricity consumption of 4.75 kWh/Nm^3 including all auxiliaries for a 4,000 Nm^3/h electrolysis (63.2% efficiency of 63.2%. For a 60 Nm^3/h unit (HPE 60) the electricity consumption including all auxiliaries is indicated with 4.8 kWh/Nm^3 (thereof auxiliaries: 0.5 kWh/Nm^3) leading to an efficiency of 62.5% based on the LHV of the delivered hydrogen.
- AccaGen SA indicates an electricity cosumption of 4.45 kWh/Nm^3 for its 50 Nm^3/h electrolyzer including all auxiliaries leading to an efficiency of 67.4%. The hydrogen pressure is 30 bar.
- Giovanola indicates an electricity consumption of 4.3 to 4.6 kWh/Nm^3 including all auxiliariesleading to an efficiency of 65.2 to 69.8%.
- The data derived from GHW lead to an average efficiency of 65% including all auxiliaries based on the LHV of the delivered hydrogen. Recent publications of GHW [*GHW 2004*] indicate an efficiency of up to 70% based on the LHV (3 MW_e for 700 Nm^3/h) including all auxiliaries.

Many studies e.g. *[Dreier 1999]* assume a far higher efficiency for the hydrogen generation via electrolysis (up to 77% related to the LHV and up to 91% related to the HHV including all auxiliaries).

The efficiency of an electrolyser does not vary significantly with size. We have therefore represented all electrolysis cases with a single process. The outlet pressure of commercially available pressurized electrolysers ranges between 1.1 and 3 MPa. The electrolyser outlet pressure is assumed to be 3 MPa. Higher pressures may be possible in the future but this is somewhat speculative at this stage. The efficiency of commercially available pressurized alkaline electrolysers ranges between 62 and 70% related to the LHV of the delivered hydrogen (or 4.3 to 4.8 kWh_e/Nm^3 of hydrogen) [*GHW 2001*], [*Hydrogen Systems 2000*], [*Vandenborre 2003*].

Membrane electrolysers are still in the development stage. A version is offered by Proton Energy Systems, USA, but their energy efficiency is rather low (5.7 to 6.4 kWh_e/Nm^3 of hydrogen) [*Proton Energy 2000*].

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

17   Hydrogen distribution and dispensing (all sources)

Code	Process	Assoc. processes	Expended energy MJx/ MJ prod.	g CO$_2$/ MJ prod.	g CH$_4$/ MJ prod.	g N$_2$O/ MJ prod.	g CO$_2$eq/ MJ prod.	km or Naut. Miles	MJx/ t.km	t.km/ MJ prod.	Min	Max	Probability distribution
CH1a	**Gasous Hyd distribution (pipeline from central plant)**												
	No distribution energy (high pressure at plant outlet, 50 km)												
CH1b	**Gasous Hyd distribution (trucking from central plant)**												
	Distance, road (ex piped gas)	Z2, Z1						50		0.0171			
	Primary energy consumption and emissions		*0.0185*	*1.40*			*1.40*						
CH2	**Liquid Hyd compression/vaporisation**												
	Energy as electricity (EU-mix, LV)		0.0196										
	Primary energy consumption and emissions		*0.0556*	*2.34*	*0.0057*	*0.0001*	*2.34*						
CH3	**Gasous Hyd dispensing**												
CH3a	Compression energy, 1.5-8.8 MPa		0.0769								0.0705	0.0842	Normal
CH3b	Compression energy, 2.0-8.8 MPa		0.0704								0.0645	0.0771	Normal
CH3c	Compression energy, 3.0-8.8 MPa		0.0617								0.0566	0.0676	Normal
	Hyd losses		0.0200										
	Primary energy consumption and emissions (EU-mix, LV)												
CH3a		Z7b	*0.2406*	*9.29*	*0.0227*	*0.0004*	*9.93*				*0.2222*	*0.2615*	
CH3b		Z7b	*0.2220*	*8.50*	*0.0207*	*0.0004*	*9.09*				*0.2050*	*0.2412*	
CH3c		Z7b	*0.1970*	*7.45*	*0.0182*	*0.0003*	*7.97*				*0.1824*	*0.2139*	
LH1	**Hyd liquefaction**												
	Energy as Electricity (on-site generation)	GG2	0.3000								0.2100	0.3900	Normal
	Primary energy consumption and emissions		*0.5455*	*30.03*	*0.0023*	*0.0014*	*30.51*						
LH2	**Liquid Hyd long-distance transport**												
	Distance (nautical miles)					g/t.km 0.1460		5500		0.0848	5000 0.0771	6000 0.0925	
	Ship's fuel (hydrogen) including return voyage		0.2304			0.0093	2.7653		2.2075		0.2051	0.2567	
LH3	**Liquid Hyd distribution and dispensing**												
LH3a	Distance, road (ex piped gas)	Z2, Z1						300		0.0196			
LH3b	Distance, road (ex remote gas)	Z2, Z1						500		0.0327			
	Transport Hyd losses		0.0050										
	Filling station, Electricity (EU-mix, LV)	Z7b	0.0010										
LH3a	*Primary energy consumption and emissions*		*0.0292*	*1.73*	*0.0003*	*0.0000*	*1.74*						
LH3b	*Primary energy consumption and emissions*		*0.0434*	*2.80*	*0.0003*	*0.0000*	*2.81*						

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

CH1a/b   Gaseous hydrogen distribution

Hydrogen is available from the various producing plants at pressures generally above 3 MPa. This is considered sufficient for distribution through a local pipeline network over a distance of maximum 50 km, without additional compression energy. The resulting pressure at the refuelling station is taken at typically 2 MPa. Gaseous hydrogen can also be transported by road in high pressure cylinders (about 20 MPa, 0.45 t of hydrogen for 26 t of steel and composite material [*Worthington 2000*]). The compression energy for this is accounted for process CH2. The energy included here is for the operation of the truck.

CH2   Liquid hydrogen vaporisation/compression

Hydrogen delivered in liquid form to the refuelling station may have to be vaporised and compressed if the vehicles require compressed hydrogen. This process is less energy-intensive than compression of gaseous hydrogen, essentially as the liquid can be pumped to the required pressure before vaporisation [*BOC 1997*], [*Linde 2001*].

CH3   Gaseous hydrogen compression

Gaseous is available at the refuelling station at a pressure of between 1.5 for a small scale on-site electrolyser and 3.0 MPa for on-site production via electrolysis. 2 MPa corresponds to piped hydrogen (see above). In the case of road transport of high pressure cylinders, the pressure is of course higher at the refuelling station but the total energy cost of compression remains essentially the same.

LH1   Hydrogen liquefaction

Liquefaction is a highly energy intensive process. Energy requirement figures vary within a wide range. One reason for this is that many of the existing liquefaction plants were not built with the objective of maximum energy efficiency as they are mostly relatively small and making hydrogen as a premium product for the chemical industry. Figures in the region of 0.35-0.40 MJ_e/MJ are not uncommon but experts agree that much lower figures down nearly 0.2 can be achieved [*LBST 2001*], [*Quack 2001/1* [*Quack 2001/2*] have therefore taken a wide range with a square probability distribution. Note that this process refers to process GG2 i.e. electricity produced with a natural gas CCGT.

In wood-based pathways electricity is assumed to be made on site also with wood. In such cases, although the energy requirement for liquefaction remains the same, the energy and GHG balances are different (more total energy and less GHG).

LH2   Liquid hydrogen long-distance transport

This process pertains to a scenario where hydrogen would be produced and liquefied at a remote location to be shipped to markets in specially built liquid hydrogen carriers. Such a so-called SWATH carrier has been proposed [*Würsig 1996*] and we have used the figures as quoted. The SWATH carrier would burn exclusively hydrogen.

LH3   Liquid hydrogen distribution

This is envisaged exclusively by road. The average distance to cover varies with the scenario. Large reformers fed with LNG would have to be located near the coastal terminal, with potential higher distribution distances (500 km) than other central plants fed with more "local" material such as piped NG, wood or electricity (300 km). The liquid hydrogen road tanker is assumed to transport 3.5 t of hydrogen in a 24 t tank [*Linde 1998*]

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

18   Synthetic fuels distribution and dispensing (all sources)

Code	Process	Assoc. processes	Expended energy	GHG emissions				Transport requirement			Range		Probability distribution
			MJx/ MJ prod.	g CO$_2$/ MJ prod.	g CH$_4$/ MJ prod.	g N$_2$O/ MJ prod.	g CO$_2$eq/ MJ prod.	km or Naut. Miles	MJx/ t.km	t.km/ MJ prod.	Min	Max	
DS1	**Syn diesel handling and loading (remote)** Energy as Electricity (on-site generation) *Primary energy consumption and emissions*	GG2	0.0008 *0.0015*	*0.08*	*0.0000*	*0.0000*	*0.09*						
DS2	**Syn diesel sea transport** Distance (nautical miles) Energy requirement as HFO for product carrier *Primary energy consumption and emissions*		*0.00*	*0.0312*	*2.50*		*2.50*	5500		0.2315	5000 *0.0284*	6000 *0.0341*	Square
											0.2105	0.2525	
DS3	**Syn diesel depot** Electricity (EU-mix, LV) *Primary energy consumption and emissions*	Z7b	0.0008 *0.0024*	*0.36*	*0.0009*	*0.0000*	*0.38*						
DS4	**Syn diesel distribution (blending component**	CD2/3/4	See conventional diesel processes										
DS5	**Syn diesel distribution (neat)** Distance, Rail Distance, road *Primary energy consumption and emissions*	Z5, Z7a Z2, Z1						250 250		0.0057 0.0061			
DS5a	*Rail+Road*		*0.0100*	*0.6413*	*0.0003*	*0.0000*	*0.65*						
DS5b	*Road only*		*0.0066*	*0.4995*	*0.0004*	*0.0000*	*0.51*						

DS1   **Synthetic diesel loading and handling (remote)**

This represents the energy required to store, handle and load the synthetic diesel near its (remote) production site. The assumed electricity consumption is that of a standard conventional diesel depot (see process CD3). This process (and the next one), are only relevant to GTL plants inasmuch as diesel from biomass is unlikely to be transported across large distances. The source of electricity is here deemed to be the gas-fired power plant part of the GTL complex (process GG2).

DS2   **Synthetic diesel sea transport**

Synthetic diesel can be transported in essentially standard product carriers (see process Z4). The distance considered here is typical of a trip from the Arab gulf to North West Europe (via Suez). The energy figure includes an allowance for the return trip.

DS3   **Synthetic diesel depot**

This is the same process as CD3. This energy is deemed to be spent at a receiving terminal.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

DS4   **Synthetic diesel distribution (blending component)**

Synthetic diesel is a valuable blending component for modern diesel and the limited quantities available are most likely to be used as such. In this case the product will enter the refinery system near the point of production. The applicable processes are thus the same as for conventional diesel (CD2/3/4).

DS5a/b   **Synthetic diesel distribution (neat)**

The use of neat synthetic diesel in niche applications cannot be ruled out. Transport of neat synthetic diesel within Europe can be envisaged either by road, rail or a combination of both. The limited volumes involved would make pipeline transportation inappropriate. We have considered two scenarios depending on the synthetic diesel source. Material imported from remote plants would have to be transported from a small number of ports for which we consider an average distance of 500 km (split 50/50 between rail and road). Material manufactured within Europe would be more "distributed" and we have considered a distance of 250 km (road) as appropriate. The transport mode parameters are in accordance with processes Z5 and Z2.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

Code	Process	Assoc. processes	Expended energy	GHG emissions				Transport requirement			Range		Probability distribution
			MJx/ MJ prod.	g CO_2/ MJ prod.	g CH_4/ MJ prod.	g N_2O/ MJ prod.	g CO_2eq/ MJ prod.	km or Naut. Miles	MJx/ t.km	t.km/ MJ prod.	Min	Max	
ME1	**Methanol handling and loading (remote)**												
	Energy as Electricity (on-site generation)	GG2	0.0018										
	NG consumption and emissions		0.0033	0.18	0.0000	0.0000	0.19						
ME2	**Methanol sea transport (average of two distances)**												
	Distance (nautical miles)							5000		0.465	0.465		
	Primary energy consumption and emissions	Z3, Z4	*0.0627*	*5.03*			*5.03*						Normal
	Distance (nautical miles)							6000		0.558		0.558	
	Primary energy consumption and emissions	Z3, Z4	*0.0753*	*6.04*			*6.04*						
ME3	**Methanol depot**												
	Electricity (EU-mix, LV)	Z7b	0.0018										
	Primary energy consumption and emissions		*0.0052*	*0.79*	*0.0019*	*0.0000*	*0.85*						
ME4	**Methanol distribution and dispensing**												
	Distance, Rail	Z5, Z7a						250		0.0126			
	Distance, road	Z2, Z1						250		0.0135			
	Filling station, Electricity (EU-mix, LV)	Z7b	0.0034										
	Primary energy consumption and emissions												
ME4a	*Rail+Road*		*0.0319*	*1.83*	*0.0018*	*0.0000*	*1.88*						
ME4b	*Road only*		*0.0244*	*1.52*	*0.0010*	*0.0000*	*1.55*						
DE1	**DME handling and loading (remote)**												
	Energy as Electricity (on-site generation)	GG2	0.0013										
	NG consumption and emissions		0.0024	0.13	0.0000	0.0000	0.13						
DE2	**DME sea transport**												
	Distance (nautical miles)			gCO2/tkm				5500		0.358	0.326	0.391	Normal
	Energy to DME carrier (as HFO)	Z3		13.11					0.163				
	Primary energy consumption and emissions		*0.06343*	*5.09*			*5.09*						
DE3	**DME depot**												
	Electricity (EU-mix, LV)	Z7b	0.0013										
	Primary energy consumption and emissions		*0.0037*	*0.56*	*0.0014*	*0.0000*	*0.59*						
DE4a	**DME distribution and dispensing**												
	Distance, Rail	Z5, Z7a						250		0.0088			
	Distance, road	Z2, Z1						250		0.0123			
	Filling station, Electricity (EU-mix, LV)	Z7b	0.0034										
	Primary energy consumption and emissions												
DE4a	*Rail+Road*		*0.0284*	*1.64*	*0.0015*	*0.0000*	*1.68*						
DE4b	*Road only*		*0.0231*	*1.42*	*0.0010*	*0.0000*	*1.45*						

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

ME1 Methanol handling and loading (remote)

This process relates to the small amount of energy (electricity) required to handle methanol from a remote NG-based plant to the loading terminal, including loading onto a ship. The figures have been inferred from those listed for gasoline (process CG3). The electricity is assumed to come from the on-site gas-fired power plant.

ME2 Methanol sea transport

Methanol can be transported in essentially standard product carriers (see process Z3). The distance considered here is typical of a trip from the Arab gulf to North West Europe (via Suez). The energy figure includes an allowance for the return trip.

ME3 Methanol depot

A small amount of energy is added to account for this intermediate handling step between unloading from the ship and further transport to customers.

ME4a/b Methanol distribution and dispensing

Transport of methanol within Europe can be envisaged either by road, rail or a combination of both. Pipeline transportation is not considered likely inasmuch as a dedicated pipeline system would be difficult to justify in all credible scenarios. Transporting methanol in the existing oil products pipelines is not a practical option for a number of reasons including, interface management, water contamination and corrosion issues. We have considered two scenarios depending on the methanol source. Methanol imported from remote plants would have to be transported from a small number of ports for which we consider an average distance of 500 km (split 50/50 between rail and road). Methanol manufactured within Europe would be more "distributed" and we have considered a distance of 250 km (road) as appropriate. The road tanker is assumed to transport 26 t of methanol in a 2 t tank. The transport mode parameters are in accordance with processes Z5 and Z2. The filling station energy requirement is inferred from the gasoline figure (see process CG4).

DE1-4 DME distribution and dispensing

These processes are similar to those for methanol with figures adapted to DME which is transported in compressed liquid form. DME is deemed to be carried on a ship similar to an LPG carrier [*Kawasaki 2000*]. The road tanker is assumed to transport 2 t of DME in a 20 t tank.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

19   Bio-fuels distribution

Code		Assoc processes	one-way distance km	t.km/ MJ prod.	MJ/ MJ prod.	MJx/ MJ	MJx/ MJ prod.	g CO₂/ MJ prod.	g CH₄/ MJ prod.	g N₂O/ MJ prod.	g CO₂eq/ MJ prod.	Loss MJ/MJ
ETd	**Ethanol distribution (blended)**											
	Road tanker to gasoline depot	Z1,Z2	150	0.022	0.0056	1.1600	0.0065	0.49			0.49	
	Gasoline depot (elect. EU-mix, LV)	CG3, Z7b			0.0024	2.8687	0.0069	0.29	0.0007	0.0000	0.31	
	Road tanker to filling station	Z1,Z2	150	0.022	0.0056	1.1600	0.0065	0.49			*0.49*	
	Filling station	CG4, Z7b			0.0034	2.8687	0.0098	0.41	0.0010	0.0000	*0.44*	
	Primary energy consumption and emissions						***0.0298***	*1.69*	*0.0017*	*0.0000*	***1.74***	
FAd	**Bio-diesel distribution (blended)**											
	FAME road tanker to diesel depot	Z1,Z2	150	0.004	0.0041	1.1600	0.0047	0.36	0.0000	0.0000	0.36	
	Diesel depot (elec. EU-mix, LV)	CD3, Z7b			0.0024	2.8687	0.0069	0.29	0.0007	0.0000	0.31	
	Road tanker to filling station	Z1,Z2			0.0041	1.1600	0.0047	0.36	0.0000	0.0000	0.36	
	Filling station	CD4, Z7b			0.0034	2.8687	0.0098	0.41	0.0010	0.0000	0.44	
	Primary energy consumption and emissions						***0.026***	*1.41*	*0.0017*	*0.0000*	***1.46***	
MEd	**Biomethanol distribution direct from plant**											
	Methanol road tanker	Z1,Z2	150	0.008	0.0076	1.16	0.009	0.67	0.0000	0	0.67	
	Filling station, Electricity (EU-mix, LV)	Z7b			0.0034	2.87	0.010	0.41	0.0010	0.0000	0.44	
	Primary energy consumption and emissions						***0.019***	*1.08*	*0.0010*	*0.0000*	***1.10***	
DEd	**Bio-DME distribution direct from plant**											
	DME road tanker	Z1,Z2	150	0.007	0.0069	1.16	0.008	0.61	0.0000	0	0.61	
	Filling station, Electricity (EU-mix, LV)	Z7b			0.0034	2.87	0.010	0.41	0.0010	0.0000	0.44	
	Primary energy consumption and emissions						***0.018***	*1.02*	*0.0010*	*0.0000*	***1.04***	
SDd	**Bio-(synthetic diesel) distribution (blended)**											
	Road tanker to diesel depot	Z1,Z2	150	0.004	0.0034	1.16	0.004	0.30	0.0000	0	0.30	
	Diesel depot (elec. EU-mix, LV)	CD3, Z7b			0.0008	2.87	0.002	0.10	0.0002	0.0000	0.11	
	Road tanker to filling station	Z1,Z2	150	0.004	0.0034	1.16	0.004	0.30	0.0000	0.0000	0.30	
	Filling station	CD4, Z7b			0.0034	2.87	0.010	0.41	0.0010	0.0000	0.44	
	Primary energy consumption and emissions						***0.020***	*1.11*	*0.0012*	*0.0000*	***1.15***	
CHd	**Bio-(compressed H2 gas) distribution**											
	Distribution and dispensing	CH1a,CH3b			0.0704	2.87	**0.202**	8.50	0.0207	0.00	**9.09**	*0.020*
LHd	**Bio-(liquid hydrogen) distribution**											
	LH2 / Liquefaction / CONCAWE / p (in) = 30 bar	LH1			0.3000	2.87	0.861	36.24	0.0884	0.0016	38.75	
	Liquid hydrogen road tanker		150	0.010			0.011	0.80	0.0000	0	0.80	*0.005*
	Liquid hydrogen filling station				0.0010	2.87	0.003	0.12	0.0003	0.0000	0.13	
	Sum primary energy and emissions						***0.874***	*37.16*	*0.0887*	*0.0016*	***39.68***	

The energy for biofuel distribution is not very important to the overall pathway. Ethanol and FAME, and synthetic diesel are blended with fossil fuels, so they are transported to the appropriate depot, and then distributed like fossil fuel. Bio-methanol, DME and hydrogen are identical to the fossil products and could be distributed directly to local filling stations. Compressed hydrogen is distributed to filling stations by pipeline.

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context
WELL-TO-TANK Report Version 2c, March 2007

WTT APPENDIX 1

20   References

References such as "[*Source: xxx*]" denote personal communications between CONCAWE/LBST and experts from member companies, not supported by a published document.

The complete reference list is given in the main body of the *WTT report*.