energy and greenhouse gas balance of biofuels for europe - an update

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ABSTRACT

Recent literature publications have been used to estimate the energy and greenhouse gas balance of the most relevant biofuels in Europe, i.e. ethanol and Rapeseed Methyl Ester (RME). The potential for biofuels to substitute conventional fuels on the basis of available land is also discussed.

KEYWORDS

biofuels, RME, rapeseed, ethanol, greenhouse gas, CO_2 emissions, N_2O

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SUMMARY

Biofuels can, in principle, provide a renewable source of energy and, by displacing fossil fuels, reduce greenhouse gas (GHG) emissions to the atmosphere. However, the biofuels production process itself consumes energy and emits greenhouse gases. To identify whether there are real savings in energy and GHG emissions, a careful evaluation of the field-to-tank process including by-products usage and land use emissions is needed.

In 1995, CONCAWE published a report (2/95) on alternative fuels, based on an extensive literature review. This work updates the earlier report, including results from recent studies on the two main biofuels under consideration in Europe, ethanol from either wheat or sugar beet and Rapeseed Methyl Ester (RME). There are still significant areas of uncertainty and further work is needed to provide a full understanding.

The main conclusions of this review are summarised below. It is to be noted that, due to the spread in the literature data, there is significant uncertainty attached to all figures. The spread is quantified in the main body of this report. There are large differences in ethanol figures depending on the original crop, sugar beet being generally more favourable. In view of the fact that beet cannot practically be grown on all available land, we present average figures between wheat and beet in this summary.

1. Comparing simply the energy required to produce the biofuel to the energy content of the substituted gasoline or diesel, RME represents on average a saving of 37% of the energy contained in the fuel. Ethanol from beet or wheat produces on average no energy saving, since the production energy is virtually equal to the energy in the ethanol produced.

2. In reality, the savings are somewhat larger, since production of gasoline or diesel also consumes energy, which is saved if a biofuel is substituted. On this basis, the energy saving for RME becomes 47% and there is a saving of 17% on average for ethanol.

3. The GHG balance can be calculated in the same way, by comparing the net GHG emissions incurred in producing the biofuel to the emissions from producing and burning an amount of fossil fuel with the same energy content. The CO_2 emitted during combustion of the biofuel does not enter into the balance, because it was absorbed from the atmosphere by the growing crop.

   There is, however, a significant uncertainty, particularly over the RME figures. Some studies, using IPCC[1] data, calculate high emissions of N_2O, a potent greenhouse gas, from decomposition of nitrogen compounds in the soil and from fertilisers. A similar effect is expected for ethanol although to a lesser extent, inasmuch as ethanol crops require less nitrogen than oilseed rape. In one comprehensive study, taking into account N_2O emissions in this way resulted in an estimated GHG saving for RME of less than 10%. Excluding the IPCC N_2O emissions data, the GHG balance figures show on average 53% GHG savings for RME and 26% for ethanol, with a slight advantage for sugar beet.

   CO_2 emissions arising from changes in land use can be significant for long periods of time and should also be taken into account.

[1] Intergovernmental Panel for Climate Change

4. Effective use of by-products can improve the energy and GHG balances. The ethanol production process produces protein-rich by-products which can, in principle, displace crops grown specifically for animal feed. RME production also produces animal feed as well as glycerine. The figures with and without animal feed credits are:

% saving	Ethanol		RME	
Animal feed credit	Without	With	Without	With
Energy saving	17	31	47	56
GHG saving	26	37	53/7*	58/21*

* Including IPCC N_2O emissions evaluation

From these figures, the introduction of 5% biofuels (on an energy basis) into the market would at best displace some 1.6% of gasoline and 2.8% of diesel.

In theory, additional credits are achievable by using the waste biomass to provide fuel towards the production process. This is, however, by no means general practice and the exact credit figures as well as the economics are rather uncertain at this point in time. Although figures published in the literature are included in this report, the figures quoted below do not include any credit for such use of waste biomass, nor do they include the more pessimistic N_2O emissions figures. They do include credits for animal feed substitution.

5. Since the volumetric energy content of biofuels is less than that of conventional gasoline and diesel, the impact of introducing a fixed volume of biofuel onto the market is even less. Also accounting for animal feed credit, each litre of RME would replace 0.51 litres of diesel and each litre of ethanol would replace 0.21 litres of gasoline.

The amount of land available for fuel crops in Europe is limited. The EU-15 set-aside land amounts to 5.6 million hectares from which some 6.2 Mtoe/a[2] of RME or between 7.3 and 16.0 Mtoe/a of ethanol could be produced, representing 2.3 to 5.9% of the EU-15 road transport fuel market. Taking into account the energy used in biofuel and conventional fuel production, the net energy substituted would be 3.4 Mtoe/a for RME or 4.1 Mtoe/a for ethanol. The net effect is that use of all EU-15 set-aside land would offset only 1.3 to 1.5% of EU-15 road fuel demand, or 0.6% of the crude oil used in the EU.

6. The potential CO_2 avoidance is in the order of 11 Mt/a for RME or 14 Mt/a for ethanol, or say 13 Mt/a for a combination of both fuels. This is about 0.3% of current total EU-15 CO_2 emissions or 1.5% of transport fuels emissions, even when excluding the effects of field N_2O emissions and soil carbon sequestration.

7. Some modern biofuel plants achieve better energy and GHG efficiencies than shown above by taking the opportunity to use waste products (e.g. straw) and/or energy efficient schemes such as improved distillation technologies or co-generation to produce and export electricity. Efficient use of waste products is crucial to the future of biofuels, however the EU draft Directive on biofuels does nothing to encourage such schemes and it is not clear to what extent such processes are economic and will be adopted in the future.

[2] Mtoe: Million ton oil equivalent, i.e. a fuel having a heat content (LHV) of 42.6 GJ/t

8. Production of ethanol from wood or grass has been proposed as an efficient future process. However, the energy balance for ethanol produced in this way is strongly negative and the process only becomes justifiable through the use of waste biomass as fuel. The rationale for producing bio-fuels rather than concentrating on bio-energy is therefore called into question. Optimising land use for the production of high-yield crops for heat and power generation is likely to be considerably more CO_2-effective than biofuel production.
9. Production of biofuels involves more fuel combustion than fossil fuels and may therefore lead to an increase in combustion-related pollutants such as NOx and particulates.
10. Although this study does not include cost considerations, there is no ground to believe that the figures previously quoted (e.g. in the draft Directive's explanatory memorandum) should be significantly altered. Biofuels are likely to remain considerably less cost-effective than conventional equivalents.

1. INTRODUCTION

Substitution of fossil fuels by those produced from biomass potentially reduces emissions of greenhouse gases (GHG), since the CO_2 produced is derived from carbon extracted from the atmosphere during plant growth. In practice, however, energy input is needed to cultivate the crop and to process it into biofuel, so the net energy gain and CO_2 saving could be significantly reduced. Emissions of N_2O, a potent greenhouse gas, from agriculture can also significantly affect the GHG balance. Identification and correct attribution of by-product credits is essential to reach sound conclusions.

In 1995 CONCAWE published a report (2/95) on alternative fuels [1] based on an extensive literature review. This included the major biofuels relevant to the EU, namely bio-ethanol and RME[1]. In the context of the proposed EU Directive on biofuels [2], the data on biofuels production available in the literature has been revisited. The focus has been on energy efficiency as well as CO_2 and other GHG emissions. An attempt was made to present the results of different studies on a simple and common basis. This review is limited to the production of biofuels and does not consider their end use. This approach is justified, since biofuels will in general be used in existing vehicles and their efficiency will not change significantly when operated on biofuel blends or on pure RME.

There is uncertainty over many of the component parts of the field-to-tank process and continued study is needed to refine our understanding. This review of existing literature should be seen as part of that continuing process.

[1] Rapeseed Methyl Ester

2. TYPES OF BIOFUELS CONSIDERED AND RELEVANT STUDIES

In addition to the sources used in report 2/95 we have considered more recent studies that either complement or supersede older ones. In line with the EU Commission's draft Directive, we have concentrated on RME and ethanol as substitutes to diesel and gasoline respectively.

Rapeseed appears to be the most likely crop for bio-diesel production in the EU, and it is also the most studied. We have not considered other potential routes such as sunflower or the recycling of waste cooking oils, because published data are scarce and the potential volumes are much lower than for RME.

Wheat and sugar beet are the most relevant ethanol crops in the EU. For the sake of completeness we have also included some data on corn and cellulose crops such as wood and grass, including a few studies relevant to the USA. In practice some of the ethanol will be converted into ETBE[2]. This extra production step that involves additional energy consumption and GHG emissions has not been considered.

A complete list of references is given at the end of this report.

[2] Ethyl Tertiary Butyl Ether

3. DATA COLLECTION AND PRESENTATION

Different studies use different premises and methodologies, so a direct comparison is not always possible. The single major source of differences between studies is the type and use of by-products. When it comes to the potential of biofuels in absolute terms, the crop yield per hectare is also a source of variation, as yields can vary significantly between regions and according to the assumed agricultural practices.

The detailed results are given in **Appendix 1** for RME and **Appendix 2** for ethanol. In an attempt to keep the results transparent we have listed the data from each study as published. When no data were available in the study we have, where appropriate, inferred or estimated figures in order to make the comparative analysis more significant. Estimated figures are clearly identified as such.

In order to compare the different studies from the point of view of energy as well as GHG "efficiency", we have endeavoured to calculate common parameters defined as follows.

Energy balance

R_o is the "overall energy balance" defined as the ratio of the total energy[3] required by the biofuel production process (regardless of its source) to the energy content of the biofuel.

Three sources of credit can be subtracted from R_o, namely:

- R_{cc} is the ratio of the energy required to produce an amount of conventional fuel equivalent to the biofuel to the energy content of the biofuel.
- R_{cf} is the ratio of the energy credit for the animal feed products substituted by the appropriate biofuel by-product(s) to the energy content of the biofuel.
- R_{cs} is the same as R_{cf} for the energy credit from the biomass potentially usable as fuel during the production process.

An R figure of zero would indicate a fully renewable fuel while a value of 1.0 indicates that there is no net energy saving.

Conventional fuel substitution potential

S_o, S_{cc}, S_{cf}, S_{cs} are calculated from the corresponding R's by correcting for the heating value and density of the conventional fuel and the biofuel. They represent the volume of conventional fuel that is substituted by the biofuel when all energy streams are expressed in terms of volume of conventional fuel.

[3] Assumed to be primary energy

GHG balance

- R_g is the "CO_2 balance"[4] defined as the ratio of the net GHG, expressed in CO_2 equivalent, emitted in producing the biofuel to the amount of CO_2 equivalent emitted in producing and burning an amount of fossil fuel representing the same end-use energy.
- R_{gf} is the same as the above applied to the GHG credit for the animal feed products substituted by the appropriate biofuel by-product(s).
- R_{gs} is the same again applied to the GHG credit for the biomass potentially usable as fuel during the production process.

A value of R_g below one denotes a net reduction of GHG emissions.

[4] This includes all GHGs (specifically N_2O) expressed as "CO_2 equivalent" as presented in the literature.

4. COMPARISON AND EVALUATION OF RESULTS

The results are summarised **Tables 1a, 1b & 1c** that include data from all studies considered.

Table 1a Summary of common parameters for RME

Growing region	UK	North France Aver.	North France Best	Germ.	North France	UK	North Germ.	UK	**Aver.**
Ref./Case	3	4a	4b	6&7	8a	8b	8c	9	
RME yield t/ha	1.2	1.2	1.4	1.1	1.3	1.1	1.3	1.5	**1.3**
Energy balance									
Ro	1.01	0.67	0.62	0.57	0.66	0.73	0.59	0.56	**0.63**
Rcc	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	**-0.10**
Rcf	-0.09			-0.15	-0.08	-0.08	-0.08	-0.06	**-0.09**
Rcs	-0.33	*-0.10*	*-0.09*		-0.10	*-0.12*	*-0.10*	*-0.13*	**-0.11**
Net amount of conventional diesel substituted (l/l RME)									
So	-0.01	*0.30*	*0.35*	0.38	0.30	*0.24*	*0.37*	*0.38*	**0.33**
Scc	0.09	*0.09*	*0.09*	0.09	0.09	*0.09*	*0.09*	*0.09*	**0.09**
Scf	0.08			0.14	0.07	*0.07*	*0.07*	*0.05*	**0.08**
Scs	0.29	*0.09*	*0.09*		0.09	*0.10*	*0.09*	*0.11*	**0.10**
GHG balance									
Rg	0.50	*0.56*	*0.52*	0.93	0.45	0.50	0.40	*0.47*	**0.48**
Rgf	-0.06			-0.14	-0.06	-0.06	-0.06	*-0.05*	**-0.05**
Rgs	-0.23	*-0.08*	*-0.08*		-0.08	-0.10	-0.08	*-0.11*	**-0.09**

Table 1b Summary of common parameters for ethanol from wheat and sugar beet

Crop	Wheat						Beet			
Growing region	UK	North France Aver.	North France Best	UK	EU	**Aver.**	North France Aver.	North France Best	EU	**Aver.**
Ref./Case	3	4a	4b	9	10		4a	4b	10	
Ethanol yield t/ha	2.2	1.9	2.5	2.5	1.7	**2.1**	5.3	6.2	3.8	**4.5**
Energy balance										
Ro	1.07	0.91	0.91	0.90	1.26	**1.04**	0.90	0.62	0.96	**0.93**
Rcc	-0.15	-0.15	-0.15	-0.15	-0.15	**-0.15**	-0.15	-0.15	-0.15	**-0.15**
Rcf	-0.09	*-0.10*	-0.10	*0.00*	*-0.23*	***-0.10***	*-0.06*	*-0.06*	-0.32	***-0.19***
Rcs	-0.47	*-0.46*	*-0.45*	*-0.48*	*-0.47*	***-0.47***	*-0.06*	*-0.06*	*-0.11*	***-0.08***
Net amount of conventional gasoline substituted (l/l ethanol)										
So	-0.05	0.06	0.06	0.07	-0.17	**-0.02**	0.07	0.25	0.03	**0.05**
Scc	0.11	0.10	0.10	0.11	0.10	**0.10**	0.10	0.10	0.10	**0.10**
Scf	0.07	0.06	0.06	0.00	0.15	***0.07***	*0.04*	0.04	0.21	***0.13***
Scs	0.35	0.30	0.30	0.35	0.31	***0.33***	*0.04*	*0.04*	*0.07*	***0.06***
GHG balance										
Rg	0.59	*0.72*	*0.71*	*0.71*	*0.99*	***0.75***	*0.70*	*0.49*	*0.75*	***0.73***
Rgf	-0.06	*-0.04*	*-0.06*	*0.00*	*-0.18*	***-0.07***	*-0.05*	*-0.05*	*-0.25*	***-0.15***
Rgs	-0.29	*-0.36*	*-0.36*	*-0.38*	*-0.37*	***-0.35***	*-0.05*	*-0.05*	*-0.08*	***-0.07***

Note: In both tables, the figures in italics are not available from the published material and have been estimated by CONCAWE. Data in the shaded columns have not been included in the “average” column and in the figures below.

Table 1c Summary of common parameters for ethanol from other crops

Crop	Corn					Wood		Grass
Growing region	North France		USA	USA	USA	USA	Scan.	USA
	Aver.	Best						
Ref./Case	4a	4b	5	11	12*	12	13	12
Ethanol yield t/ha	2.0	2.8	2.2	2.4				
Energy balance								
Ro	0.97	1.06	0.88	1.65	0.59	1.56	1.25	1.26
Rcc	-0.15	-0.15	-0.15					
Rcf	*-0.12*	*-0.11*	-0.10					
Rcs	*-0.48*	*-0.53*				-1.55	-1.23	-1.15
Net amount of conventional gasoline substituted (l/l ethanol)								
So	0.02	-0.04	0.08	-0.43				
Scc	0.10	0.10	0.10	0.10				
Scf	*0.08*	*0.07*	0.06					
Scs	*0.32*	*0.35*						
GHG balance								
Rg	*0.76*	*0.83*	0.89	*1.30*				
Rgf	*-0.09*	*-0.13*	-0.10					
Rgs	*-0.38*	*-0.42*						

4.1. ENERGY BALANCE

R_o figures are reasonably consistent for RME with the exception of the ETSU study [3] that reports a much higher value. Figures that include credit for animal feed and straw are more variable reflecting a wide range of different assumptions. The IFEU work [6,7] indicates an energy credit for animal feed which is not in line with other RME studies. Levington [9] also suggests a high figure for the heating value of the rape straw.

For ethanol, the EU Commission report [10] appears to be overly pessimistic. The Pimentel work [11] quotes very high figures for agriculture and process energy which are not in line with those from other studies.

The “best” data from the Levy report [4] are included for the sake of completeness but have not been further considered. Although these figures were presented by Levy as feasible targets for the future, they are now over 10 years old and do not seem to have been confirmed by more recent developments.

4.2. GHG BALANCE

The high GHG figures proposed by IFEU [6,7] stem largely from the assumptions on N_2O emissions linked to fertiliser use (the authors have used IPCC[5] factors). Such results have been a constant in past German studies although others, such as INRA[6] in France, have challenged the figures. The data are otherwise fairly consistent, but this demonstrates how much uncertainty can be attached to such figures. Note that the available ethanol data do not include the pessimistic IPCC view on N_2O.

[5] Intergovernmental Panel for Climate Change
[6] Institut National de la Recherche Agronomique

The ETSU study [3] appears to be inconsistent in that it reports high figures for energy use but low GHG emissions.

4.3. SAVINGS

Figures 1 to 3 show the achievable savings in terms of energy, conventional fuel substitution and GHG emissions. The averages are restricted to the most relevant/consistent data as indicated in **Table 1**. For RME we have eliminated results from the ETSU study [3], which are clearly out of line with all other studies. For ethanol we have only considered data relevant to the EU for beet and wheat. For both fuels we have only considered the "average" figures from the Levy report [4]. The GHG figures from the IFEU work [6,7] are shown separately on the plots and have been excluded from the average. The figures also show the spread of data to give an idea of the magnitude of the differences between published studies.

The credits for animal feed and biomass, shown separately in **Table 1,** have now been added to the base case.

Figure 1 shows the percentage of the biofuel energy content that can actually be saved, taking into account the production energy of the substituted conventional fuel.

Figure 2 shows the volume of conventional fuel that is substituted by a volume of biofuel.

Figure 3 shows the GHG emissions that can be saved, as a percentage, by substituting the biofuel for an equivalent amount of conventional fuel.

The bars therefore represent:

Figure	1	2	3
Base case, no credits	$(1-R_o)*100$		
With conventional fuel production credit	$(1-R_o-R_{cc})*100$	S_o+S_{cc}	$(1-R_g)*100$
With animal feed credit	$(1-R_o-R_{cc}-R_{cf})*100$	$S_o+S_{cc}+S_{cf}$	$(1-R_g-R_{gf})*100$
Theoretical, maximum use of co-products	$(1-R_o-R_{cc}-R_{cf}-R_{cs})*100$	$S_o+S_{cc}+S_{cf}+S_{cs}$	$(1-R_g-R_{gf}-R_{gs})*100$

Figure 1 Net conventional energy saved

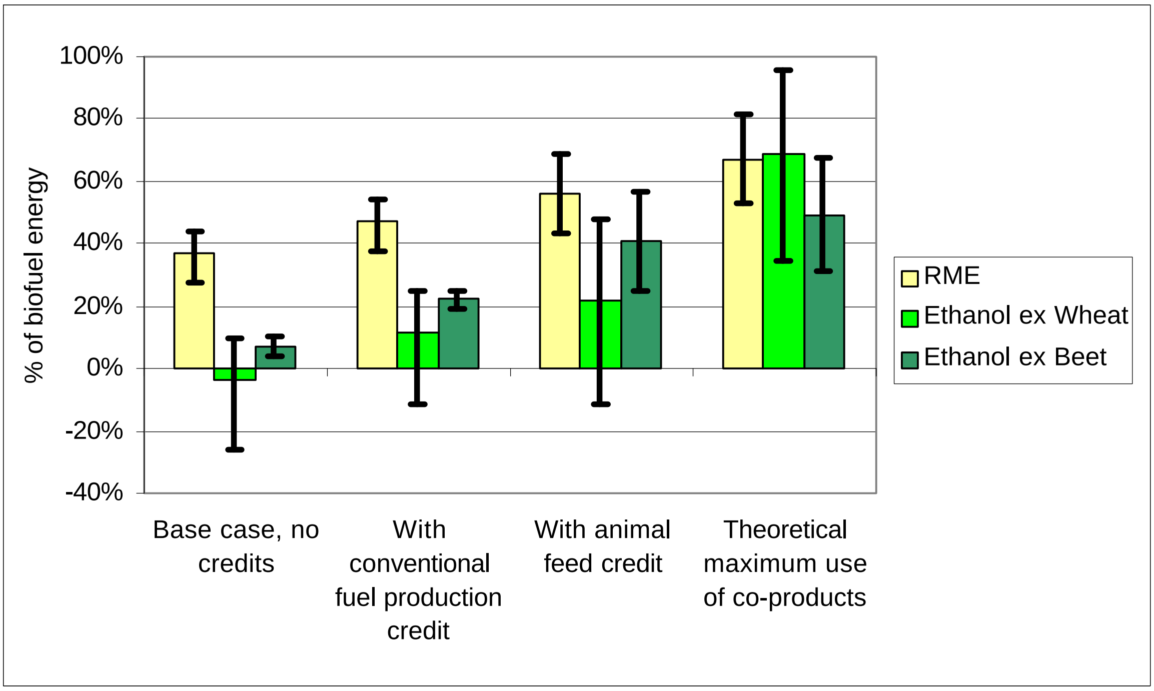


Figure 2 Net volume of conventional fuel substituted

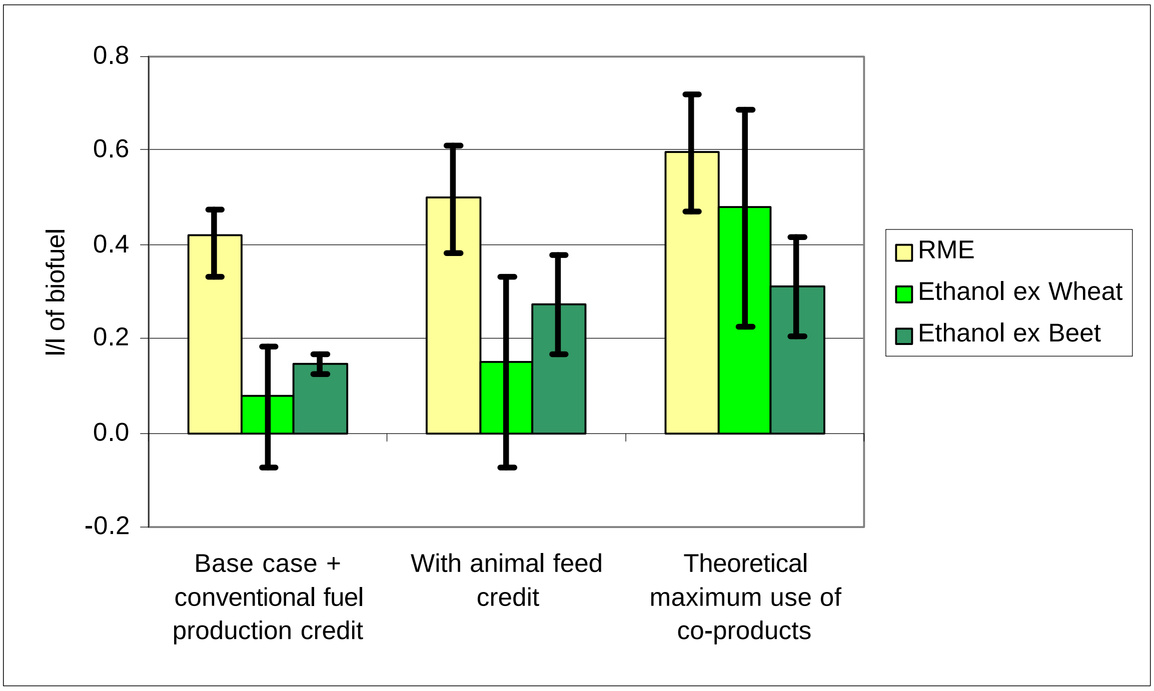
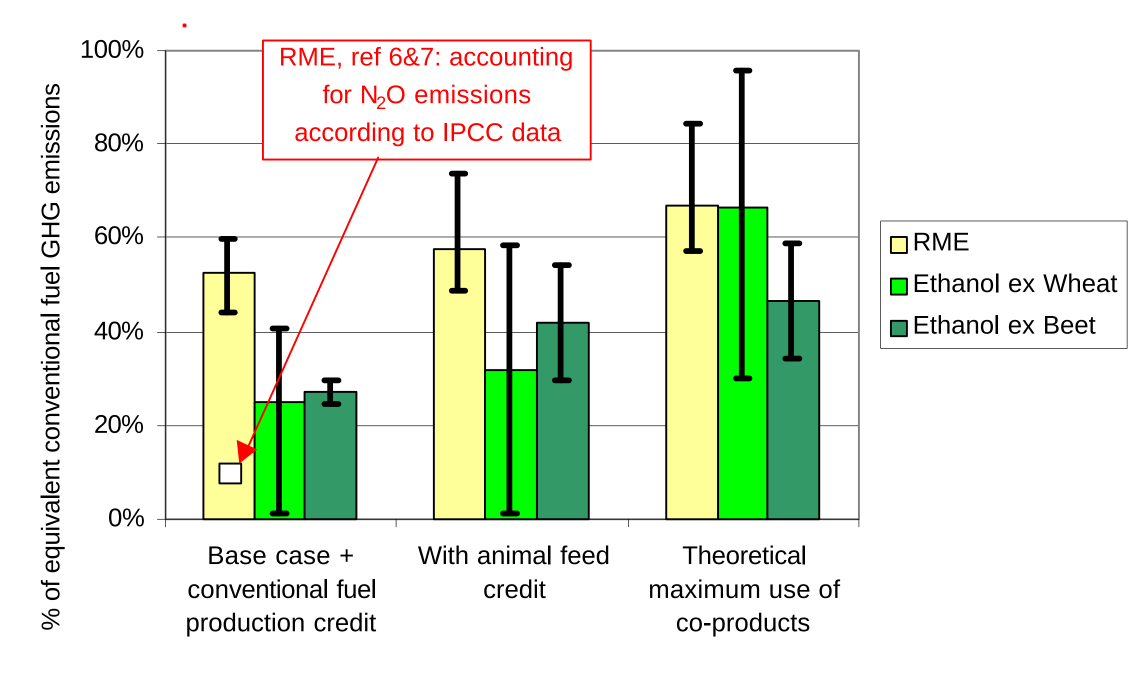


Figure 3 GHG savings



Although there is some spread in the figures, RME appears to be generally more efficient than ethanol with regards to all indicators. Ethanol can only achieve figures that come close to RME with optimum use of all co-products, sugar beet being somewhat more favourable than wheat. In particular, the substitution potential of ethanol is very low unless maximum use of biomass can be achieved. Whether this is practical and economically viable on a large scale remains to be seen, and some studies indicate that this is unlikely.

4.4. POTENTIAL VERSUS REALITY: A HEALTH CHECK

In evaluating and further using the results it is important to consider the real-world production processes and practices. Current biofuel production generates by-products that can potentially be used as animal feed, as well as straw or other biomass that can be used as a source of energy. Actual energy and GHG savings from these sources are, however, subject to uncertainty. The credits that can reasonably be taken into account for the by-products are therefore key elements of the debate. It is also where the largest differences are to be found, possibly illustrating the fact that such figures are often speculative rather than based on real-life experience.

For instance, savings from potential animal feed products will only accrue if alternative animal feed production is actually reduced. The key is to consider the effect of substitution rather than the heat content of the material itself, which is irrelevant if it is not burned. An amount of animal feed produced as by-product can substitute an equivalent amount (in terms of feed value) of e.g. soy meal that would otherwise be produced and transported at the cost of an amount of energy that is thereby saved. Experience in the USA suggests, however, that soy meal production may not have declined significantly as ethanol production has increased. The by-product benefits may therefore be less than expected.

The most favourable figures for energy and GHG savings occur where straw and other waste biomass are used as an energy source, thereby saving conventional energy. Current biofuel production makes, however, little use of such waste products, so the figures represent in most cases a theoretical potential only. It is important to consider what fraction of the process energy the by-products can practically supply.

Some modern plants (e.g. in Spain, Sweden) do make effective use of waste material as an energy source and use energy-efficient schemes such as co-generation to produce and export electricity. Recent improvements in the key distillation step in ethanol production, using energy-efficient distillation and molecular sieve technology, have been demonstrated e.g. in the Agroetanol plant in Sweden. New plants built in the EU in response to the biofuels Directive may use such technologies if commercially proven and economically justified. It is not clear, however, to what extent this will be the case in practice.

The results for ethanol from wood or grass further highlight the importance of by-products. For these processes, more energy is used for producing the fuel than is available in the fuel itself. The process can only make sense through the use of the associated biomass as internal fuel.

Efficient use of waste products is clearly crucial to the future of biofuels, however the EU draft Directive does nothing to encourage such schemes and it is not clear to what extent such processes will be adopted in the future. Logistics considerations amongst others are likely to favour a large number of small to medium size plants near the point of production. In practice a diversity of technical and commercial options will be selected and it is unlikely that all will be state-of-the-art in terms of energy efficiency.

At this point we are of the opinion that animal feed substitution credits can be taken into account with reasonable credibility. A significant credit for massive biomass use is speculative and only represents a “theoretical best”.

Finally the large spread of figures from different studies must be pointed out. Beyond the differences in basic assumptions and methodologies, this is a reflection of the wide diversity in agricultural practices and yields as well as in crop processing technologies and the fuel mix that is used to provide energy to the various stages of the process. The wide divergence of estimates for N_2O emissions requires further study to resolve.

4.5. LAND USE AND GLOBAL POTENTIAL

In a situation where the available land is limited, optimum use thereof also becomes an issue.

The yields of RME and ethanol per hectare are shown in **Table 1 a/b**. The rapeseed and RME yield per hectare are reasonably consistent with the exception of the Levington study [9], which appears to take an optimistic view, especially as it applies to the UK. Whereas wheat and corn yield in the order of 2 t of ethanol per hectare, sugar beet has a much higher potential, in the region of 5 t per hectare. A more meaningful measure, however, is the amount of gasoline or diesel that can be substituted by the produce of each hectare, taking into account the energy efficiency of the production and the possible use of co-products.

The land potentially available for biofuel crops is often equated to the set-aside land, about 5.6 Mha in EU-15[7]. On that basis the total EU substitution potential can be estimated. The relevant figures are summarised in **Table 2**.

Table 2 Global potential of biofuels in EU-15

		RME	Ethanol from			Biomass
			Wheat	Beet	50/50	
Potential biofuel production	Mt/a					
Average		7.1	11.5	25.3	18.4	
min		6.3	9.2	21.0	15.1	
Max		8.5	13.8	29.6	21.7	
Oil equivalent	Mtoe/a	6.2	7.3	16.0	11.7	
% of total road fuels						
Average		2.3%	2.7%	5.9%	4.3%	
min		2.0%	2.1%	4.9%		
Max		2.7%	3.2%	6.9%		
Diesel equivalent	Mt/a	6.0				
% of diesel		3.8%				
Petrol equivalent	Mt/a		7.2	15.8	11.5	
% of petrol			6.7%	14.7%	10.7%	
Production debits and credits (average)						
Biofuel production energy	Mtoe/a	-3.9	-7.6	-14.9	-11.2	
Conv. fuel production energy credit		0.6	1.1	2.4	1.8	
Animal feed credit		0.6	0.8	3.0	1.9	
Straw/biomass credit		0.7	3.4	1.3	2.4	
Overall balance	Mtoe/a					
Base case without credits		2.3	-0.3	1.1	0.4	
With conventional fuel production credit (1)		2.9	0.8	3.5	2.2	
Theoretical best (2)		4.1	5.0	7.9	6.5	
Probably achievable (3)		**3.4**	**1.6**	**6.6**	**4.1**	**26.3**
% of diesel		**2.2%**				
% of petrol			**1.5%**	**6.2%**	**3.9%**	
% of total road fuels	**Av.**	**1.3%**	**0.6%**	**2.4%**	**1.5%**	
	min	**0.9%**	**-0.2%**	**1.2%**	**0.5%**	
	Max	**1.9%**	**1.5%**	**3.9%**	**2.7%**	
% of total crude processed	**Av.**	**0.5%**	**0.2%**	**1.0%**	**0.6%**	**4.0%**
CO_2 avoidance	Mt/a					
With conventional fuel production credit (1)		10.0	5.7	13.6	9.7	
Theoretical best (2)		12.8	15.3	23.4	19.3	
Probably achievable (3)		**11.0**	**7.3**	**21.1**	**14.2**	**89.6**
	t/ha	**2.0**	**1.3**	**3.8**	**2.5**	**16.0**

(1) including correction for fossil fuel production

(2) including all credits for animal feed and straw/biomass

(3) including animal feed credit but excluding straw/biomass credit

7 According to the estimate indicated in the explanatory memorandum to the draft biofuels Directive

Underlying assumptions:

Land area (set-aside)	Mha	5.6
EU-15 road transport fuels demand in 2010 (1)		
Diesel	Mt/a	160
Petrol	Mt/a	107
Total road fuels	Mtoe/a	273
Total crude processed	Mt/a	650
Total EU-15 GHG emissions	Mt/a (2)	4000
EU-15 CO_2 emissions from road fuels (3)		847

(1) Source: Wood Mackenzie

(2) Expressed as CO_2 equivalent

(3) Estimated

Simply based on the potential production volumes, considerably more ethanol than RME can be produced, especially from sugar beet. The figures look, however, more balanced when the production efficiency is taken into account. Sugar beet retains an advantage in terms of overall yield of biofuel energy. A 100% sugar beet scenario is, however, unrealistic for Europe as a whole, as this crop can practically be grown only in certain areas. We have shown a 50/50 wheat/beet scenario which may represent a European achievable average. It must also be noted that the scenarios are not additive as the land can only be used once.

If all the EU-15 set-aside land were used to produce RME, 6.2 Mtoe/a could be produced, representing 2.3% of total road fuel demand. Using all the land for ethanol the figures are 11.7 Mtoe/a, equivalent to 4.3% of total fuel demand, assuming a 50/50 mix of beet and wheat ethanol. When the energy used in the production process is accounted for the potential net savings are reduced to 3.4 Mtoe/a for RME and 4.1 Mtoe/a for ethanol, representing only 1.3-1.5% of total EU-15 road fuel demand. In practice, both RME and ethanol will be produced, so that the total expected figures are somewhere in between. These numbers must be compared to the Directive’s objective of 5.75% biofuels in transport fuels by 2010. Even if this refers only to the gross biofuels content (i.e. without taking the production energy into account), it appears to be only achievable if a significant portion of the land currently devoted to food crops is used for biofuels production.

The EU-15 arable land area covers 76 Mha, the 5.6 Mha set-aside therefore representing 7.3% of the total. Suitable land may also be available from Eastern European so-called “accession” countries. Arable land in the 12 accession countries represents 43 Mha. How much of this could practically be used for biofuels crops remains to be established.

Also based on the EU-15 set-aside land area, 9 to 13 Mt/a of animal feed would be produced, to be compared to some 31 Mt/a of soy meal currently consumed in the EU.

It should also be noted that the EU currently has a surplus of gasoline and a deficit of diesel which are projected to grow in the coming years.

In terms of CO_2 avoidance, the impact would be 11 Mt/a for RME or 14.2 Mt/a for ethanol, i.e. around 13Mt/a for a mix of RME and ethanol. This represents around 0.3% of total annual EU-15 emissions or 1.5% of the emissions from transport fuels. This figure could, however, be seriously curtailed if the most pessimistic views on N_2O emissions associated to crop production were to be proven.

4.6. BIO-FUELS VERSUS BIO-ENERGY

The current focus is very much on the use of available land for the production of motor fuels. This may not, however, represent the optimum use of land from an energy or GHG point of view. Motor fuels are increasingly complex products that need to meet a number of requirements and specifications. Making such fuels from crops requires extensive processing (fermentation, distillation, esterification) and concerns only a part of the available biomass (oil or carbohydrates). The preferred crops are selected for their ability to produce such compounds rather than their potential for metabolising CO_2.

An alternative is to simply use the biomass as a fuel to raise steam and produce electricity or use the opportunity for a combined heat and power scheme. The process is considerably simpler while the crops can now be selected solely on their ability to produce large amounts of biomass from a given land area. Such crops could include various grass varieties or fast-growing wood (short rotation coppicing). Indicative data can be found in recent work undertaken in the UK [14]. Adapted grass varieties can produce some 200 GJ/ha of net biomass energy (i.e. after accounting for the production energy), compared to 30 to 60 in the best scenario for RME or ethanol. When used for power generation this could displace an equivalent fossil fuel energy with a CO_2 emission factor of say 80 kg CO_2/GJ (typical of heavy fuel oil or intermediate between gas and coal). This would equate to 16 t CO_2 /ha, four to eight times more than could be achieved through RME or ethanol (see **Table 2**).

Production of syngas by partial oxidation would be a more sophisticated route that would open additional options for increased efficiency or further production of hydrogen or even GTL[8]. The size of such plants, however, is bound to be limited by the amount of feed obtainable within a realistic geographic area. Biomass generally has a low energy density and contains a lot of water. Various literature sources mention a collection radius of some 70 km as the maximum beyond which transport costs become prohibitive. At this limited scale technical and economic considerations may well make such schemes unrealistic.

4.7. CARBON SEQUESTRATION IN SOIL

Land under cultivation contains considerably less carbon than land bearing natural vegetation (see e.g. [15]). Although finite and reversible in the long-term, the release of carbon from putting fallow land into cultivation is sizeable. An experiment carried out by INRA and IACR[9] over 35 years has shown that land could typically release the equivalent of some 3 t/ha of CO_2 per year over this or even a longer period of time. This would cancel out a significant part, or in some cases all, of the CO_2 benefit from transportation biofuels for many decades.

4.8. OTHER EMISSIONS

Production of biofuels involves burning significantly more fuel than the production of an equivalent amount of fossil fuel. If, with regards to CO_2 emissions, this is compensated by the fact that the fuel energy is renewable, this is not the case when it comes to emissions of other pollutants such as NOx or particulates. Globally

[8] Gas-to-liquids

[9] Institute of Arable Crop Research, Rothamsted

therefore, production of biofuels increases the emissions of such combustion-related pollutants. This has been described e.g. in the ETSU study [3]. There is no evidence that this could be compensated by significant reduction of emissions from vehicles. Of course the additional emissions take place mainly at the production plant rather than on the road but it may be a point to consider in a global programme such as CAFE [10].

Some studies have also mentioned emissions of methane associated with degradation of biomass in the soil. Indications are that these are relatively small and their contribution to total GHG emissions are only in the order of a few percent.

[10] EU Commission's "Clean Air For Europe" programme

5. CONCLUSIONS

Published studies on biofuels in the last decade give a globally consistent picture and do not reveal major changes in the key parameters. In terms of overall energy balance, production of RME and bio-ethanol gives modest net gains. Judicious use of by-products such as protein-rich residues for animal feed and wheat straw as an energy source can improve the efficiency of the process. However, it remains to be seen whether practicality and economics will support the use of straw or other biomass energy, and therefore what real energy and GHG savings can be achieved.

The proposed EU Directive target of 5.75% of biofuels by 2010 does not appear to be achievable on the basis of the EU-15 set-aside land area alone. This is even more so when only the net biofuel energy is considered. As there is no evidence of dramatic yield improvements, considerably more land would have to be devoted to biofuel crops. There are still considerable uncertainties with regards to the overall GHG balance. The real magnitude and effect of N_2O emissions is one point in question. Changes in the equilibrium content of carbon when land is put under cultivation can also have a major impact for several decades to come.

The rationale for producing bio-fuels rather than concentrating on bio-energy can be called into question. For example, optimising land use for the production of high-yield crops for heat and power generation is likely to be considerably more CO_2-effective than biofuels production. In the same way as the use of the various crude oil fractions has been optimised over the years, the use of land and of the different elements of crops may need to be carefully considered to make best use of a limited resource.

6. REFERENCES

1. CONCAWE (1995) Alternative fuels in the automotive market. Report No. 2/95. Brussels: CONCAWE

2. EU (2001) Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions on alternative fuels for road transportation and on a set of measures to promote the use of biofuels. COM(2001) 547

3. Gover, M.P. et al (1996) Alternative road transport fuels – a preliminary life-cycle study for the UK. ETSU report R92 volumes 1 & 2. Oxford: Energy Technology Support Unit

4. Levy, R.H. (1993) Les biocarburants. Report to the French government based on figures from the Commission Consultative pour la Production des Carburants de Substitution, 1991

5. Marland, G. and Turhollow, A.F. (1991) CO_2 emissions from the production and combustion of fuel ethanol from corn. *Energy* *16, 11/12, 1307-1316*

6. Reinhardt, G.A. and Zemanek, G. (2000) Ökobilanz Bioenergieträger – Basisdaten, Ergebnisse, Bewertungen. Heidelberg: IFEU-Institut

7. Reinhardt, G.A. and Jungk, N. (2001) Pros and cons of RME compared to conventional diesel fuel. Proceedings of the International Colloquium on fuels, 17-18 January 2001, Esslingen

8. Scharmer, K. and Gosse, G. (1996) Energy balance, ecological impact and economics of vegetable oil methylester production in Europe as substitute for fossil diesel. ALTENER programme commissioned by GET Germany and INRA France

9. Richards, I.R. (2000) Energy balances in the growth of oilseed rape for biodiesel and of wheat for bioethanol. Report for the British Association of Bio Fuels and Oils (BABFO). Ipswich: Levington Agriculture Ltd

10. EU (1994) Application of biologically derived products as fuels or additives in combustion engines. Publication No. EUR 15647 EN. Directorate-General XII Science, Research and Development

11. Pimentel, D. (2001) The limits of biomass utilization. In: The Encyclopaedia of Physical Science & Technology. New York: Academic Press

12. Argonne National Laboratory (2001) Well-to-wheel energy use and greenhouse gas emissions of advanced fuel/vehicle systems - North American Analysis. Detroit MI: General Motors Corporation

13. Ahlvik, P. and Brandberg, Å. (2001) Well-to-wheel efficiency for alternative fuels from natural gas or biomass. Publication No. 2001:85. Borlänge: Swedish National Road Administration

14. Metcalfe, P. and Bullard, M.J. (2001) Life-cycle analysis of energy grasses. *Aspects of Applied Biology 65, 29-37*

15. Jenkinson, D.S. et al (1987) Modelling the turnover of organic matter in long-term experiments at Rothamsted. *INTECOL Bulletin 15, 1-8*

APPENDIX 1 RME

Study reference		3	4		6&7	8			9
		ETSU	Levy		IFEU	Alterner			Levington
Case		3a	4a	4b		8a	8b	8c	
Yields									
Rapeseed	t/ha	3.20	3.00	3.50	3.09	3.50	3.00	3.50	4.08
RME	t/ha	1.18	1.18	1.37	1.14	1.32	1.13	1.32	1.51
Cake/meal	t/ha	1.86	1.77	2.07		1.33	1.14	1.33	2.37
Straw	t/ha	2.56	6.00	6.00		4.41	3.78	4.41	4.00
Energy									
Produced									
Assumed heating value	GJ/t								
RME		35.80	37.70	37.70	36.80	36.73	36.73	36.73	35.99
Cake/meal			17.35	17.35		24.04	24.04	24.04	
Straw total		15.00	13.80	13.80		13.70	13.70	13.70	28.92
Energy content	GJ/ha								
RME		42.4	44.3	51.8	42.1	48.5	41.6	48.5	54.35
Cake/meal			30.7	35.9	6.37	34.0	29.1	34.0	
Straw total		38.4	82.8	82.8	0.0	60.4	51.8	60.4	115.66
Consumed	GJ/ha	-42.8	-29.8	-32.2	-24.02	-32.2	-30.2	-28.7	-30.51
Agricultural fuel & machinery		-4.6			-2.48	-7.9	-7.5	-7.5	-4.69
Fertilisers		-13.4			-8.65	-10.3	-10.7	-7.4	-7.19
Agrochems/seeds		-0.2				-0.9	-0.7	-0.7	-0.37
Packaging									-0.28
Transport		-0.7			-1.74	-1.1	-1.0	-1.1	-0.72
Oil extraction		-10.0			-2.99	-6.1	-5.2	-6.1	
Processing		-13.9			-8.17	-6.0	-5.1	-6.0	-17.25
Energy saved from animal feed	GJ/t feed	1.99				2.94	2.94	2.94	1.32
Animal feed credit	GJ/ha	3.7			6.37	3.92	3.36	3.92	3.12
Other credits	GJ/ha				24.39				
Max straw for processing	GJ/ha	13.9	*4.5*	*4.8*		*4.8*	*4.8*	*4.8*	*6.90*
Balance									
No credits	GJ/ha	-0.39	14.52	19.55	18.05	16.32	11.37	19.85	23.84
	Ro	**1.01**	**0.67**	**0.62**	**0.57**	**0.66**	**0.73**	**0.59**	**0.56**
Conv. fuel prod.credit	Rcc	**-0.10**	**-0.10**	**-0.10**	**-0.10**	**-0.10**	**-0.10**	**-0.10**	**-0.10**
Animal feed credit	Rcf	**-0.09**			**-0.15**	**-0.08**	**-0.08**	**-0.08**	**-0.06**
Biomass credit	Rcs	**-0.33**	***-0.10***	***-0.09***		***-0.10***	***-0.12***	***-0.10***	***-0.13***
Energy used as diesel	t/ha	-0.98	-0.68	-0.74	-0.55	-0.74	-0.69	-0.66	-0.70
	t/t RME	-0.83	-0.58	-0.54	-0.48	-0.56	-0.61	-0.50	-0.46
Net amount of fossil diesel substituted	t/t RME								
No credits		**-0.01**	**0.28**	**0.33**	**0.36**	**0.28**	**0.23**	**0.34**	**0.36**
Conv. fuel prod.credit		**0.08**	**0.09**	**0.09**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**
Animal feed credit		**0.07**			**0.13**	**0.07**	**0.07**	**0.07**	**0.05**
Biomass credit		**0.27**	***0.09***	***0.08***		***0.08***	***0.10***	***0.08***	***0.10***
	l/lRME								
No credits	So	**-0.01**	**0.30**	**0.35**	**0.38**	**0.30**	**0.24**	**0.37**	**0.38**
Conv. fuel prod.credit	Scc	**0.09**	**0.09**	**0.09**	**0.09**	**0.09**	**0.09**	**0.09**	**0.09**
Animal feed credit	Scf	**0.08**			**0.14**	**0.07**	**0.07**	**0.07**	**0.05**
Biomass credit	Scs	**0.29**	***0.09***	***0.09***		***0.09***	***0.10***	***0.09***	***0.11***
GHG emissions	kg CO2/GJ RME	40.3	*44.7*	*41.3*	74.1	36.0	39.9	32.3	*37.3*
	t CO2eq/ha	1.71	*1.98*	*2.14*	3.12	1.75	1.66	1.56	*2.03*
Agricultural fuel & machinery		0.32			0.19				
Fertilizers		0.15			1.20				
Agrochems/seeds									
Field emissions		0.10			0.88				
Packaging									
Transport		0.06			0.13				
Oil extraction		0.58			0.18				
Processing		0.51			0.54				
Credit for by-products	kg CO2/GJ RME	4.53			11.17	4.47	4.47	4.47	*3.81*
Credit for animal feed	kg CO2/t					162	162	162	*87*
Credit for animal feed	t CO2eq/ha	0.19			0.47				
Other credits					1.44				
Credit for straw		*0.76*	*0.30*	*0.32*		*0.32*	*0.32*	*0.32*	*0.46*
Eq diesel on HV basis	kg CO2/GJ RME	80.0	*80.0*	*80.0*	80.0	80.0	80.0	80.0	*80.0*
Balance									
Base+Conv. fuel prod.credit	t CO2eq/ha	1.71	*1.98*	*2.14*	3.12	1.75	1.66	1.56	*2.03*
	net t CO2/ha	-1.68	*-1.57*	*-2.00*	-0.25	-2.13	-1.67	-2.32	*-2.32*
	Rg	**0.50**	***0.56***	***0.52***	**0.93**	**0.45**	**0.50**	**0.40**	***0.47***
Animal feed credit	Rgf	**-0.06**			**-0.14**	**-0.06**	**-0.06**	**-0.06**	***-0.05***
Biomass credit	Rgs	**-0.23**	***-0.08***	***-0.08***		***-0.08***	***-0.10***	***-0.08***	***-0.11***

Shading = actual figures from study reports

Italics = estimated figures

APPENDIX 2 ETHANOL

Study reference		3 ETSU	4 Levy						5 Marland	9 Levington	10 Commission		11 Pimentel	12 Argonne			13 Ecotraffic
Case			4.1a	4.1b	4.2a	4.2b	4.3a	4.3b	(LHV base)		10a	10b					
Crop		Wheat	Beet		Wheat		Corn			Wheat	Wheat	Beet	Corn	Corn	Wood	Grass	Wood
Yields	t/ha																
Grain/crop		8.00	66.00	78.00	7.00	9.00	7.00	9.50	7.47	8.96	5.42	87.70	7.96				
EtOH		2.19	5.28	6.24	1.93	2.48	2.03	2.75	2.20	2.47	1.65	3.75	2.42				
Cake/meal		3.31	1.12	1.33	2.80	3.60	2.60	3.50	0.40		2.30	4.10					
Gluten feed									1.73								
Oil									0.22								
Biogas																	
Straw/Biomass		4.24	4.36	5.14	6.50	6.50	9.91	13.45	0.00	6.50	7.70	48.00					
Energy																	
Produced																	
Assumed heating value	GJ/t																
EtOH		30.15	26.80	26.80	26.80	26.80	26.80	26.80	26.80	30.04	26.97	27.15	27.12				
Feed by-products			12.00	12.00	12.50	12.50	16.25	16.25									
Biogas																	
Straw/Biomass total		15.00	13.82	13.82	13.95	13.95	9.45	9.45		15.00	13.52	0.23					
Energy content	GJ/ha																
EtOH		66.12	141.5	167.2	51.6	66.3	54.4	73.7	58.9	74.2	44.5	101.8	65.6				
Feed by-products		6.0	13.5	15.9	35.0	45.0	42.3	56.9	5.7	0.0	10.1	32.3	0.0				
Biogas											9.6	14.7					
Straw/Biomass total		31.3	60.2	71.0	90.7	90.7	93.6	127.1	0.0	97.5	104.1	11.0	0.0				
Consumed	GJ/ha	-70.9	-127.1	-104.5	-47.2	-60.1	-52.5	-78.1	-51.6	-66.8	-56.1	-97.8	-108.6				
Agricultural fuel & machinery		-4.2							-4.9	-4.30	-26.20	-33.70	-22.80				
Fertilisers		-12.3							-10.6	-7.82			-13.00				
Agrochems/seeds		-1.6							-1.1	-1.97			-4.80				
Packaging										-0.45							
Transport		-1.3								-1.50			-4.50				
Oil extraction																	
Processing		-51.5							-34.9	-50.81	-29.90	-64.10	-63.50				
Energy saved from feed by-products	GJ/t feed	1.82							2.41		4.39	7.88					
	GJ/t EtOH	2.7							2.59		6.12	8.61					
	GJ/ha	6.0	*8.84*	*10.45*	*5.10*	*6.55*	6.26	8.43	5.68		10.10	32.30					
Max straw for processing	GJ/ha	31.3	*8.3*	*9.8*	*23.6*	*30.1*	*26.2*	*39.1*		*35.57*	*20.93*	11.00					
Balance																	
No credits	GJ/ha	-4.75	14.40	62.76	4.39	6.21	1.90	-4.40	7.29	7.35	-11.60	4.00	-42.97				
	Ro	**1.07**	**0.90**	**0.62**	**0.91**	**0.91**	**0.97**	**1.06**	**0.88**	**0.90**	**1.26**	**0.96**	**1.65**	**0.59**	**1.56**	**1.26**	**1.25**
Conv. fuel prod.credit	**Rcc**	**-0.15**	**-0.15**	**-0.15**	**-0.15**	**-0.15**	**-0.15**	**-0.15**	**-0.15**	**-0.15**	**-0.15**	**-0.15**	**-0.15**				
Animal feed credit	**Rcf**	**-0.09**	***-0.06***	***-0.06***	***-0.10***	***-0.10***	***-0.12***	***-0.11***	**-0.10**	***0.00***	**-0.23**	**-0.32**					
Straw credit	**Rcs**	**-0.47**	***-0.06***	***-0.06***	***-0.46***	***-0.45***	***-0.48***	***-0.53***		**-0.48**	***-0.47***	***-0.11***			**-1.55**	**-1.23**	**-1.15**
Energy used as gasoline	t/ha	-1.64	-2.93	-2.41	-1.09	-1.39	-1.21	-1.80	-1.19	-1.54	-1.30	-2.26	-2.51				
	t/t EtOH	-0.75	-0.56	-0.39	-0.57	-0.56	-0.60	-0.66	-0.54	-0.62	-0.79	-0.60	-1.04				
Net amount of fossil gasoline substituted	t/t EtOH																
No credits		**-0.05**	**0.06**	**0.23**	**0.05**	**0.06**	**0.02**	**-0.04**	**0.08**	**0.07**	**-0.16**	**0.02**	**-0.41**				
Conv. fuel prod.credit		**0.10**	**0.09**	**0.09**	**0.09**	**0.09**	**0.09**	**0.09**	**0.09**	**0.10**	**0.09**	**0.09**	**0.09**				
Animal feed credit		**0.06**	***0.04***	***0.04***	***0.06***	***0.06***	***0.07***	***0.07***	**0.06**	***0.00***	**0.14**	**0.20**					
Biomass credit		**0.33**	***0.04***	***0.04***	***0.28***	***0.28***	***0.30***	***0.33***		***0.33***	***0.29***	***0.07***					
	l/l EtOH																
No credits	**So**	**-0.05**	**0.07**	**0.25**	**0.06**	**0.06**	**0.02**	**-0.04**	**0.08**	**0.07**	**-0.17**	**0.03**	**-0.43**				
Conv. fuel prod.credit	**Scc**	**0.11**	**0.10**	**0.10**	**0.10**	**0.10**	**0.10**	**0.10**	**0.10**	**0.11**	**0.10**	**0.10**	**0.10**				
Animal feed credit	**Scf**	**0.07**	***0.04***	***0.04***	***0.06***	***0.06***	***0.08***	***0.07***	**0.06**	***0.00***	**0.15**	**0.21**					
Biomass credit	**Scs**	**0.35**	***0.04***	***0.04***	***0.30***	***0.30***	***0.32***	***0.35***		***0.35***	***0.31***	***0.07***					
GHG emissions	kg CO2/GJ EtOH	50.4	*59.7*	*41.5*	*60.8*	*60.2*	*64.1*	*70.4*	75.4	*60*	*84*	*64*	*110*				
	t CO2eq/ha	3.33	*8.45*	*6.94*	*3.14*	*3.99*	*3.49*	*5.19*	4.44	*4.44*	*3.73*	*6.50*	*7.22*				
Agricultural fuel & machinery		0.29							0.45								
Fertilizers		0.12							0.61								
Agrochems/seeds									0.10								
Field emissions		0.08							0.00								
Packaging																	
Transport		0.07															
Oil extraction																	
Processing		2.77							3.28								
Credit for animal feed	t CO2/t EtOH								0.23								
	kg CO2/GJ EtOH	4.7	*4.2*	*4.2*	*3.7*	*4.7*	*7.8*	*10.6*	8.5		*15.1*	*21.1*					
	t CO2eq/ha	0.31	*0.59*	*0.69*					0.50		*0.67*	*2.15*					
Emissions avoided by straw	t CO2eq/ha	1.63	*0.55*	*0.65*	*1.57*	*2.00*	*1.74*	*2.59*		*2.36*	*1.39*	*0.73*					
Credit for straw firing	kg CO2/GJ EtOH	24.6	*3.9*	*3.9*	*30.4*	*30.1*	*32.1*	*35.2*		*31.9*	*31.3*	*7.2*					
Eq gasoline on HV basis	kg CO2/GJ EtOH	84.7	84.7	84.7	84.7	84.7	84.7	84.7	84.7	*84.7*	*84.7*	*84.7*	*84.7*				
Balance																	
Base+Conv. fuel prod.credit	t CO2eq/ha	3.33	*8.45*	*6.94*	*3.14*	*3.99*	*3.49*	*5.19*	4.44	*4.44*	*3.73*	*6.50*	*7.22*				
	net t CO2/ha	-2.27	*-3.54*	*-7.22*	*-1.23*	*-1.62*	*-1.12*	*-1.05*	-0.55	*-1.84*	*-0.04*	*-2.12*	*1.66*				
	Rg	**0.59**	***0.70***	***0.49***	***0.72***	***0.71***	***0.76***	***0.83***	**0.89**	***0.71***	***0.99***	***0.75***	***1.30***				
Animal feed credit	**Rgf**	**-0.06**	***-0.05***	***-0.05***	***-0.04***	***-0.06***	***-0.09***	***-0.13***	**-0.10**	***0.00***	***-0.18***	***-0.25***					
Biomass credit	**Rgs**	**-0.29**	***-0.05***	***-0.05***	***-0.36***	***-0.36***	***-0.38***	***-0.42***		***-0.38***	***-0.37***	***-0.08***					

Shading = actual figures from study reports

Italics = estimated figures