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Report on life cycle greenhouse gas impacts of ethanol supply chains at BEST sites

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Stockholm (SE), BioFuel Region (SE), Rotterdam (NL), Somerset (UK), Brandenburg (DE), Basque Country (ES), Madrid (ES), La Spezia (IT), Nanyang (CH), São Paulo (BR)

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Table of Content

Introduction **9**
The need for life cycle calculations in BEST **10**
Data gathering **11**
Calculation methods **13**
GHG emissions from identified supply chains **16**
Stockholm 17
Biofuel Region 19
Nanyang 20
Basque Country 20
Madrid 23
Rotterdam 25
Brandenburg 26
La Spezia 30
Somerset 32
Implications of calculations for effectiveness of BEST demonstrations **33**
References **35**
Appendix 1 Ethanol Supply Chain Survey (sent to sites June 2007) **37**

Summary in English

This report describes the results of a study carried out to evaluate the life-cycle greenhouse gas emissions (GHG) impacts of the supply chains providing ethanol at BEST sites. The study was carried out to support the BEST Evaluation Work Package (WP9) task of assessing the effectiveness of BEST demonstration activities at achieving a major strategic objective of the project – mitigation of the growth of greenhouse gas emissions from transport.

The study collected information from BEST sites to identify as many ethanol supply chains as possible. Detailed life cycle inventories were then produced for all supply chains for which there was sufficient information. Twenty-five ethanol supply chains were identified across the eight European BEST sites and Nanyang, China. Of these, sufficiently detailed and reliable data was obtained to carry out life cycle GHG emissions calculations for thirteen supply chains. Much information was gathered for a further five supply chains, but because important pieces of information were missing or uncertain for these pathways, they are not presented in this report.

The study found a wide range of GHG emissions impacts of the supply chains analysed. The calculated GHG savings compared with petrol covered a range from 4% to 79%. This range serves to highlight the importance of selecting and promoting appropriate ethanol production and distribution pathways to achieve GHG reduction objectives.

Of the ethanol supply chains analysed, the most effective for reducing greenhouse gas emissions are those that use renewable energy to supply the production process, and use nitrogen fertilizer efficiently. Ethanol produced from sugarcane in Brazil was the basis for most of the best performing supply chains, but European ethanol produced using renewable energy and with high nitrogen use efficiency, also achieved high GHG emissions reductions.

Introduction

Reducing greenhouse gas emissions is a strategic objective of the BEST project. The project Description of Work envisages greenhouse gas savings through substitution of bioethanol for petrol and/or diesel at BEST demonstration sites, and significant national and global impacts through stimulation of large scale markets for bioethanol.

However, the net savings in greenhouse gas emissions achievable with bioethanol depend very much on the origins of the ethanol, so it is very important to identify and analyze supply chains for ethanol being sold in BEST site regions, in order to verify whether use of ethanol from these supply chains can be expected to lead to the desired objective of reducing greenhouse gas emissions. The results of such analysis can also be of great value in policy development for incentivizing the use of ethanol on the basis of greenhouse gas emissions benefits.

This report describes a study carried out to identify the ethanol supply chains at BEST sites and to determine the full life cycle greenhouse gas emissions attributable to ethanol from these supply chains. The objectives of this report are:

- To explain the need for full life cycle calculations in assessing greenhouse gas emissions impacts of BEST activities
- To describe the data gathering exercise carried out to identify ethanol supply chains in BEST sites, and present the identified supply chains
- To explain the life cycle calculations and present the results of the calculations
- To assess the implications of the calculated greenhouse gas benefits of the BEST supply chains for achievement of the strategic objective of reducing greenhouse gas emissions.

The need for life cycle calculations in BEST

The combustion of bioethanol in a vehicle engine produces, at the vehicle exhaust, the greenhouse gas carbon dioxide (CO2) in quantities similar to those produced from the combustion of petrol or diesel, measured as mass of CO2 emitted per unit of thermal energy released from combustion of the fuel (assuming complete combustion, ethanol produces 71.4 gCO2/MJ, while petrol typically emits 73.3 gCO2/MJ and diesel 73.2 gCO2/MJ [JEC, 2007]). However, the CO2 emitted during combustion of bioethanol is part of a cycle, in which CO2 is absorbed from the atmosphere by growing plants that are eventually transformed into bioethanol, which on combustion emits CO2.

The cycle repeats with subsequent cultivation of bioethanol feedstock. This is in contrast to the situation with petrol or diesel, as the formation of crude oil takes millions of years, meaning that over the relatively minuscule time scales of manufacture and use of petrol and diesel, there are no significant natural CO2-absorbing processes involved. Consideration of these basic differences in CO2 emissions impacts between bioethanol on the one hand and petrol and diesel on the other makes it clear that determination of the true greenhouse gas emissions impacts of fuel use requires analysis of emissions not just at the point of use, but throughout the life cycle of the fuel, from production or extraction of the raw material through to fuel production, distribution and use. The analysis must also consider emissions not just of carbon dioxide, but of other greenhouse gases such as methane and nitrous oxide as well.

Greenhouse gas emissions occur at all stages in the life cycle of bioethanol (and all other fuels). Figure 1 shows, in generic terms, the different stages in the life cycle of bioethanol. Depending on specific properties of life cycle stages (resulting from particular agronomic practices, technological choices and operating efficiencies), the total GHG emissions can vary considerably from one supply chain to another. Indeed, it is possible for the total GHG emissions from some bioethanol supply chains to be so high that they completely cancel out the inherent GHG emissions advantage of bioethanol supply chains over those for petrol or diesel – that of CO2 absorption during growth of the feedstock. Understanding whether any given supply of bioethanol fuel genuinely provides GHG savings requires clear identification of the specific processes involved in that fuel’s supply chain and an analysis that takes account of the completely specified life cycle.

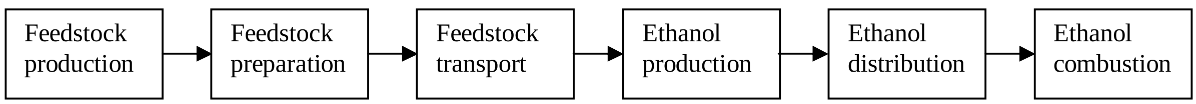

Figure 1: Processes in bioethanol fuel life cycle

Data gathering

The data gathering for this study took place in two stages. In the first stage, sites were asked to provide information to identify all known supply chains for ethanol sold in their site regions in 2006. This was done through a survey sent to local evaluation managers in June 2007. The survey solicited information describing all known ethanol flows into and out of local markets – total volumes, places of origin and types of feedstock used – as well contact details of local ethanol producers and suppliers (see Appendix 1).

The responses to the surveys and additional information provided by ethanol producers and suppliers were used to draw up a list of ethanol supply chains in BEST sites. Each ethanol supply chain consists of a sequence of processes in the fuel life cycle from feedstock production to ethanol distribution (Figure 2). Since the GHG emissions from combustion of ethanol in any given vehicle are independent of the source of the ethanol (providing the fuel meets specifications), the combustion phase of the fuel life cycle is not necessary for characterising ethanol supplies.

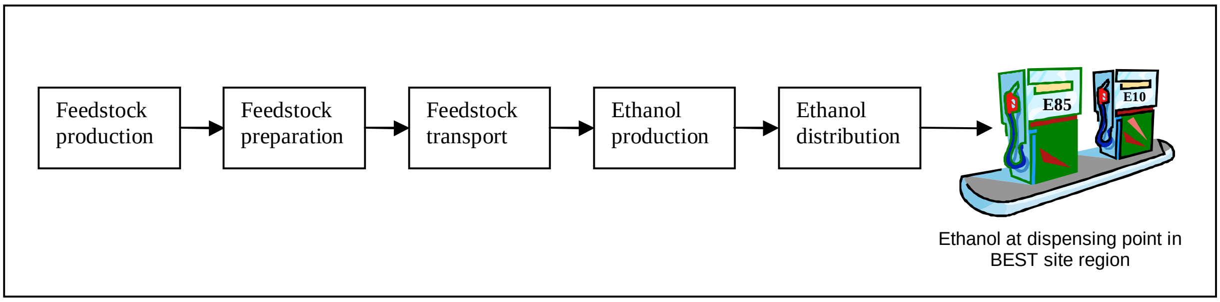

Figure 2: Generic bioethanol supply chain

In the second stage of data gathering, information was collected to enable calculations of greenhouse gas emissions associated with the identified ethanol supply chains. These calculations require complete inventories of all material and energy inputs and outputs of all the processes in the supply chain. In order to develop these inventories, data was sought from the following sources:

- published life-cycle studies
- interviews with feedstock and fuel producers and distributors
- data collection during site visits
- official statistics from national, European, and international agencies (e.g., Statistics Sweden, the Netherlands' StatLine databank, Eurostat and FAOSTAT)

For each supply chain identified, the set of data in Table 1 was collected as a minimum. This data collection served as the basis of calculations of GHG emissions per unit volume or energy of fuel.

Table 1: Data collected for life cycle calculations

Process	**Data collected**
Feedstock production	Types of feedstock Location of feedstock production Total N, P and K fertilizer applied per hectare year Average fuel use per hectare per year Pesticide use per hectare per year

	Seed material used per hectare per year Use or disposal of straw and husks Average feedstock yield
Feedstock preparation	Amount of heat and electricity used in drying feedstock Type of fuel used in drying
Feedstock transport	Mode of feedstock transport Feedstock transport distance
Ethanol production	Location of ethanol plant Average ethanol yield Amount of heat and electricity used in ethanol production Fuels used for heat and electricity production Amounts of co-products produced Use of co-products
Ethanol Distribution	Mode of transport of ethanol fuel Average distribution distance

Calculation methods

The greenhouse gas emissions calculations are based on standard life-cycle analysis (LCA) principles. Site-specific data were used to produce inventories of inputs, outputs and GHG emissions for all supply chain stages from farming to delivery of produced fuel for use in vehicles. Where site-specific data were unavailable or not sufficiently reliable, default data from previous peer-reviewed studies were used instead.

A Biofuels Greenhouse Gas Calculator was used to carry out most of the calculations. This is a spreadsheet-based tool for calculating life cycle GHG emissions inventories from biofuel supply chains, and comparing GHG emissions from biofuels with those from petrol and diesel. Figure 3, Figure 4, Figure 5 and Figure 6 show some of the sequential stages in GHG calculations using this calculator.

A web version of the Biofuel GHG Calculator (which I developed for the UK Home Grown Cereals Authority) is available at http://www.hgca.com/biofuelcalc/StartSheet.aspx

The calculations use the following important methodological approaches:

- Direct and indirect emissions resulting from all life cycle stages are considered. Thus, the GHG emissions resulting from production and use of all fertilizers, fuels and chemicals used in agricultural, industrial and other processes required for production and delivery of the final fuel are accounted for in the life cycle inventory.
- Emissions associated with the construction of buildings and equipment have not been included in the analysis. These emissions should strictly be included in the calculations, but reliable data are not available for most processes, and these emissions are known to constitute a very small proportion of the total
- Where ethanol production is accompanied by production of useful co-products, GHG emissions credits are assigned to account for the impact of the displacement of other products by the co-products.
- Indirect land use changes resulting from ethanol feedstock production are not considered. Depending on particular circumstances, these might have significant impacts on the GHG emissions resulting from ethanol production, but identification of a quantifiable causal relationship between agricultural production in one area and land use change in another is usually highly uncertain.

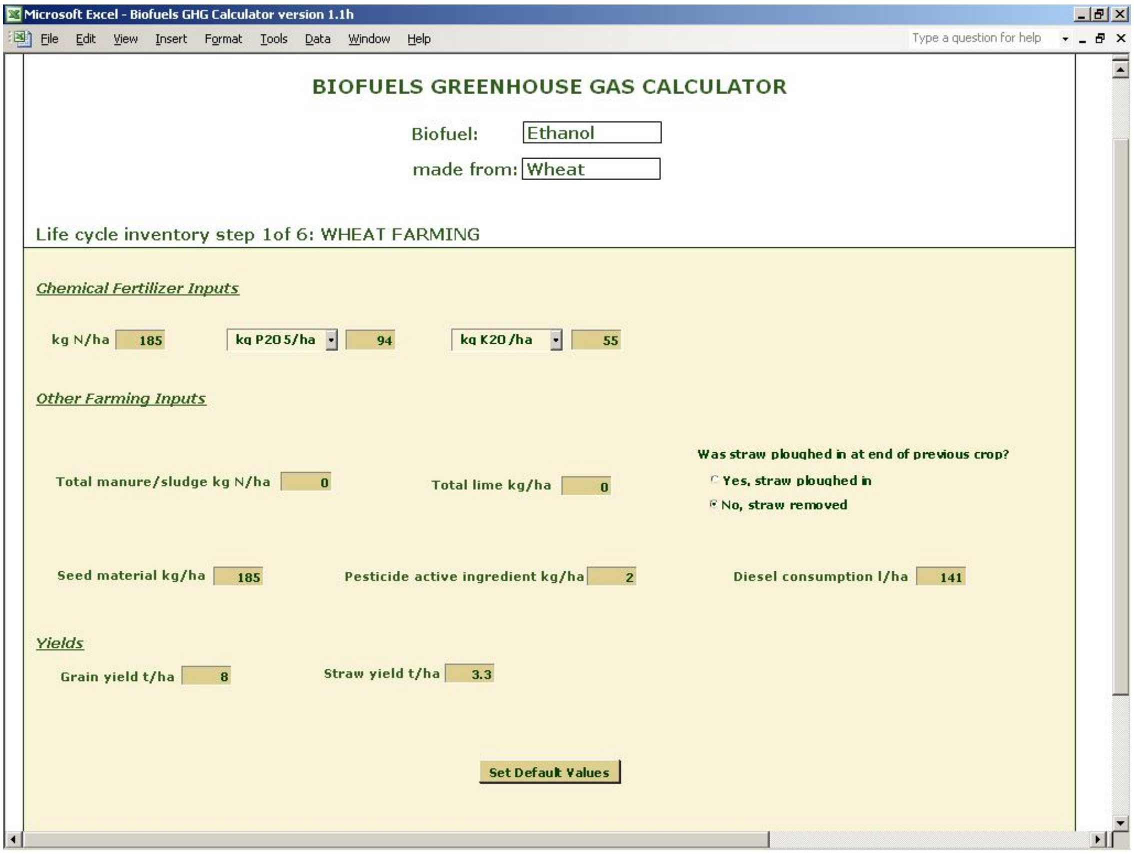

Figure 3: Biofuels Greenhouse Gas Calculator – wheat farming page

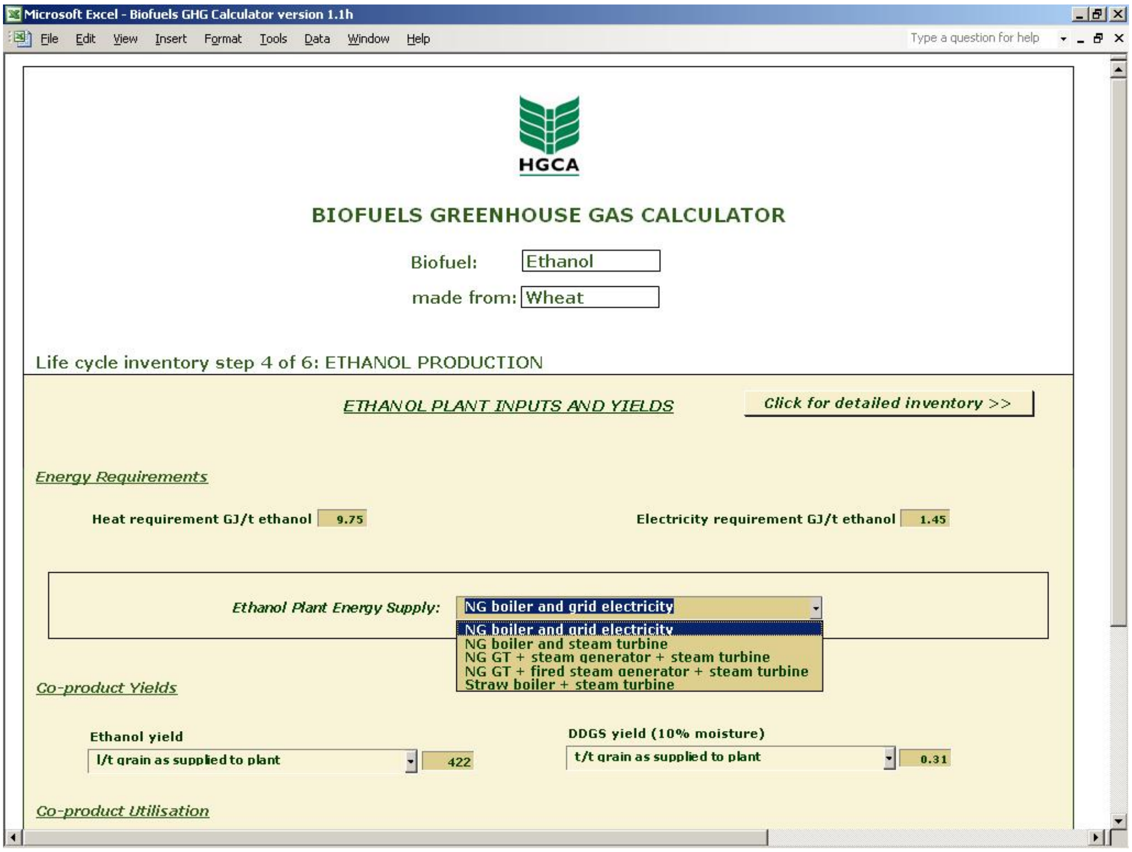

Figure 4: Biofuels Greenhouse Gas Calculator – ethanol production page

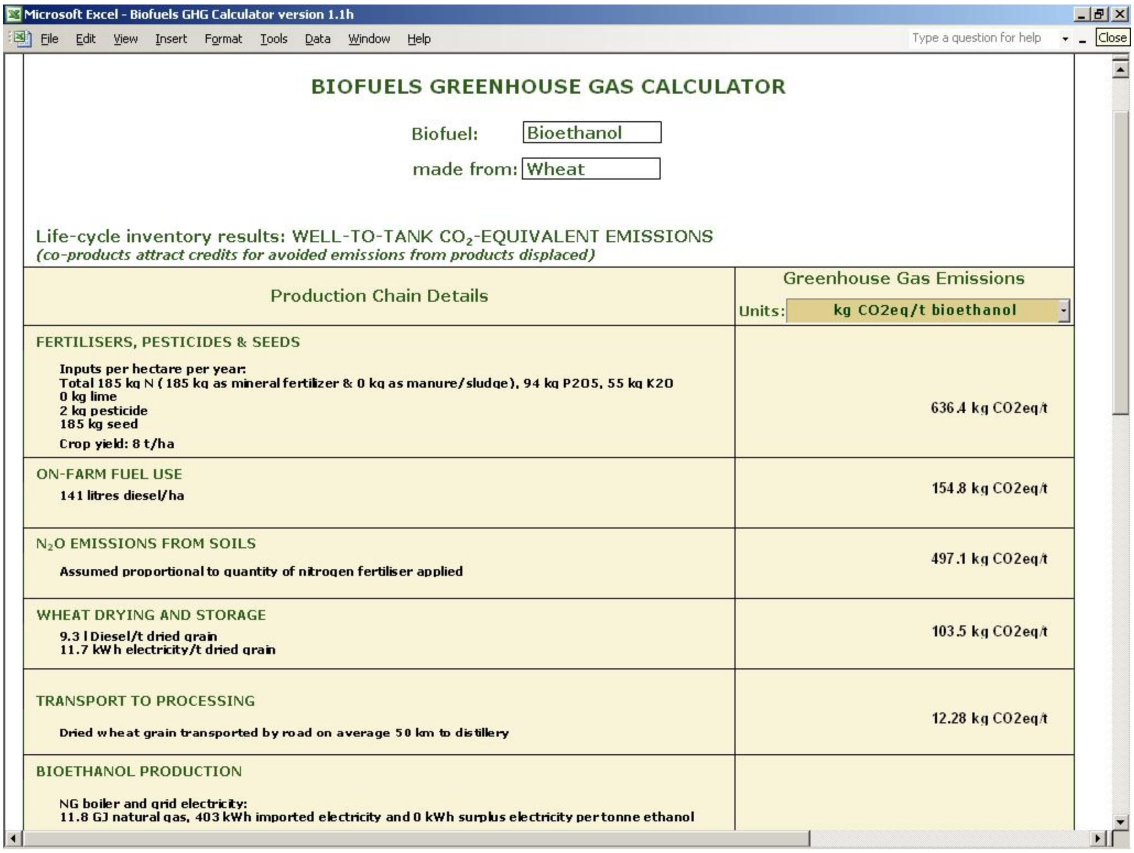

Figure 5: Biofuels Greenhouse Gas Calculator - bioethanol results page

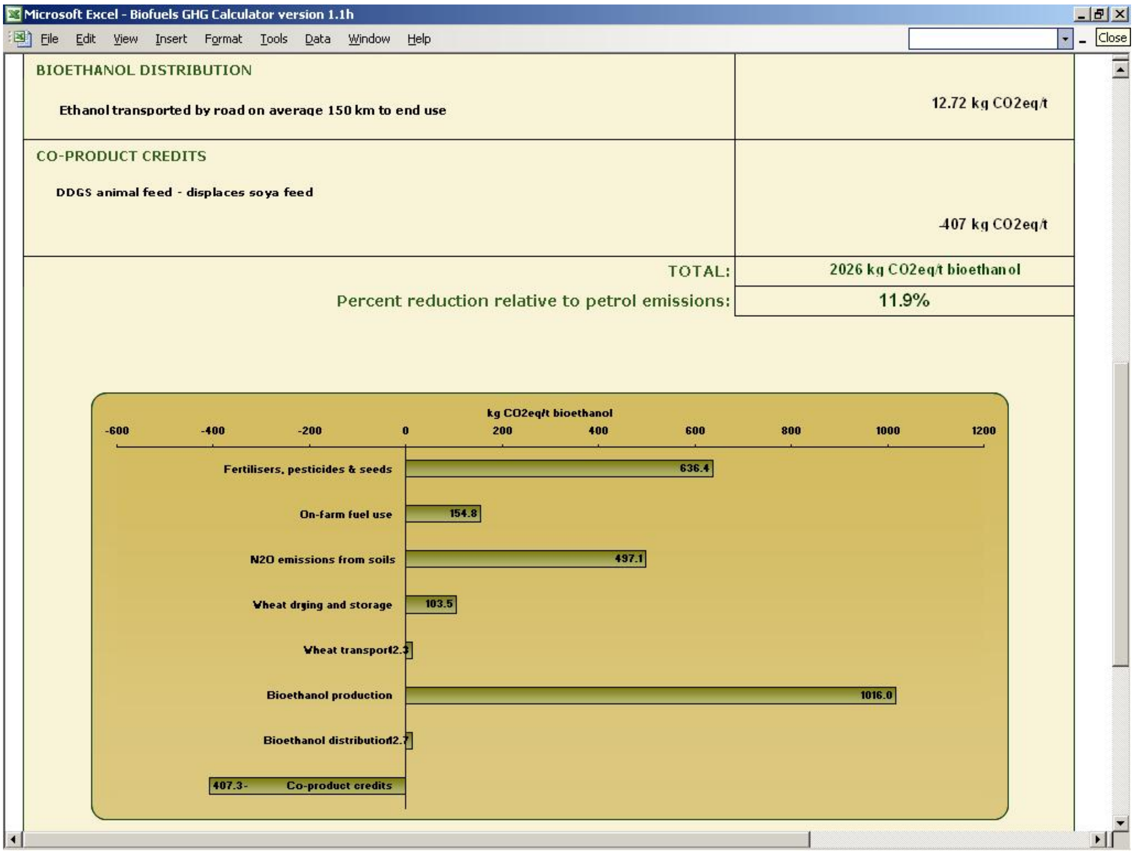

Figure 6: Biofuels Greenhouse Gas Calculator - bioethanol results and comparison with petrol

GHG emissions from identified supply chains

Based on information provided by sites, twenty five supply chains were identified across the eight European sites and Nanyang, China. Supply chains within the Saõ Paulo site were not analysed individually, but average emissions factors from peer-reviewed life cycle studies were used for those supply chain sections based in Brazil. Of the twenty five supply chains identified, sufficient information was found to enable calculation of greenhouse gas emissions factors for thirteen supply chains (Table 2).

Imperial College will continue to seek information in order to characterise as many ethanol supply chains into BEST sites as possible, and perform detailed calculations of their greenhouse gas emissions impacts.

Table 2: Bioethanol supply chains in BEST regions in 2006

Site	Supply chain ID	Feedstock	Feedstock country of origin	Location of ethanol plant(s)	Availability of data for LCA?
Somerset	SMSBRSC1	sugar cane	Brazil	Sao Paulo	Yes
Stockholm	STMSWWH1	wheat	Sweden	Norrköping	Yes
	STMSWSR1	sulphite residues	Sweden	Örnsköldsvik	No
	STMBRSC1	sugar cane	Brazil	Sao Paulo	Yes
	STMEUWR1	wine residues	EU	undefined	No
Biofuel Region	BFRSWWH1	wheat	Sweden	Norrköping	Yes
	BFRSWSR1	sulphite residues	Sweden	Örnsköldsvik	No
	BFREUWR1	wine residues	EU	undefined	No
Nanyang	NYNNYWH1	wheat	China	Nanyang City	insufficient
	NYNNYCO1	corn	China	Nanyang City	insufficient
	NYNNYSP1	sweet potato	China	Nanyang City	insufficient
	NYNNYCS1	cassava	China	Nanyang City	No
Basque Country	BSQSPWH1	wheat	Spain	Teixeiro, Galicia	Yes
	BSQSPBR1	barley	Spain	Cartagena, Murcia	Yes
	BSQSPBR2	barley	Spain	Babilafuente, Salamanca	No
Madrid	MDRSPWH1	wheat	Spain	Teixeiro, Galicia	Yes
	MDRSPBR1	barley	Spain	Cartagena, Murcia	Yes
	MDRSPBR2	barley	Spain	Babilafuente, Salamanca	No
Rotterdam	RTMNDSB1	sugar beets	Netherlands	Bergen op Zoom	Yes
	RTMNDWS1	wheat slurry	Netherlands	Bergen op Zoom	No
Brandenburg	BRDGRRW1	rye, wheat, triticale	Germany	Seyda, Saxony-Anhalt	Yes
	BRDGRRW2	rye, wheat, triticale	Germany	Schraden, Brandenburg	Yes
	BRDGRRW3	rye, wheat, triticale	Germany	Zörbig, Saxony-Anhalt	Yes
La Spezia*	LSPITWR1	surplus wine	Italy	Silicy	No
	LSPSWSC1	sugar cane	Brazil	Brazil**	Yes

*2007 supply chains ** via Sweden

The calculated greenhouse gas emissions impacts of those supply chains for which there were sufficient, reliable data and information are presented in the following sections. The ethanol supply chain emissions are given in units of kg CO_2eq/GJ ethanol, for easy comparison with petrol, which has life cycle emissions of 86 kg CO_2eq/GJ (LowCVP, 2004). The spreadsheets showing the detailed calculations for those supply chains analysed can be found in separate excel-files.

Stockholm

The Stockholm BEST site reported that in 2006, 19% of the ethanol consumed in Stockholm was produced in Sweden, 23% was imported from within the EU, and 58% was from Brazil. The ethanol produced in Sweden was made from wheat and from residues from the sulphite process for pulp and paper production. The ethanol imported from the EU was produced from wine residues and the Brazilian ethanol was made from sugar cane. Four separate supply chains were identified for site Stockholm (Table 3).

Table 3: Supply chains for bioethanol sold in Stockholm

Supply chain ID	Feedstock	Feedstock country of origin	Location of ethanol plant(s)	Data available for LCA?	Ethanol plant energy sources	Co-products	Co-product usage / disposal	Fraction of total ethanol provided by this supply chain
STMSWWH1	wheat	Sweden	Norrköping	Yes	wood chp	DDGS	animal feed	19%
STMSWSR1	sulphite residues	Sweden	Örnsköldsvik	No				
STMBRSC1	sugar cane	Brazil	Sao Paulo	Yes	bagasse CHP	vinasse	spread on fields	58%
STMEUWR1	wine residues	EU	undefined	No				23%

Data and information collected to date has enabled calculation of GHG emissions factors for the supply chains based on Swedish wheat and Brazilian sugar cane. These calculations are summarised in Table 4 and Table 5 . The supply chains based on sulphite residues and wine residues are not sufficiently well specified to allow GHG calculations.

Table 4: Summary of life cycle GHG emissions inventory for supply chain STMSWWH1 – ethanol on sale in Stockholm after production from wheat in Sweden

Supply chain process	Description	Data and information sources	Life-cycle GHG emissions kg CO_2eq / GJ ethanol
Feedstock production and preparation	Wheat farming using mineral fertilizer, yielding 6t/ha; drying to 14% moisture	FAOSTAT, 2008; FertiStat, 2008; IFDC, 2007; Statistiska centralbyrån, 2008	49
Feedstock transport	Average 100km	Assumption based on plant size and location	1
Ethanol production	435 litres ethanol per dry tonne wheat; heat supplied by biomass boiler, electricity from grid	Lantmännen Agroetanol, 2008; European Environment Agency, 2007	38

Supply chain process	Description	Data and information sources	Life-cycle GHG emissions kg CO_2eq / GJ ethanol
Ethanol distribution	150 km	Norrköping Trade and Industry Office, 2003	0.5
Co-product credits	DDGS co-product substitute for imported soya meal	Lantmännen Agroetanol, 2008;	-15
Total			**42**
Percent reduction relative to petrol emissions:			**51%**

This supply chain provides greater GHG emissions reductions than most other wheat-based ethanol supply chains that do not use combined heat and power (CHP) for the ethanol plant energy supply. This is primarily as a result of the use of waste biomass (forest residue) as the source of heat for ethanol production.

Table 5: Summary of life cycle GHG emissions inventory for supply chain STMBRSC1 – ethanol on sale in Stockholm after production from sugarcane in Brazil and shipping to Sweden

Supply chain process	Description	Data and information sources	Life-cycle GHG emissions kg CO_2eq / GJ ethanol
Feedstock production and preparation	Sugarcane farming using mineral fertilizer, yielding 69 t/ha	FAOSTAT 2008; Macedo et. al., 2002	16.0
Feedstock transport	average 20km	Macedo et. al., 2002	1.4
Ethanol production	89 litres per tonne cane; bagasse CHP	Macedo et. al., 2002	2.0
Ethanol distribution	450km by road, 11500km by ship	Macedo et. al., 2002; Maritime Chain, 2008; JEC, 2007	6.1
Co-product credits	credit for surplus bagasse (8% of total exported as replacement for fuel oil)	Macedo et. al., 2002	-6.6
Total			**18.9**
Percent reduction relative to petrol emissions:			**78%**

The calculations for the Brazil-based sections of this supply chain are based on a detailed life cycle study carried out by Macedo, et. al. in 2002. There is now some information indicating that the GHG emissions performance of Brazilian ethanol has improved further since publication of that report, but detailed data were not available in time to be included in this study.

Despite the shipping of ethanol from Brazil to Sweden, this ethanol supply chain provides considerable GHG emissions savings. These savings derive from the use of sugarcane residue (bagasse) for energy and a high yield of ethanol (6100 l/ha/yr) for a relatively modest nitrogen fertilizer input (average 75 t/ha/yr).

Biofuel Region

The Biofuel Region (BFR) reported that in 2006, 30% of the ethanol used in BFR was produced in Sweden and 70% was imported from within the EU. Three ethanol supply chains were identified for this site.

Table 6: Supply chains for bioethanol sold in Biofuel Region

Supply chain ID	Feedstock	Feedstock country of origin	Location of ethanol plant(s)	Data available for LCA?	Ethanol plant energy sources	Co-products	Co-product usage / disposal	Fraction of total ethanol provided by this supply chain
BFRSWWH1	wheat	Sweden	Norrköping	Yes	wood chp	DDGS	Animal feed	30%
BFRSWSR1	sulphite residues	Sweden	Örnsköldsvik	No				
BFREUWR1	wine residues	EU	undefined	No				70%

Enough data were obtained to calculate life cycle GHG emissions for the supply chain based on Swedish wheat (Table 7).

Table 7: Summary of life cycle GHG emissions inventory for supply chain BFRSWWH1 – ethanol on sale in Biofuel Region after production from wheat in Sweden

Supply chain process	Description	Data and information sources	Life-cycle GHG emissions kg CO_2eq / GJ ethanol
Feedstock production and preparation	Wheat farming using mineral fertilizer, yielding 6t/ha; drying to 14% moisture	FAOSTAT, 2008; FertiStat, 2008; IFDC, 2007; Statistiska centralbyrån, 2008	49
Feedstock transport	Average 100km	Assumption based on plant size and location	1
Ethanol production	435 litres ethanol per dry tonne wheat; heat supplied by biomass boiler, electricity from grid	Lantmännen Agroetanol, 2008; European Environment Agency, 2007	38
Ethanol distribution	600 km by road	Norrköping Trade and Industry Office, 2003	1.9
Co-product credits	DDGS co-product substitute for imported soya meal	Lantmännen Agroetanol, 2008;	-15
Total			**43**
Percent reduction relative to petrol emissions:			**50%**

The use of waste biomass (forest residue) as the source of heat for ethanol production contributes to significant GHG emissions savings for this supply chain.

Nanyang

In 2006, all the ethanol consumed in Nanyang was produced in Nanyang. 60% of this was produced from wheat, 20% from corn, and 20% from cassava and sweet potato. Four ethanol supply chains were identified (Table 8).

Table 8: Supply chains for bioethanol sold in Nanyang

Supply chain ID	Feedstock	Feedstock country of origin	Location of ethanol plant(s)	Data available for LCA?	Ethanol plant energy sources	Co-products	Co-product usage / disposal	Fraction of total ethanol provided by this supply chain
NYNNYWH1	wheat	China	Nanyang City	insufficient	coal chp	DDGS	animal feed	60%
NYNNYCO1	corn	China	Nanyang City	insufficient	coal chp	DDGS	animal feed	20%
NYNNYSP1	sweet potato	China	Nanyang City	insufficient	coal chp			20%
NYNNYCS1	cassava	China	Nanyang City	No				

The Nanyang site has provided much information on the ethanol supply chains based on wheat, corn and sweet potato. However, there is some uncertainty about some important items of data from these supply chains, especially the data related to fertilizer used for crop production and energy used in the ethanol plant. Since each of these data values typically has a major impact on the net GHG emissions of the ethanol supply chains, the supply chain calculations are currently too uncertain to include in this report. The Nanyang BEST partners are currently working to clarify the uncertainties in the supply chain descriptions.

Basque Country

In 2006, 100% of the ethanol sold in Basque Country was produced in Spain. This ethanol was produced in three Spanish ethanol plants, using wheat and barley (

Table 9). The proportions of wheat and barley used were not specified.

A detailed LCA study published in 2005 (Lechón, et.al., 2005) provides greenhouse gas emissions information for ethanol supply chains based on ethanol production in Teixeiro, Galicia, using wheat as feedstock, and in Cartagena, Murcia, using barley as feedstock. GHG emissions calculations for these two supply chains are presented in

Table 10 and Table 11. Detailed information was not available on ethanol production at the Salamanca plant. According to press reports, this plant was opened in April, 2006, then suspended operations in September, 2007, and is due to restart operations in late 2008 (Ethanol Statistics, 2007; CheckBiotech, 2008).

Table 9: Supply chains for bioethanol sold in Basque Country

Supply chain ID	Feedstock	Feedstock country of origin	Location of ethanol plant(s)	Data available for LCA?	Ethanol plant energy sources	Co-products	Co-product usage / disposal	Fraction of total ethanol provided by this supply chain
BSQSPWH1	wheat	Spain	Teixeiro, Galicia	Yes	natural gas CHP	DDGS, electricity	DDGS for animal feed, electricity replacing grid mix	unknown
BSQSPBR1	barley	Spain	Cartagena, Murcia	Yes	natural gas CHP	DDGS, electricity	DDGS for animal feed, electricity replacing grid mix	unknown
BSQSPBR2	barley	Spain	Babilafuente, Salamanca	No				unknown

Table 10: Summary of life cycle GHG emissions inventory for supply chain BSQSPWH1 – ethanol on sale in Basque Country after production from wheat in Teixeiro, Galicia, Spain

Supply chain process	Description	Data and information sources	Life-cycle GHG emissions kg CO_2eq / GJ ethanol
Feedstock production and preparation	Wheat farming using mineral fertilizer, yielding 3.4t/ha; drying to 14% moisture	Lechón et. al., 2005	59.6
Feedstock transport	400km	Lechón et. al., 2005	3.5
Ethanol production	450 litres ethanol per dry tonne wheat; energy supplied by natural gas-fired gas turbine and recovery boiler	Lechón et. al., 2005	67.6
Ethanol distribution	520 km by road (Teixeiro to Bilbao)	Lechón et. al., 2005	1.6
Co-product credits	DDGS co-product substitute for imported soya meal, exported electricity replaces grid electricity	Lechón et. al., 2005	-49.7
Total			**82.6**
Percent reduction relative to petrol emissions:			**3.7%**

Table 11: Summary of life cycle GHG emissions inventory for supply chain BSQSPBR1 – ethanol on sale in Basque Country after production from barley in Cartagena, Murcia, Spain

Supply chain process	Description	Data and information sources	Life-cycle GHG emissions kg CO_2eq / GJ ethanol
Feedstock production and preparation	Barley farming using mineral fertilizer, yielding 3.0/ha; drying to 14% moisture	Lechón et. al., 2005	58.4
Feedstock transport	600km	Lechón et. al., 2005	6.3
Ethanol production	382 litres ethanol per dry tonne wheat; energy supplied by natural gas-fired gas turbine and recovery boiler	Lechón et. al., 2005	65.8
Ethanol distribution	835 km by road (Cartagena to Bilbao)	Lechón et. al., 2005	2.6
Co-product credits	DDGS co-product substitute for imported soya meal, exported electricity replaces grid electricity	Lechón et. al., 2005	-56.6
Total			**76.4**
Percent reduction relative to petrol emissions:			**11%**

The GHG emissions reductions calculated for the ethanol supply chains in

Table 10 and Table 11 above are very modest, and substantially lower than those calculated by Lechón, et.al. (Lechón, et.al. do not provide explicit, per GJ, net GHG emissions figures for the fuels, but go on to calculate net reductions per km using E85 and E5 based on ethanol derived from both plants in the ratio 56% from Teixeiro to 44% from Cartagena. The calculated GHG emissions reductions for E85 are given as 70%). One reason for the difference in results between these two studies is that the current study does not apply a credit for net carbon fixation in the soil, while the Lechón study applies credits of 520.86 kg CO_2/ha for wheat (equivalent to 19.2 kg CO_2/GJ ethanol) and 453.79 kg CO_2/ha for barley (equivalent to 22.6 kg CO_2/GJ ethanol). For this study, it was felt there was insufficient evidence of continued soil carbon increases over successive crop cycles to justify such a credit.

The different approaches to soil carbon fixation does not appear to be enough to account for the different results produced by these two studies, and further detailed analysis is required to explain the differences completely.

Madrid

The Madrid site was not able to provide complete supply chain data, but reported that all the ethanol consumed in Madrid in 2006 was produced in Spain. The ethanol supply chains identified (Table 12) were almost identical to those identified for the Basque Country, being based on the same feedstock and ethanol production plants. The Madrid supply chains had different final fuel distribution distances from the Basque chains. GHG emissions calculations for Madrid ethanol supply chains originating in Teixeiro, Galicia, and Cartagena, Murcia, are presented in Table 13 and Table 14.

Table 12: Supply chains for bioethanol sold in Madrid

Supply chain ID	Feedstock	Feedstock country of origin	Location of ethanol plant(s)	Data available for LCA?	Ethanol plant energy sources	Co-products	Co-product usage / disposal	Fraction of total ethanol provided by this supply chain
MDRSPWH1	wheat	Spain	Teixeiro, Galicia	Yes	natural gas CHP	DDGS, electricity	DDGS for animal feed, electricity replacing grid mix	unknown
MDRSPBR1	barley	Spain	Cartagena, Murcia	Yes	natural gas CHP	DDGS, electricity	DDGS for animal feed, electricity replacing grid mix	unknown
MDRSPBR2	barley	Spain	Babilafuente, Salamanca	No				unknown

Table 13: Summary of life cycle GHG emissions inventory for supply chain MDRSPWH1 – ethanol on sale in Madrid after production from wheat in Teixeiro, Galicia, Spain

Supply chain process	Description	Data and information sources	Life-cycle GHG emissions kg CO_2eq / GJ ethanol
Feedstock production and preparation	Wheat farming using mineral fertilizer, yielding 3.4t/ha; drying to 14% moisture	Lechón et. al., 2005	59.6
Feedstock transport	400km	Lechón et. al., 2005	3.5
Ethanol production	450 litres ethanol per dry tonne wheat; energy supplied by natural gas-fired gas turbine and recovery boiler	Lechón et. al., 2005	67.6
Ethanol distribution	550 km by road (Teixeiro to Madrid)	Lechón et. al., 2005	1.7
Co-product credits	DDGS co-product substitute for imported soya meal, exported electricity replaces grid electricity	Lechón et. al., 2005	-49.7
Total			**82.7**
Percent reduction relative to petrol emissions:			**3.6%**

Table 14: Summary of life cycle GHG emissions inventory for supply chain MDRSPBR1 – ethanol on sale in Basque Country after production from barley in Cartagena, Murcia, Spain

Supply chain process	Description	Data and information sources	Life-cycle GHG emissions kg CO_2eq / GJ ethanol
Feedstock production and preparation	Barley farming using mineral fertilizer, yielding 3.0/ha; drying to 14% moisture	Lechón et. al., 2005	58.4
Feedstock transport	600km	Lechón et. al., 2005	6.3
Ethanol production	382 litres ethanol per dry tonne wheat; energy supplied by natural gas-fired gas turbine and recovery boiler	Lechón et. al., 2005	65.8
Ethanol distribution	450 km by road (Cartagena to Madrid)	Lechón et. al., 2005	2.6
Co-product credits	DDGS co-product substitute for imported soya meal, exported electricity replaces grid electricity	Lechón et. al., 2005	-56.6
Total			**75.2**
Percent reduction relative to petrol emissions:			**12.4%**

As with the Basque Country supply chains, the GHG emissions reductions calculated for the Madrid ethanol supply chains are very modest, and substantially lower than those calculated by Lechón, et.al.

Rotterdam

Site Rotterdam reported that 100% of the fuel ethanol consumed in Rotterdam in 2006 was produced in the Netherlands, at a single plant in Bergen op Zoom. Sugar beets and wheat slurry were used as feedstock (Table 15). The proportions of ethanol produced from the different feedstock are not known. The Rotterdam site partners have not been able to provide detailed supply chain details (the owner of the Bergen op Zoom plant is no longer a partner in BEST), but a detailed LCA study for a UK sugar beet ethanol plant was used along with data from various Netherlands sources to develop a supply chain description for GHG emissions calculations. These calculations are summarised in Table 16. No detailed information was available for calculations on the wheat slurry supply chain.

Table 15: Supply chains for bioethanol sold in Rotterdam

Supply chain ID	Feedstock	Feedstock country of origin	Location of ethanol plant(s)	Data available for LCA?	Ethanol plant energy sources	Co-products	Co-product usage / disposal	Fraction of total ethanol provided by this supply chain
RTMNDSB1	sugar beets	Netherlands	Bergen op Zoom	Yes	Assumed natural gas boiler and grid electricity	Sugar beet pulp, lime	Sugar beet pulp animal feed	unknown
RTMNDWS1	wheat slurry	Netherlands	Bergen op Zoom	No				unknown

Table 16: Summary of life cycle GHG emissions inventory for supply chain RTMNDSB1 – ethanol on sale in Rotterdam after production from sugar beet in Bergen op Zoom, Netherlands

Supply chain process	Description	Data and information sources	Life-cycle GHG emissions kg CO_2eq / GJ ethanol
Feedstock production and preparation	Sugar beet farming using mineral fertilizer, yielding 62 t/ha	FAOSTAT 2008; IFDC, 2003; Mortimer et. al., 2004	17.6
Feedstock transport	75 km one-way	IRS, 2006	5.6
Ethanol production	95 litres ethanol per tonne sugar beet; energy supplied by natural gas-fired boiler and grid electricity	Mortimer et. al., 2004	42.2
Ethanol distribution	distance Bergen op Zoom to Rotterdam, 75 km	RAC, 2008	0.4
Co-product credits	sugar beet pulp as animal feed, lime for agricultural use	Mortimer et. al., 2004	-20.1
Total			**45.6**
Percent reduction relative to petrol emissions:			**47%**

The high ethanol yield of 5900 litres per hectare (with nitrogen fertilizer input 108 kg/ha) contributes to significant net GHG emissions per GJ of ethanol.

Brandenburg

The Brandenburg site has not been able to identify all ethanol supply chains in the region, but has provided detailed data for life cycle calculations for three supply chains. These supply chains were based on varying proportions of rye, wheat and triticale, processed in three ethanol plants in Eastern Germany (Table 17).

Table 17: Supply chains for bioethanol sold in Brandenburg

Supply chain ID	Feedstock	Feedstock country of origin	Location of ethanol plant(s)	Data available for LCA?	Ethanol plant energy sources	Co-products	Co-product usage / disposal	Fraction of total ethanol provided by this supply chain
BRDGRRW1	rye, wheat, triticale	Germany	Seyda, Saxony-Anhalt	Yes	fuel oil, grid electricity	distillers' grains, slurry	animal feed	unknown
BRDGRRW2	rye, wheat, triticale	Germany	Schraden, Brandenburg	Yes	biogas for heat and electricity	distillers' grains	animal feed	unknown
BRDGRRW3	rye, wheat, triticale	Germany	Zörbig, Saxony-Anhalt	Yes	natural gas, grid electricity	distillers' grains	animal feed	unknown

The ethanol producers in Brandenburg have indicated that they routinely produce ethanol using combinations of rye, triticale and wheat, so each supply chain calculation for this site is based on a specified mixture of these grains as feedstock, with average farming input and yield values to represent the specified feedstock combination. The full supply chain calculations are summarised in Table 18, Table 19 and

Table 20.

Table 18: Summary of life cycle GHG emissions inventory for supply chain BRDGRRW1 – ethanol on sale in Brandenburg after production from rye, triticale and wheat in Seyda, Saxony-Anhalt, Germany

Supply chain process	Description	Data and information sources	Life-cycle GHG emissions kg CO_2eq / GJ ethanol
Feedstock production and preparation	Farming of wheat, rye and triticale using mineral fertilizer, average yield 5.5 t/ha	Seyda Plant, 2007; FAOSTAT, 2008	35.4
Feedstock transport	average 15 km by road	Seyda Plant, 2007	0.1
Ethanol production	360 litres per tonne grain; oil-fired boiler and grid electricity	Seyda Plant, 2007	25.3
Ethanol distribution	average 300km by road	Seyda Plant, 2007	1.0
Co-product credits	distiller's wet grains animal feed replaces soy meal	Seyda Plant, 2007	-15.9
Total			**45.9**
Percent reduction relative to petrol emissions:			**47%**

The Seyda supply chain calculation is based on a feedstock composed of 80% rye, 10% triticale and 10% wheat. Ethanol produced at the Seyda plant achieves a fairly high level of greenhouse gas emissions reductions despite using light fuel oil and grid electricity to provide the energy requirements of the ethanol production process. The availability of a ready market for the wet distiller's grains and slurry co-products obviates the need for the energy-intensive drying operations normally used to produce distiller's dried grains and solubles (DDGS). The Seyda plant energy usage per tonne of ethanol produced is about 60% that of a typical modern ethanol plant that also produces DDGS.

Table 19: Summary of life cycle GHG emissions inventory for supply chain BRDGRRW2 – ethanol on sale in Brandenburg after production from rye, triticale and wheat in Schraden, Brandenburg, Germany

Supply chain process	Description	Data and information sources	Life-cycle GHG emissions kg CO_2eq / GJ ethanol
Feedstock production and preparation	Farming of wheat, rye and triticale using mineral fertilizer, average yield 6.2 t/ha	Schraden Plant, 2007; FAOSTAT, 2008	34.5
Feedstock transport	average 30 km by road	Schraden Plant, 2007	0.3
Ethanol production	350 litres per tonne grain; biogas CHP	Schraden Plant, 2007	2.5
Ethanol distribution	average 300km by road	Schraden Plant, 2007	0.9
Co-product credits	distiller's wet grains for animal feed as replacement for soy meal, fusel oil to biogas for heat and electricity	Schraden Plant, 2007	-15.5
Total			**22.7**
Percent reduction relative to petrol emissions:			**74%**

The Schraden supply chain is based on design phase specifications and calculations for a grain-based ethanol plant that uses biogas for all its heat and electricity needs. The feedstock composition is 40% wheat, 30% triticale and 30% rye. The biogas is produced in an adjacent plant using manure and organic wastes, supplemented with smaller amounts of fusel oil and other residues from the ethanol production process. The main co-products of ethanol production are distiller's wet grains and slurry.

For these calculations, biogas is considered a carbon-neutral fuel. This is a conservative approach, compared with many major studies (e.g., JEC, 2007), which apply significant credits for avoided methane emissions from alternative disposal of biogas feedstock, making biogas fuel carbon-negative. The alternative destination of the biogas feedstock in the case of Schraden would have been burning, since previous disposal options (animal feed for some residues, and land filling) are no longer allowed (Schraden Plant, 2007).

The use of biogas as the source of energy for the ethanol plant results in substantial greenhouse gas emissions savings.

Table 20: Summary of life cycle GHG emissions inventory for supply chain BRDGRRW3 – ethanol on sale in Brandenburg after production from rye, triticale and wheat in Zörbig, Saxony-Anhalt, Germany

Supply chain process	Description	Data and information sources	Life-cycle GHG emissions kg CO_2eq / GJ ethanol
Feedstock production and preparation	Farming of wheat, rye and triticale using mineral fertilizer, average yield 7 t/ha	Zörbig plant, 2007	31.5
Feedstock transport	average 80km, using biodiesel	Zörbig plant, 2007	0.5
Ethanol production	380 litres per tonne grain; natural gas-fired boiler and grid electricity	Zörbig plant, 2007	27.0
Ethanol distribution	300 km; 70% by train, 30% by road	Zörbig plant, 2007	0.5
Co-product credits	DDGS as animal feed, replacing soya	Zörbig plant, 2007	-14.6
Total			**44.9**
Percent reduction relative to petrol emissions:			**48%**

The Zörbig supply chain uses 57 % rye, 30% wheat and 13% triticale as feedstock. The ethanol plant uses natural gas and grid electricity. The use of biodiesel for feedstock transport and some train transport for ethanol distribution provides some GHG reductions relative to the more typical diesel-based road transport, but these supply chain processes normally contribute small proportions of the total emissions burdens anyway. The average agricultural yields are relatively high (7t/ha) while the nitrogen fertilizer inputs are modest (120 kg N/ha). This high efficiency of nitrogen use, along with ethanol plant energy consumption at the low end of the range expected for modern plants, gives this supply chain a favourable GHG emissions performance.

La Spezia

The La Spezia site has not provided any detailed supply chain information, but has identified two supply chains for ethanol into the site. There was no fuel ethanol on sale in La Spezia in 2006, and the supply chains referred to here came into being in 2007. These are based on surplus wine in Sicily, and sugarcane-based Brazilian ethanol shipped to Sweden and then transported to La Spezia (Table 21). During this study, no data has been found on the wine-based ethanol supply chain. The GHG emissions calculations for the ethanol supply chain from Brazil to La Spezia via Sweden is summarised in Table 22.

Table 21: Supply chains for bioethanol sold in La Spezia

Supply chain ID	Feedstock	Feedstock country of origin	Location of ethanol plant(s)	Availability of data for LCA?	Ethanol plant energy sources	Co-products	Co-product usage / disposal	Fraction of total ethanol provided by this supply chain
LSPITWR1	surplus wine	Italy	Sicily	No				unknown
LSPSWSC1	sugar cane	Brazil	Brazil**	Yes	bagasse CHP	vinasse	spread on fields	unknown

*2007 supply chains

** via Sweden

Table 22: Summary of life cycle GHG emissions inventory for supply chain LSPSWSC1 – ethanol on sale in La Spezia after production from sugarcane in Brazil, shipping to Sweden and road transport to La Spezia

Supply chain process	Description	Data and information sources	Life-cycle GHG emissions kg CO_2eq / GJ ethanol
Feedstock production and preparation	Sugarcane farming using mineral fertilizer, yielding 69 t/ha	FAOSTAT 2008; Macedo et. al., 2002	16.0
Feedstock transport	average 20km	Macedo et. al., 2002	1.4
Ethanol production	89 litres per tonne cane; bagasse CHP	Macedo et. al., 2002	2.0
Ethanol distribution	2710km by road, 11500km by ship	Macedo et. al., 2002; Maritime Chain, 2008; RAC, 2008; JEC, 2007	13.2
Co-product credits	credit for surplus bagasse	Macedo et. al., 2002	-6.6
Total			**26.1**
Percent reduction relative to petrol emissions:			**70%**

Despite 11500 km of shipping and 2710 km of transport by road, this supply chain still provides large GHG savings compared with petrol. This favourable emissions performance results principally from the substantial GHG emissions savings provided by Brazilian sugarcane-based ethanol, which in turn result from the use of sugarcane residues (bagasse) for heat and power in the ethanol plants, and from the high yields of fermentable sugars produced by sugarcane, using mineral nitrogen fertilizer applications that are relatively modest compared with those typically used in cereal farming. The high GHG savings of this supply chain also highlight the relatively low GHG emissions produced by long-distance shipping per unit weight and distance shipped. In fact, 65% of the GHG emissions from ethanol distribution in this supply chain result from road transportation, with the remaining 35% generated by shipping. If this supply chain were modified to reduce the amount of road-based distribution, it could achieve a significant further reduction in net GHG emissions.

Somerset

The Somerset site has not provided detailed supply chain information, but has indicated that 100% of the ethanol in use in the site in 2006 originated in Brazil (Table 23). It was therefore possible to calculate net GHG emissions from ethanol on sale in Somerset. These calculations are summarised in Table 24.

Table 23: Supply chains for bioethanol sold in Somerset

Supply chain ID	Feedstock	Feedstock country of origin	Location of ethanol plant(s)	Data available for LCA?	Ethanol plant energy sources	Co-products	Co-product usage / disposal	Fraction of total ethanol provided by this supply chain
SMSBRSC1	sugar cane	Brazil	Sao Paulo	Yes	bagasse CHP	vinasse	spread on fields	100%

Table 24: Summary of life cycle GHG emissions inventory for supply chain SMSBRSC1 – ethanol on sale in Somerset after production from sugarcane in Brazil and shipping to the UK

Supply chain process	Description	Data and information sources	Life-cycle GHG emissions kg CO_2eq / GJ ethanol
Feedstock production and preparation	Sugarcane farming using mineral fertilizer, yielding 69 t/ha	FAOSTAT 2008; Macedo et. al., 2002	16.0
Feedstock transport	average 20km	Macedo et. al., 2002	1.4
Ethanol production	89 litres per tonne cane; bagasse CHP	Macedo et. al., 2002	2.0
Ethanol distribution	450km by road, 9600km by ship	Macedo et. al., 2002; Maritime Chain, 2008; JEC, 2007	5.3
Co-product credits	credit for surplus bagasse	Macedo et. al., 2002	-6.6
Total			**18.2**
Percent reduction relative to petrol emissions:			**79%**

Sugarcane-based Brazilian ethanol, produced in residue-fired ethanol plants, provide large GHG emissions savings, of which only a small fraction is cancelled by the additional GHG emissions generated in shipping this fuel to Somerset.

Implications of calculations for effectiveness of BEST demonstrations

The greenhouse gas benefits of using a litre of ethanol instead of the equivalent quantity of petrol or diesel are clearly very dependent on the source of the ethanol. The GHG benefits of ethanol currently on sale in Europe vary from marginal to substantial (Figure 7). The ethanol supply chains that are most effective for greenhouse gas emissions mitigation are those that are most efficient at reducing GHG emissions from what are typically the most GHG-intensive processes in ethanol production - the use of mineral nitrogen fertilizers for feedstock production and the use of energy in the ethanol plant.

The manufacture of mineral nitrogen fertilizer is very GHG-intensive, and applications of nitrogen fertilizer increase the emissions of the potent greenhouse gas nitrous oxide (N2O) from soils, so the use of nitrogen fertilizer in ethanol production is a major determinant of the GHG-intensity of the entire supply chain. Where nitrogen is used in ethanol feedstock production, the efficiency in terms of crop yield per unit of nitrogen applied should be maximised.

Ethanol production requires energy in the form of heat and electricity. The GHG-intensity of ethanol production is lower in those plants that use less energy per unit of ethanol production, or use low-carbon forms of energy supply. Many modern ethanol plants use a range of heat recovery and other efficiency measures to minimize energy use. Grain-based ethanol plants usually dry the non-starch residues of the grain to produce DDGS, a valuable animal feed.

However, the drying process for producing DDGS normally consumes around 40% of the total energy in a modern grain-based ethanol plant (Jacques, et al, 2003). Where conditions allow, elimination of this energy-intensive drying process and production of wet distillers grains with solubles (WDGS) instead results in considerable reductions in GHG emissions. Whether the co-production of WDGS is feasible or not, the use of low-carbon forms of energy such as biomass and biogas-based heat and electricity can produce some of the greatest reductions in GHG emissions from ethanol production.

The high greenhouse gas emissions savings calculated for Brazilian sugarcane-based ethanol, even after accounting for transportation from South America to Europe, shows that supply chains based on such sugarcane-based ethanol can play a major role in achievement of the BEST strategic objective of mitigating the growth in greenhouse gas emissions from transport. However, ethanol produced in Europe from European feedstock, using low-carbon energy supplies and with efficient use of nitrogen fertilizer, has also been shown to offer significant GHG emissions savings.

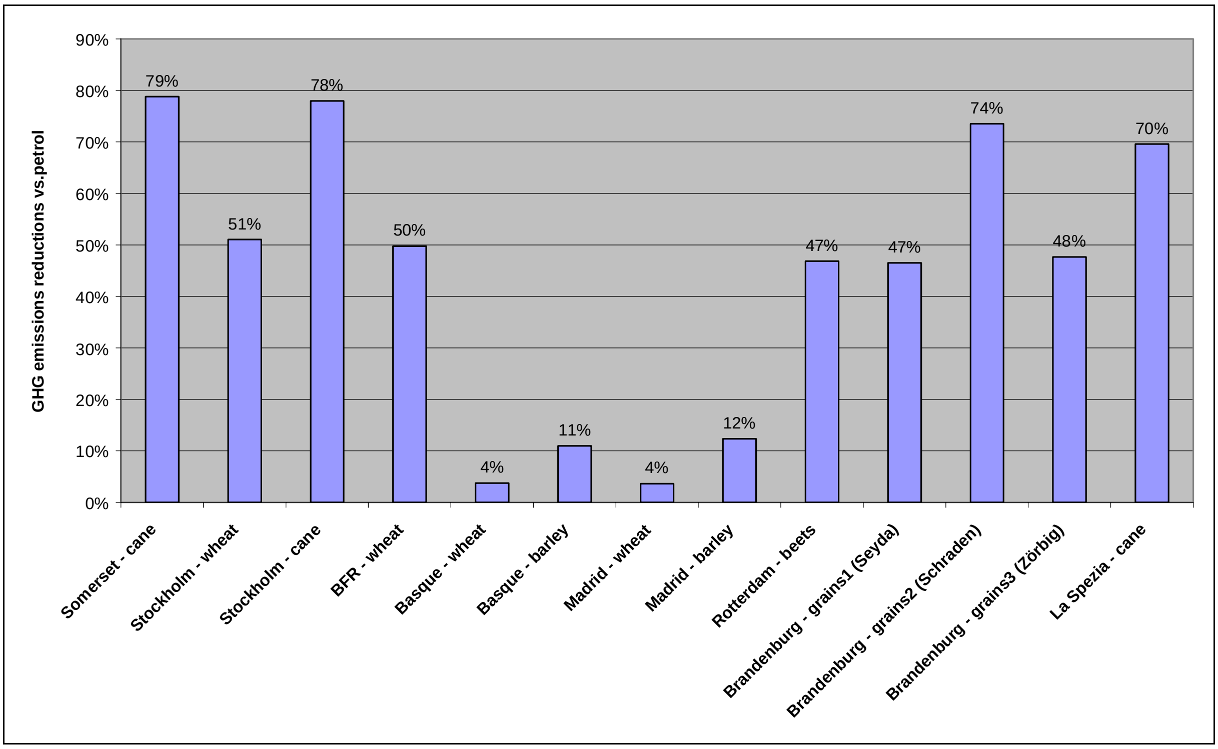

Figure 7: Greenhouse gas emissions reductions per GJ of ethanol compared with petrol for the thirteen supply chains analyzed

On the whole, the implications of the calculated GHG emissions savings are favourable for the project strategy of mitigating the growth in GHG emissions through the use of ethanol, since all the supply chains analysed show some positive GHG savings in comparison with petrol. However, the calculations also show that some of the existing ethanol supply chains are considerably more effective than others at making progress towards that strategic objective.

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Appendix 1 Ethanol Supply Chain Survey (sent to sites June 2007)

Required information on supply chains for ethanol used at BEST sites

1. Name of site:

2. What was the total fuel ethanol consumption (in litres) in your site region in 2006?

3. What was the total fuel ethanol production (in litres) in your site region in 2006?

4. Please provide the following information for each fuel ethanol producer in your site region:

    Name of company:

    What percent of the ethanol consumed in your site region is produced by this company?

    Location(s) of ethanol production plant(s) in site region:

    Total fuel ethanol production at plants in site region in 2006 (in litres):

    Feedstock used for producing fuel ethanol at plants in site region:

    Location(s) of feedstock production:

    Details of contact person in company (whom we may contact for further details of the ethanol production chain):
    Name:
    Position in company:
    Email address:

    If the number of fuel ethanol producers in your site region is more than one, please copy the section in italics above and fill in for each additional producer.

5. What was the total amount of fuel ethanol (in litres) imported into your site region in 2006? This figure will include ethanol brought into your site region from production sites in other parts of your country as well as from other countries.

6. Please indicate the percentage contribution of each external source of ethanol (i.e., from outside your site region) to the total imports into your site region in 2006 (e.g., 85% from Brazil, 15% from Norrköping, Sweden)

7. For each source of ethanol imported into your site region, please indicate what feedstock is used for producing the ethanol (e.g., Brazil – sugarcane; Sweden - wheat).

8. Please provide the following information for external producers of ethanol that is used in your site. Please provide information for as many producers as you can:

   Name of company:

   Location(s) of ethanol plant(s) producing fuel that is used in your site region:

   Total fuel ethanol production at these plants in 2006 (in litres):

   Feedstock used for producing fuel ethanol at these plants:

   Location(s) of feedstock production:

   Details of contact person in company (whom we may contact for further details of the ethanol production chain):

   Name:
   Position in company:
   Email address:

   Please copy the section in italics above and fill in for each additional producer.

9. Please provide contact details for the main ethanol supplier(s) in your site region. Here we are looking for the companies that sell ethanol or ethanol blends, whether or not they produce it themselves.

   Company:

   Address:

   Percentage share of ethanol sales in site region:

   Contact person:

   Position in company:

   Email address:

   Please copy the section in italics above and fill in for each additional supplier.

10. Please provide references for any life-cycle energy or greenhouse gas emissions studies that have been carried out for ethanol produced or used in your site region. Please give the study title, author(s), publisher, place of publication and date of publication. If you know of people or organizations that have carried out these studies for your site, please provide their contact details.