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SCHOOL OF ENVIRONMENT AND DEVELOPMENT

SHEFFIELD HALLAM UNIVERSITY

EVALUATION OF THE COMPARATIVE ENERGY, GLOBAL WARMING AND SOCIO-ECONOMIC COSTS AND BENEFITS OF BIODIESEL

Final Report

for the Department for Environment, Food and Rural Affairs

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Report No. 20/1

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EXECUTIVE SUMMARY

1. This study was commissioned by the Department for the Environment, Food and Rural Affairs and has been undertaken by the Resources Research Unit of Sheffield Hallam University. Its aims are to provide an independent, comprehensive and rigorous evaluation of the comparative energy, global warming and socio-economic costs and benefits of producing biodiesel from oilseed rape in the United Kingdom. It is set within the context of present debate about the current (20p per litre) and possible increased (40p per litre) levels of fuel excise duty derogation for biodiesel as a road transport fuel. As commissioned, representative results are derived using existing work rather than by performing entirely new evaluations.

2. The study focuses on specific aspects of the current debate. In particular, implications for fossil fuel depletion have been addressed by estimating primary energy inputs. Environmental concerns have been considered by examining tailpipe emissions and by evaluating total carbon dioxide and total greenhouse gas emissions that are implicated in global climate change. Primary energy savings and net savings of carbon dioxide and greenhouse gas emissions have been derived as indicators of comparative benefits. Other possible benefits which have been investigated include the impact on the rural economy as represented by the generation of total local income from the cultivation of particular crops. Costs are interpreted in terms of total government subsidies.

3. The costs and benefits of producing biodiesel from oilseed rape are assessed in relation to a number of alternative options. Initial comparison is between biodiesel and ultra low sulphur diesel which is likely to be the most prominent type of conventional diesel used by road transport in the United Kingdom. Further comparisons are drawn with relevant measures that are intended to mitigate carbon dioxide and greenhouse gas emissions. This includes comparison with compressed natural gas as an alternative road transport fuel. Particular comparison is made with another biomass form of renewable energy, or biofuel, consisting of wood chips derived from short rotation coppice and used for electricity and heat generation. Illustrative energy efficiency measures are also considered including condensing gas boilers and glass fibre loft insulation.

4. A number of studies which report measurements of tailpipe emissions from a variety of road transport vehicles using conventional diesel and biodiesel. It was concluded that consistent differences could not be established definitively for the tailpipe emissions of carbon monoxide, hydrocarbons including methane and non-methane volatile compounds, oxides of nitrogen, sulphur dioxide and particulates. The reasons for this are differences between test conditions and fundamental variability in observed measurements. At present, the only clear consensus is that tailpipe emissions of carbon dioxide are balanced by the take up of carbon dioxide by oilseed rape during its growth.

5. The need to determine total carbon dioxide and greenhouse emissions which arise during the production of biodiesel from oilseed rape is set within the established framework of life cycle assessment, as specified by the International Standard ISO 14040 series. The basic principles, definitions, conventions and methods of calculation of life cycle assessment are summarised. Against this background, a review was conducted of eleven existing studies which adopt life cycle assessment or related approaches to the evaluation of energy and global warming aspects of biodiesel production from oilseed rape.

6. Existing studies were subjected to both qualitative and quantitative assessment. It was concluded that work undertaken by the Institut für Energie- und Umweltforschung (Institute for Energy and Environmental Research; IFEU) in Germany was the most detailed, had the greatest coverage and was the most transparent. It was decided that this work provided the most suitable basis for deriving representative results for biodiesel production from oilseed rape in the United Kingdom.

7. The starting point for deriving representative results was the formulation of a flow chart describing the processes involved in the conventional production (based on solvent extraction) of biodiesel from oilseed rape and specifying assumed typical values for the intermediate products (raw rapeseed and rapeseed oil), the final main product (biodiesel), and co- , by- and waste products (rape straw, rape meal and glycerine) associated with this process chain. All other data and assumptions, which are intended to reflect typical current conditions in the United Kingdom, are clearly summarised. In particular, the allocation procedures for the main, co- , by- and waste products are stated. Subsequent estimates are obtained for the total primary energy input (16,269 $\pm$ 896 MJ per tonne of biodiesel), the total carbon dioxide emissions (916 $\pm$ 52 kg CO_2 per tonne of biodiesel) and the total greenhouse gas emissions (1,516 $\pm$ 88 kg equivalent CO_2 per tonne of biodiesel).

8. The relative contributions to the total primary energy input, the total carbon dioxide emissions and greenhouse gas emissions from different activities which contribute to biodiesel production are illustrated in Figures I, II and III, respectively. It can be seen that, in terms of primary energy inputs and carbon dioxide emissions, the single largest contribution is associated with the esterification process (especially as a result of methanol consumption). The next highest single contribution is the manufacture of nitrogen fertiliser. This order is reversed for the greenhouse gas output, for which nitrogen fertiliser production and use is responsible for just over half of total emissions.

Figure I Representative Primary Energy Inputs for Biodiesel by Conventional Production from Oilseed Rape in the United Kingdom

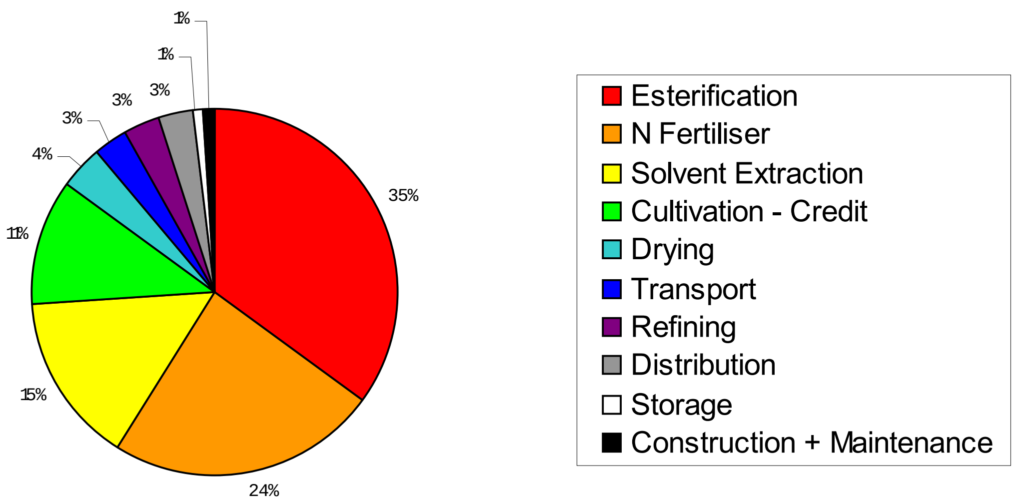


Figure II Representative Carbon Dioxide Outputs for Biodiesel by Conventional Production from Oilseed Rape in the United Kingdom

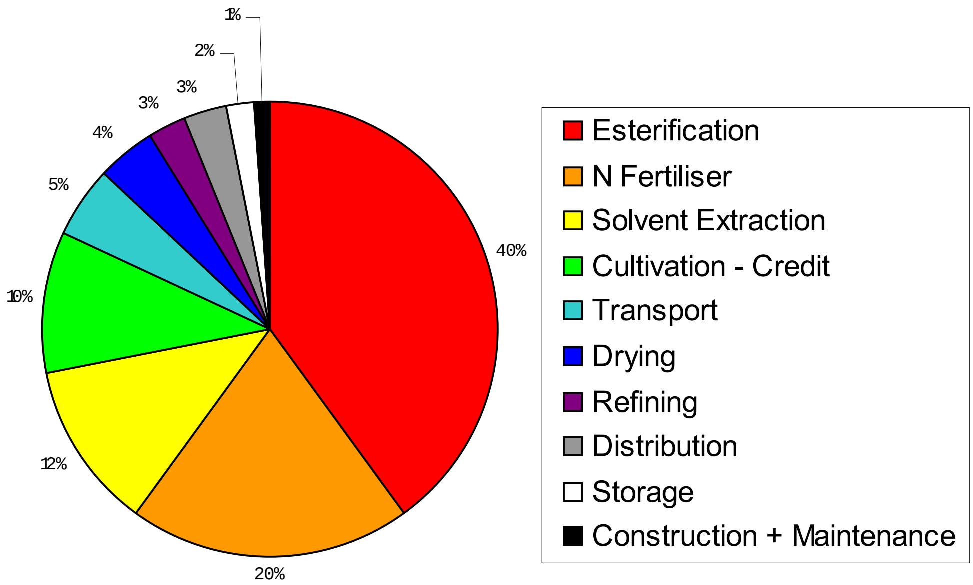
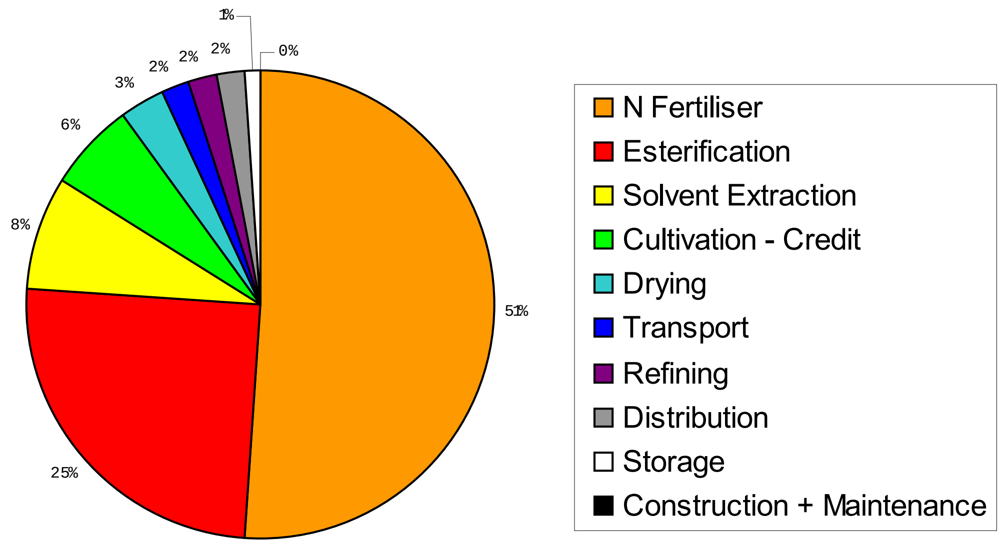


Figure III Representative Greenhouse Gas Outputs for Biodiesel by Conventional Extraction from Oilseed Rape in the United Kingdom

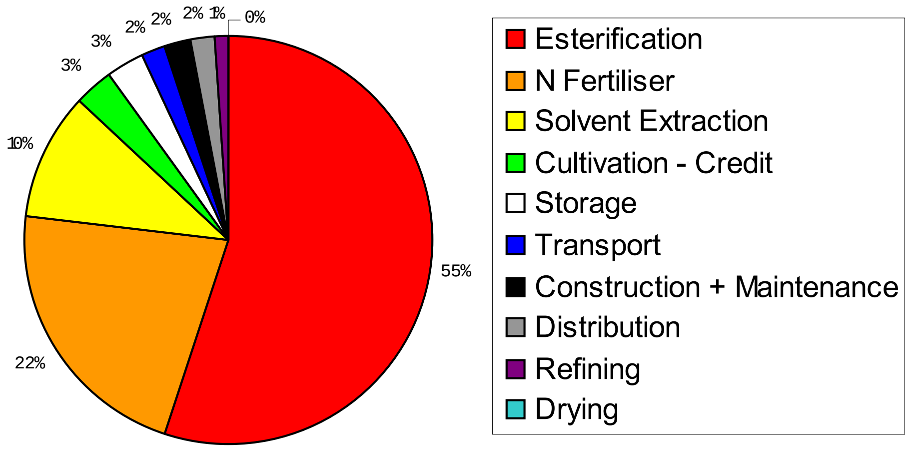


9. Possible reductions in total primary energy input, and carbon dioxide and greenhouse gas emissions are evaluated by considering modifications to the conventional production of biodiesel from oilseed rape. These modifications consist of low-nitrogen cultivation of oilseed rape, the use of rape straw as an alternative heating fuel in the processing of biodiesel, and the replacement of convention diesel by biodiesel in agricultural operations and road transport vehicles. Assuming that such modified production can be achieved in practice, reduced estimates are derived for the total

primary energy input (7,750 ± 638 MJ per tonne of biodiesel), the total carbon dioxide emissions (437 ± 42 kg CO_2 per tonne of biodiesel) and the total greenhouse gas emissions (702 ± 53 kg equivalent CO_2 per tonne of biodiesel).

10. Significant changes in the contributions to the total primary energy input, and carbon dioxide and greenhouse gas emissions are apparent from Figures IV, V and VI, respectively. In particular, the importance of contributions from esterification, and the manufacture and use of nitrogen fertiliser is magnified further. Along with contributions from solvent oil extraction, these three activities account for the majority of total primary energy inputs, and carbon dioxide and greenhouse gas emissions.

Figure IV Representative Primary Energy Inputs for Biodiesel by Modified Production from Oilseed Rape in the United Kingdom



11. The effect of varying the assumed values of key factors on these representative results is explored by means of sensitivity analysis. The factors considered are the rapeseed yield, the energy and carbon data for nitrogen fertiliser manufacture, the cultivation reference system, and price ratios of raw rapeseed to rape straw, rapeseed oil to rape meal and biodiesel to glycerine. This demonstrates the relative importance of nitrogen fertiliser in the calculations. Additionally, the influence of rapeseed yield is illustrated, especially in terms of the greater significance of lower rather than higher values of yield for representative results. It is noted that the effects of nitrogen fertiliser application rates and yield may be linked and that values for these factors must be chosen to reflect typical national practice instead of special trials.

12. The main initial results derived in this study consist of the following; the energy requirement (total primary energy input per unit of output), the carbon requirement (total carbon dioxide emissions per unit output) and the greenhouse gas requirement (total greenhouse gas emissions per unit output). Representative values for the energy requirement of biodiesel from conventional and modified production of 0.44 ± 0.02 MJ per MJ (net) and 0.21 ± 0.02 MJ per MJ (net), respectively, are obtained in this study. Comparison with values from existing studies is provided in Figure VII. This study also derives representative values for the carbon requirement of biodiesel by conventional and modified production of 0.025 ± 0.001 kg CO_2 per MJ (net) and 0.012 ± 0.001 kg CO_2 per MJ (net), respectively. These results are compared with values from existing studies in Figure VIII. The estimated values of the representative greenhouse gas requirement of biodiesel by conventional and modified production are 0.041 ± 0.002 kg equivalent CO_2 per MJ (net) and 0.019 ± 0.001 kg equivalent CO_2 per MJ (net), respectively.

Figure V Representative Carbon Dioxide Outputs for Biodiesel by Modified Production from Oilseed Rape in the United Kingdom

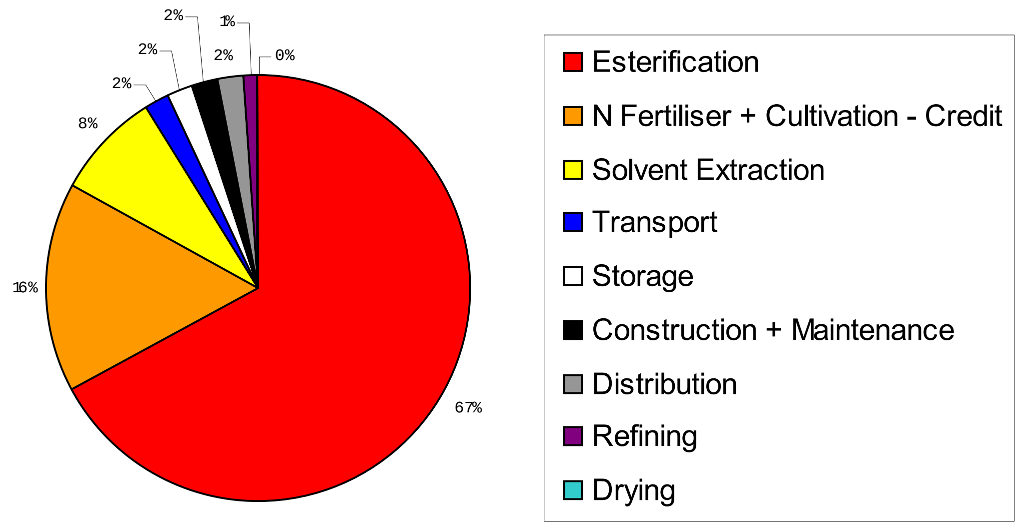


Figure VI Representative Greenhouse Gas Emissions for Biodiesel by Modified Production from Oilseed Rape in the United Kingdom

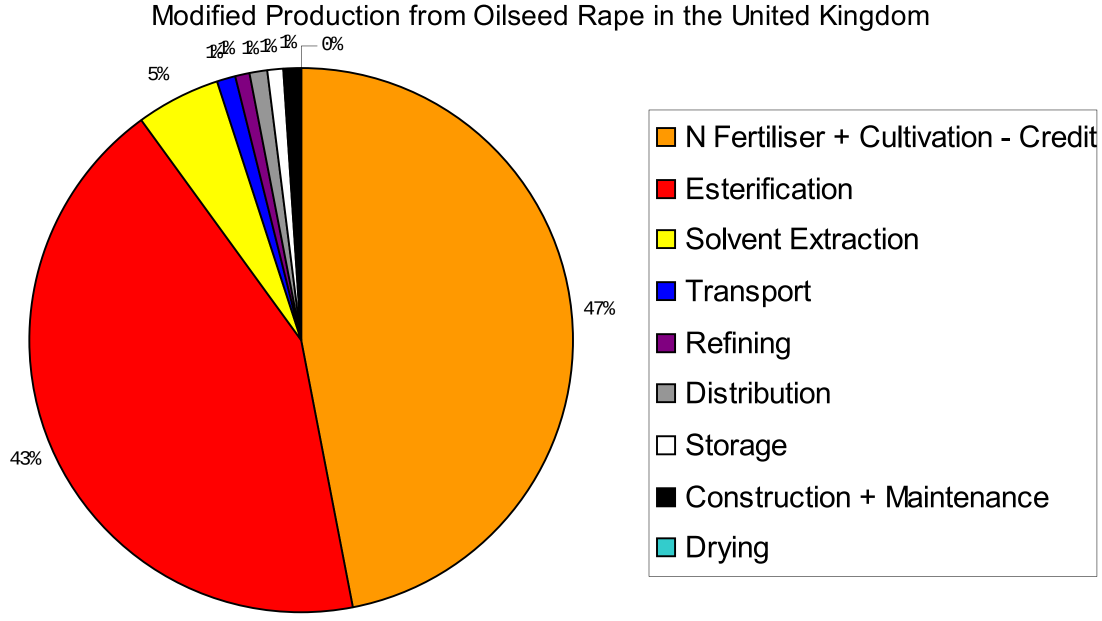


Figure VII Comparison of Energy Requirements of Biodiesel Produced from Oilseed Rape

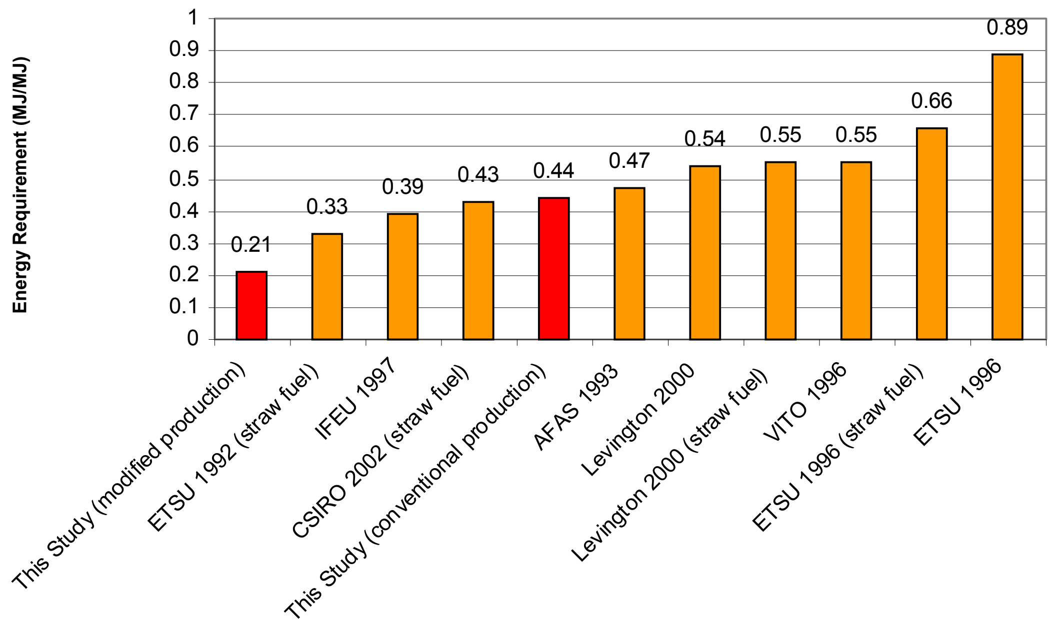
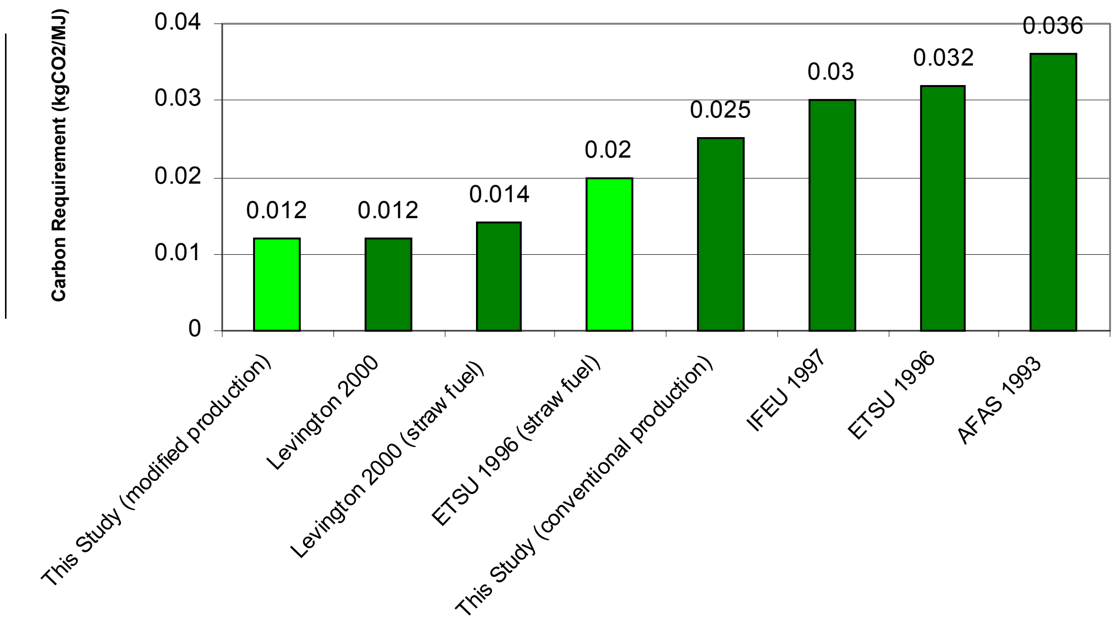
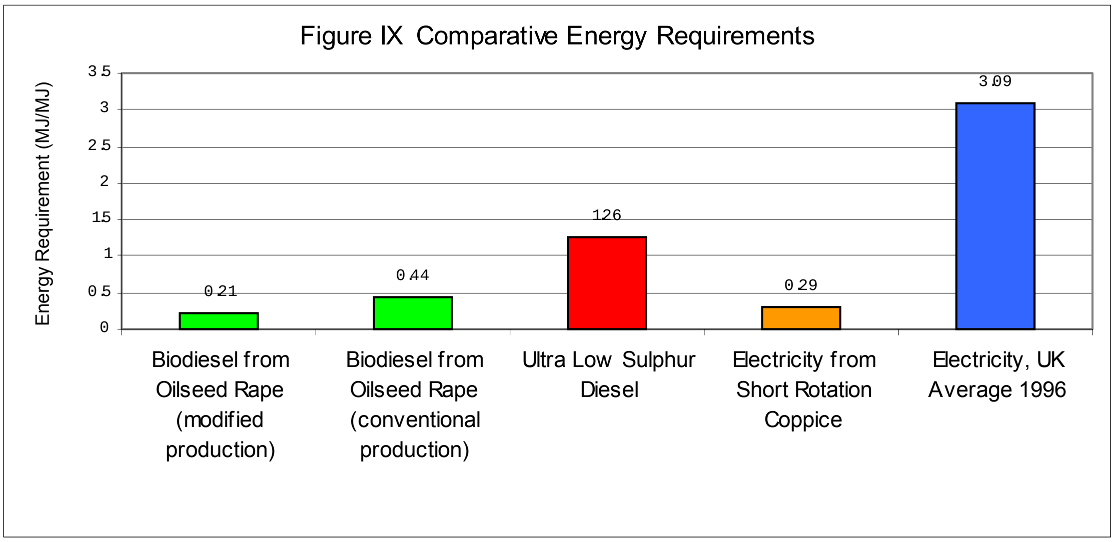
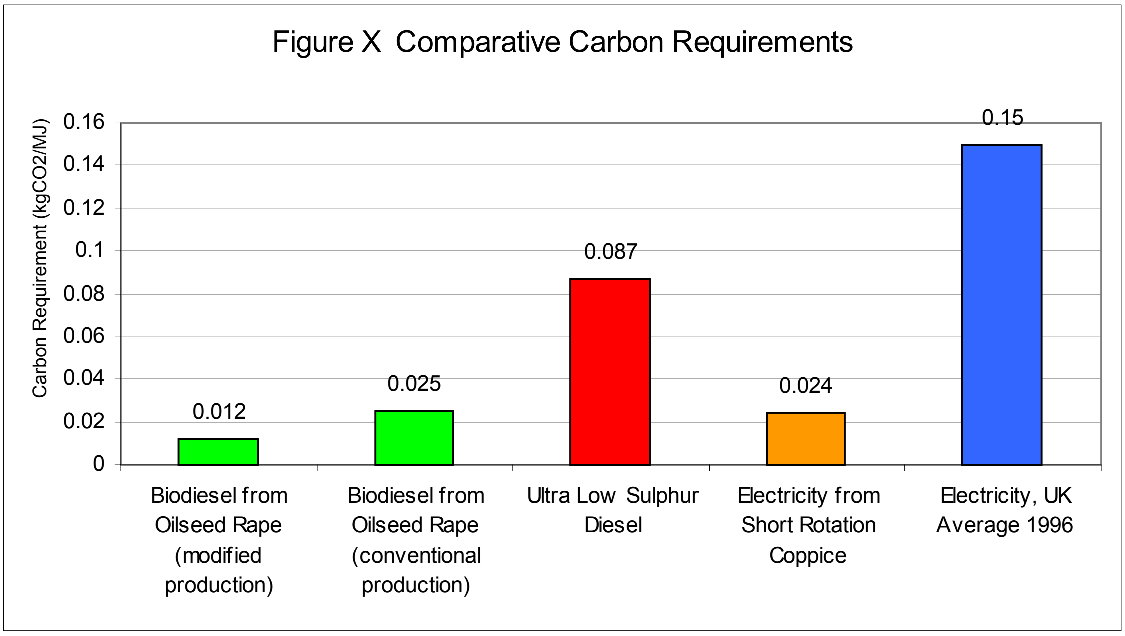


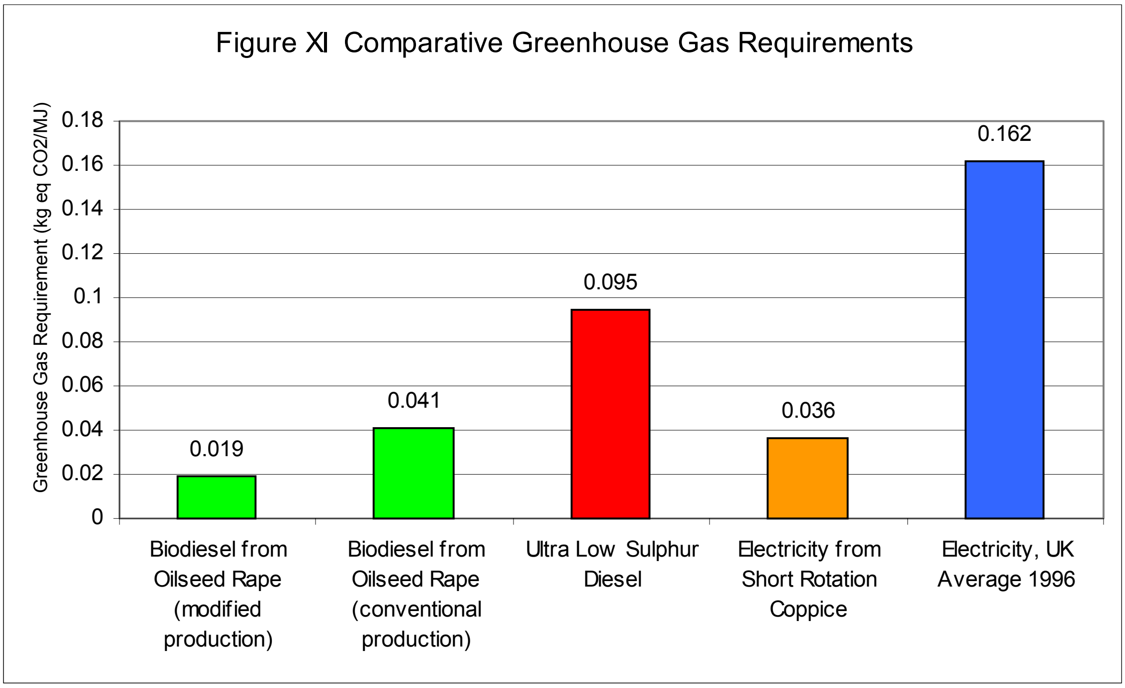
Figure VIII Comparative Carbon Requirements for Biodiesel Produced from Oilseed Rape



13. Energy, carbon and greenhouse gas requirements for biodiesel produced from oilseed rape, ultra low sulphur diesel derived from crude oil, electricity generated by gasification from short rotation coppice wood chips, and average electricity supplies in the United Kingdom are illustrated and compared in Figures IX, X and XI, respectively. Relative benefits of biodiesel from oilseed rape and electricity from short rotation coppice are assessed by contrasting these biofuels with comparative references consisting of ultra low sulphur diesel and average electricity supplies, respectively. From this, it can be shown that 63% or 83% reductions in fossil fuel depletion, 72% or 86% net savings in carbon dioxide emissions and 56% or 80% net savings in greenhouse gas emissions would be achieved by replacing ultra low sulphur diesel with biodiesel from conventional or modified production, respectively. By comparison, the benefits of displacing average electricity supplies in the United Kingdom with electricity from short rotation coppice wood chip amount to a 91% reduction in fossil fuel depletion, a 84% net saving in carbon dioxide emissions and a 78% net saving in greenhouse gas emissions.

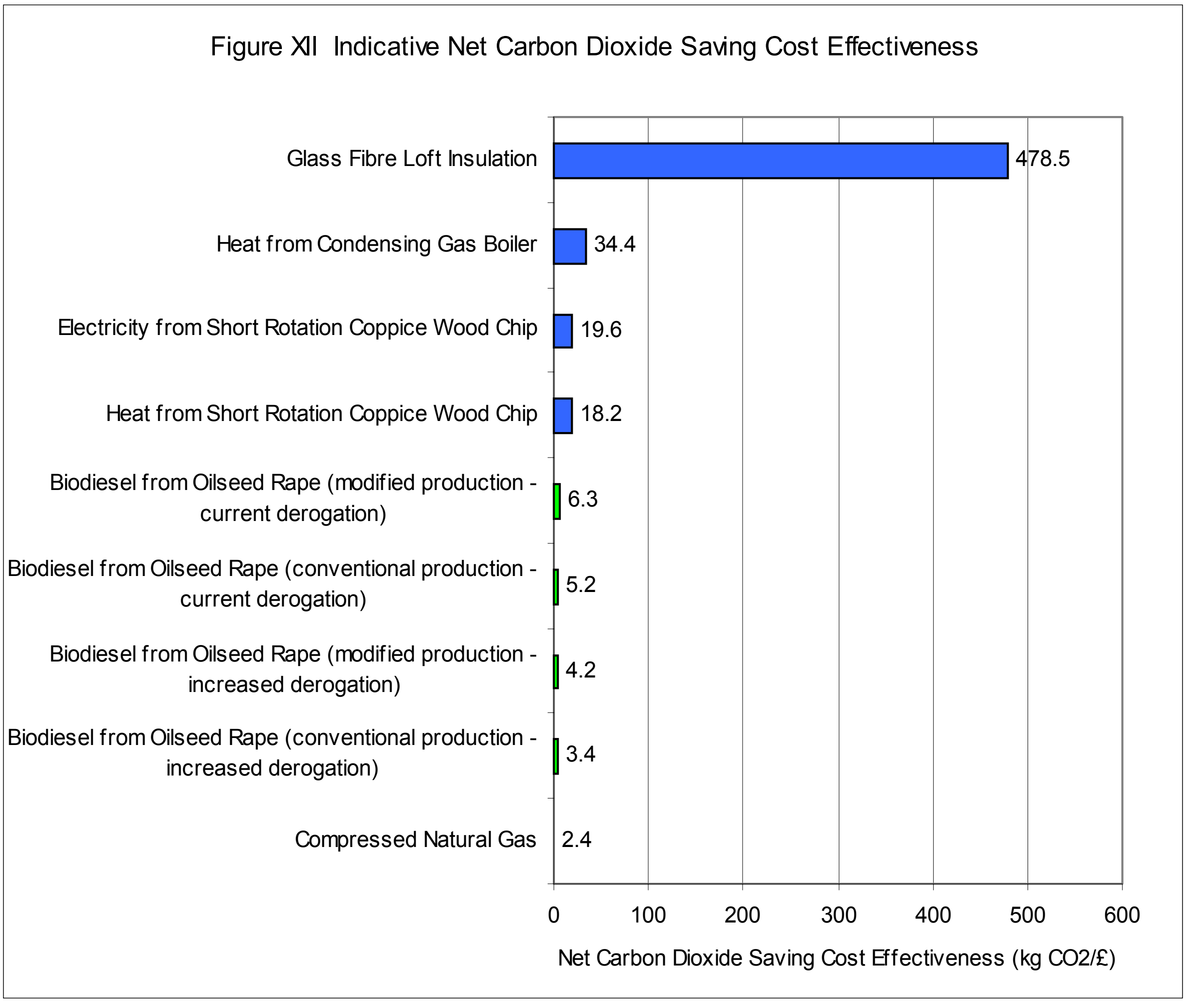






14. Environmental benefits can be assessed in terms of their respective costs. In this instance, such costs are measured in terms of indicative net carbon dioxide and greenhouse gas saving cost effectiveness. This cost effectiveness is equal to the ratio of the net carbon dioxide or greenhouse gas savings of a particular option to the total government subsidy which it receives. Relevant subsidies include all support payments to agriculture, grant schemes and market stimulation mechanisms, as well as the derogation of fuel excise duty. In order to calculate these ratios, it is necessary to compare the total carbon dioxide or greenhouse gas emissions of an option (for example, biodiesel) against those of an alternative option, or comparative reference (for example, ultra low sulphur diesel). The net carbon dioxide and greenhouse gas emissions cost effectiveness of biodiesel are calculated at current (20 pence per litre) and increased (40 pence per litre) levels of fuel excise duty derogation. These results are compared with those for compressed natural gas, heat and electricity from short rotation coppice wood chip, condensing gas boilers and glass fibre loft insulation. The indicative results are presented in Figures XII and XIII.

15. The relative impact of biodiesel production from oilseed rape on the rural economy is addressed by evaluating the ratio of total net annual income to total government subsidy. The net annual income is equal to total farm revenue less off-farm expenditures and the total impact of this income is determined by means of the rural multiplier which indicates the additional income generated as cash flows through the local economy. It is noted that existing assessments of these considerations are limited and lack detail. However, some appropriate data are reported on the net annual incomes for growing oilseed rape and short rotation coppice. Additionally, approximate values of multipliers are also established. Subsequent analysis indicates values of cost effectiveness of rural economic impact for oilseed rape cultivated for biodiesel production of 1.67 £ income per £ total subsidy, with an increased fuel excise duty derogation of 40 pence per litre. This can be compared with values of 2.05 £ income per £ total subsidy for short rotation coppice grown for energy use.



16. In addition to these specific conclusions, a number of relevant recommendations are made in the study. Clarification of comparative tailpipe emissions is required and this should be based on any new tests which provide results, qualified by actual variability, for biodiesel and other fully specified road transport fuels. Results of future life cycle assessment and related studies of other biofuels, such as bioethanol, should be taken into account and compared with current results for biodiesel. Values of net carbon dioxide and greenhouse gas saving cost effectiveness for other biofuels and a wider range of energy efficiency measures should be compared with the current values for biodiesel. The comparison of results should be set within the context of a comprehensive, complementary and coherent framework for carbon dioxide and greenhouse gas emissions mitigation in the United Kingdom. Finally, the comparative economics of oilseed rape and short rotation coppice cultivation should be monitored, along with any specific evaluation of the rural multiplier and the effects of more recent indirect government subsidies, such as new grants for wood fuel schemes.

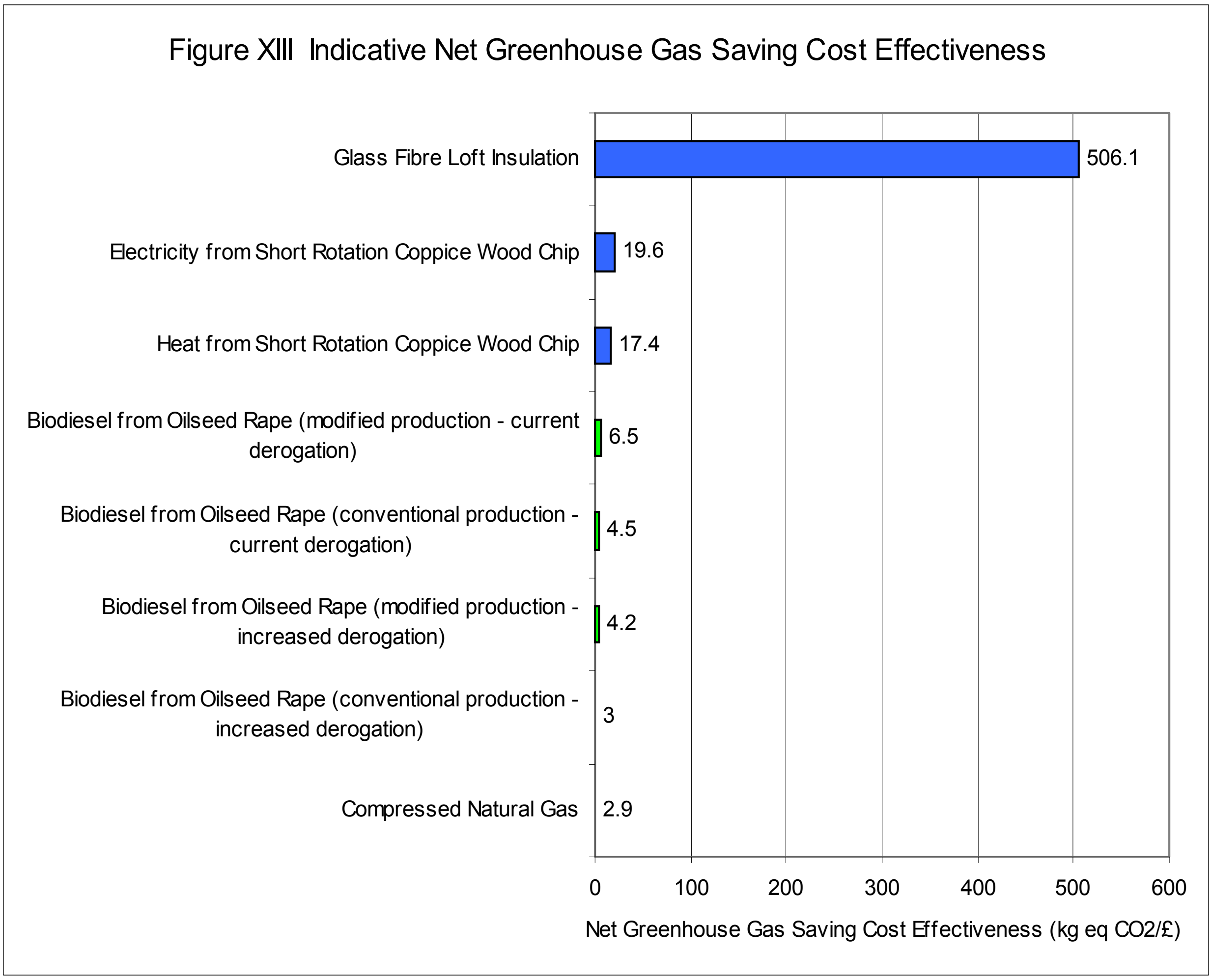


Figure XIII Indicative Net Greenhouse Gas Saving Cost Effectiveness
Glass Fibre Loft Insulation
Electricity from Short Rotation Coppice Wood Chip
Heat from Short Rotation Coppice Wood Chip
Biodiesel from Oilseed Rape (modified production - current derogation)
Biodiesel from Oilseed Rape (conventional production - current derogation)
Biodiesel from Oilseed Rape (modified production - increased derogation)
Biodiesel from Oilseed Rape (conventional production - increased derogation)
Compressed Natural Gas
506.1
19.6
17.4
6.5
4.5
4.2
3
2.9
0
100
200
300
400
500
600
Net Greenhouse Gas Saving Cost Effectiveness (kg eq CO2/£)

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The authors would like to point out that the information and results presented in the final version of this report are entirely their own responsibility.

CONTENTS PAGE

1. INTRODUCTION

1.1 Context

Biodiesel is an alternative transport fuel which can be derived from various types of biomass including animal fats, waste cooking oil and **oilseed rape (OSR)**. Since animal fats and waste cooking oil are available as either waste or by-products, the supply of these sources of biodiesel can be largely dependent on other factors. Due to opportunities for its cultivation as a main product on a fairly wide range of agricultural land, OSR has been proposed as the main possible future source of biodiesel. In its principal use, biodiesel is a potential replacement for **conventional diesel**, which in this instance, is the term used to describe diesel which is produced from crude oil. Elsewhere, such diesel is sometimes referred to as mineral or fossil diesel. In contrast to conventional diesel which is derived from a depleting energy resource, in the form of a fossil fuel, biodiesel produced from OSR grown in a sustainable manner could be seen as a potential renewable source of energy which offers prospects for reducing the emissions of **carbon dioxide (CO_2)** which, as a **greenhouse gas (GHG**), is implicated in global climate change. Indeed, in some European Union (EU) member states, principally Austria, France, Germany and Italy, biodiesel production has been encouraged and promoted, through government policies and incentives, as an alternative transport fuel. In such instances, national government support is frequently justified in terms of saving imported oil, reducing CO_2 emissions, improving urban air quality, and assisting diversification, re-orientation and innovation in farming.

Typically, government support takes the form of a **derogation** (reduction or exemption) of **excise duty** on biodiesel used as a transport fuel. Such support is necessary because biodiesel produced from OSR is not currently economic in comparison with conventional diesel. There is fundamental interest in alternative transport fuels, including biodiesel, within the European Commission (EC), mainly due to the urgent need for practical action to address increasing CO_2 emissions from the transport sector which undermine commitments to the Climate Change Convention and the Kyoto Protocol. This has resulted in a proposal for a EC Directive for promoting the use of alternative transport fuels derived from biomass and reducing rates of excise duty on such fuels (Ref. 1). However, there is considerable debate about the extent and, indeed, justification of this support for biodiesel produced from oilseed rape as a GHG-mitigation measure. In general, some questions have been raised over the magnitude of benefits which might be derived from producing and using such biodiesel, and the extent of excise duty derogation which these may justify.

In the United Kingdom (UK), a derogation of 20.00 pence per litre has recently been announced for the excise duty on biodiesel (Ref. 2). This reduces the excise duty payable on biodiesel to 25.82 pence per litre compared to the normal level of excise duty of 45.82 pence per litre on conventional diesel (Ref. 3). However, it has been argued that this degree of derogation is not sufficient to promote the commercial development of the biodiesel industry based on OSR production in the UK (Ref. 4). This government subsidy for biodiesel, in the form of excise duty derogation, can be compared with potential benefits which are numerous and diverse. The most significant of these can be characterised, generally, as **energy**, **environmental** and **social benefits**. The specification of such benefits is, of course, a comparative exercise since they must be measured relative to current practice, such as the production and use of conventional diesel, other GHG-mitigation measures and the impact on the local rural economy of cultivating different crops. Ideally, the relative costs of derogation should be set at a level which can be justified by the comparison of the combination of all such benefits.

However, as a result of their fundamental diversity, it is not possible to combine all comparative benefits together in a simple manner. Instead, it is necessary to concentrate on those benefits which are associated with prominent issues. It can be argued that, at the moment, the most prominent issues for the UK are fossil fuel resource depletion, emissions of CO_2 and other GHG, and regeneration of local rural economies. A considerable number of studies have examined the production and use of biodiesel from oilseed rape from the perspective of these particular issues. In particular, numerous life cycle assessment and related studies have been conducted on biodiesel and many different estimates of the relative energy, CO_2 and GHG savings of biodiesel have been generated. Currently, there is no agreement on these estimates which provides a sound basis of consensus for setting a justified level of derogation for biodiesel in the UK. Hence, there is a need for a study which examines existing work thoroughly, investigates essential assumptions, takes into account typical practice and formulates robust representative results that can be offered as a basis for informed debate within a policy development framework where alternatives are compared.

1.2 Aims and Objectives

As specified in the original commissioning of this study, its aims are to provide an independent, comprehensive and rigorous evaluation of the comparative energy, global warming and socio-economic costs and benefits of producing biodiesel from OSR in the UK, to compare results with those for other relevant "green" fuels and relevant energy saving measures, and to evaluate findings the case for changes in current government policy. These aims are accomplished by means of the following objectives:

- to identify existing life cycle assessment and related studies of the production and use of biodiesel from OSR and their comparison with the production and use of conventional diesel derived from crude oil, compressed natural gas and relevant energy saving measures,

- to review critically these studies in terms of their relevance to the situation in the UK and their completeness of coverage, especially in relation to the full life cycles and supply chains,

- to isolate the prominent assumptions and parameters used in these studies,

- to adjust, where necessary, prominent assumptions and parameters to ensure that results are relevant to the situation in the UK,

- to update, where appropriate, input data using information available from existing databases,

- to evaluate the sensitivity of results to realistic variations in prominent assumptions and parameters,

- to establish representative results for energy and global warming costs and benefits of production and use of biodiesel in comparison with conventional diesel, compressed natural gas and other relevant energy saving measures, qualified by error bars,

- to compare the use of biodiesel and conventional diesel in relation to tailpipe emissions, safety, biodegradability and ease of use by reference to results from existing research,

- to estimate the cost effectiveness of the production and use of biodiesel in the UK as a greenhouse gas abatement measure and as an energy security measure in comparison with other selected energy saving measures,

- to investigate issues of diversity of supply and related agricultural aspects related to the production of biodiesel in the UK,

- to determine the socio-economic costs and benefits of the production of biodiesel from OSR, especially in relation to the magnitude of the impact on the rural economy through the multiplier effect,

- to contrast the development of biodiesel production in other EU member states,

- to compare the effectiveness of current derogation of biodiesel with support for other "green" fuels and with other means to incentivise bioenergy production in the UK, and

- to facilitate a consultation over the nature of this study and the results produced with representatives of relevant government departments and industry groups.

This Final Report presents the results of the study, as defined by these aims and objectives, and taking into account the feedback received through consultation after release of the Draft Report in May 2002.

1.3 Structure of the Study

In terms of the aims and objectives of this study, its subsequent structure can be outlined. The main characteristics of biodiesel and conventional diesel are summarised and compared in Section 2. The basic aspects of life cycle assessment are outlined in Section 3, with particular emphasis on features which are specifically relevant to biodiesel production from OSR. Existing life cycle assessment and related studies of biodiesel from OSR are evaluated, qualitatively and quantitatively, in Section 4. Representative primary energy inputs and CO_2 and GHG outputs are derived and the sensitivity of results to variations in key parameters is investigated in Section 5. Comparative costs and benefits, in the form of fossil fuel resource depletion, CO_2 and GHG emissions and net CO_2 and GHG saving cost effectiveness, are presented in Section 6. Agricultural impacts are considered in Section 7 which examines the potential benefits for local rural economies of growing oilseed rape and other energy crops. Conclusions and recommendations are provided in Section 8. Finally, reviews of existing life cycle assessment and related studies, summaries of their main results, and detailed data for the life cycle assessment of ammonium nitrate fertiliser production, and the conventional and modified production of biodiesel from OSR in the UK are contained in Appendices A to E, respectively.

2. FUEL CHARACTERISTICS

It is necessary to establish some of the main fuel characteristics of biodiesel and conventional diesel which it can replace in order to provide a clear basis for subsequent comparison. As with all major fuels, official specifications have been formulated for biodiesel so that producers and users have standard information on important fuel specifications including **fuel density** and **calorific value**. A summary of these specifications is provided in Table 1 which also presents comparative data for conventional low sulphur diesel and conventional ultra low sulphur diesel. It will be noted that there are significant differences between the calorific value of biodiesel and conventional diesel. In this study, fuel specifications for FAME (fatty acid methyl ester) biodiesel are assumed to be applicable in the UK.

Table 1 Fuel Specifications for Biodiesel and Conventional Diesel

Specification	Biodiesel (FAME)	Conventional Low Sulphur Diesel (> 0.005% S)	Conventional Ultra Low Sulphur Diesel (< 0.005% S)
Density (kg/l)	0.88[a, b, c]	0.85[d]	0.83[d]
Net Calorific Value (MJ/kg)	37.27[a]	42.38[a]	42.38[a]
Gross Calorific Value (MJ/kg)	37.84[b, c]	45.60[d]	45.60[d]

Notes

(a) From data quoted in Ref. 5.

(b) From data quoted in Ref. 6.

(c) From assumed conversion factors presented in Ref. 7.

(d) Average 1999 values presented in Ref. 7.

It is possible to make a direct comparison between biodiesel and conventional diesel on the basis of calorific value. However, in many instances, a more convenient and appropriate basis of comparison would be in terms of the distance travelled by road vehicles using these alternative fuels. Indeed, many studies use this particular basis of comparison. Unfortunately, such comparison can be problematic since it depends, crucially, on the relative performance of road vehicles using biodiesel and conventional diesel. Considerable research has been conducted on performance, especially in relation to resulting **tailpipe emissions** from road vehicles using alternative fuels. Results depend on a range of factors, including the category of road vehicle and the so-called "driving cycle" which reflects urban, rural, motorway, etc., driving conditions. These factors are specified in the form of standardised tests so that meaningful results can be derived, under theoretically reproducible circumstances, and used for subsequent comparison. However, it should be noted that performance varies with changes in road vehicle technology and, particularly, engine design. Hence, due to continual improvements, comparative results are likely to change with time. Consequently, results quoted in terms of distance travelled do not form a fixed basis for comparison.

The comparison of tailpipe emissions from road vehicles using biodiesel and conventional diesel is, obviously, very important and results can be obtained from a number of different studies. Results for a selection of road vehicles, reported in the UK in 1998, are shown in Table 2 (Ref. 8). In this instance, comparison is between biodiesel and conventional diesel, probably in the form of low sulphur diesel, although the original source is not wholly explicit. In general, this comparison indicates marginal reductions in carbon monoxide (CO), hydrocarbon (HC) and particulate (PM) emissions from road vehicles using biodiesel instead of conventional diesel. For biodiesel, emissions of oxides of nitrogen (NO_X) are slightly higher, whilst net CO_2 and sulphur dioxide (SO_2) emissions are, effectively, eliminated. It should, however, be noted that reductions in SO_2 emissions would be less marked with subsequent introduction of ultra low sulphur diesel. Further comparison is provided in Table 3, using results reported in Germany in 1997, for a car using biodiesel and conventional diesel (Ref. 9). Information provided by the original source suggests that, in this case, conventional diesel consists of low sulphur diesel (0.089%S). These results indicate similar levels of CO, HC, NO_X and nitrous oxide (N_2O) emissions for biodiesel and conventional diesel. There is a marginal reduction in PM emissions and a more substantial decrease in SO_2 emissions. As previously, net CO_2 emissions are eliminated.

Table 2 Sample of Tailpipe Emissions from Road Vehicles using Biodiesel and Conventional Diesel for the UK (Ref. 8)

Vehicle	Fuel	CO_2 (g/km)	CO (g/km)	HC[b] (g/km)	NO_x (g/km)	SO_2[c] (g/km)	PM[d] (g/km)
Car	Conventional Diesel[a]	139	0.42	0.08	0.64	0.05	0.15
Car	Biodiesel	0[e]	0.37	0.07	0.77	0	0.13
Light Goods Vehicle	Conventional Diesel[a]	267	1.33	0.33	1.39	0.09	0.24
Light Goods Vehicle	Biodiesel	0[e]	1.16	0.24	1.67	0	0.24
Heavy Goods Vehicle	Conventional Diesel[a]	853	3.92	0.45	13.06	0.28	1.07
Heavy Goods Vehicle	Biodiesel	0[e]	2.63	0.36	15.02	0	0.72
Bus (old)	Conventional Diesel[a]	1119	16.04	5.03	15.86	0.38	1.55
Bus (old)	Biodiesel	0[e]	10.75	4.03	18.24	0	1.04
Bus (new)	Conventional Diesel[a]	885	4.26	0.44	14.09	0.29	1.06
Bus (new)	Biodiesel	0[e]	2.86	0.35	16.21	0	0.71

Notes

(a) Low sulphur diesel produced from crude oil.

(b) HC = hydrocarbon emissions including methane.

(c) SO_2 emissions assume complete oxidation of sulphur in diesel.

(d) PM = particulate emissions.

(e) Net CO_2 emissions; tailpipe emissions of CO_2 from vehicles using biodiesel balanced by take up of CO_2 during growth of oilseed rape crop.

Table 3 Tailpipe Emissions from Road Vehicles using Biodiesel and Conventional Diesel for Germany (Ref. 9)

Vehicle	Fuel	CO_2 (g/km)	CO (g/km)	HC[b] (g/km)	NO_x (g/km)	SO_2[c] (g/km)	PM[d] (g/km)	N_2O (g/km)
Car	Conventional Diesel[a]	146	0.50	0.08	0.52	0.041	0.06	0.032
Car	Biodiesel	0[e]	0.50	0.08	0.52	0.005	0.04	0.032

Notes

(a) Ultra low sulphur diesel produced from crude oil.

(b) HC = hydrocarbon emissions including methane.

(c) SO_2 emissions assume complete oxidation of sulphur in diesel.

(d) PM = particulate emissions.

(e) Net CO_2 emissions; tailpipe emissions of CO_2 from vehicles using biodiesel balanced by take up of CO_2 during growth of oilseed rape crop.

Unfortunately, both these studies are fairly typical with regard to a lack of clarity in specifying the particular type of conventional diesel against which biodiesel has been compared. Furthermore, specific comparison with ultra low sulphur diesel is essential since this is becoming the more prominent type of conventional diesel used in the UK. However, explicit comparisons between biodiesel and ultra low sulphur diesel are limited. A recent study is undertaken in Australia attempts to provide such a comparison by combining and adjusting results from a variety of tests and other studies of alternative road transport fuels (Ref. 6). These results are presented in Table 4 which shows that CO, HC, NO_X and PM emissions are higher for buses using biodiesel compared to ultra low sulphur diesel. Strangely, a comparison of SO_2 emissions is not provided, although the elimination of net CO_2 emissions is again demonstrated. Hence, a somewhat confusing picture emerges from this limited investigation of comparative results for tailpipe emissions. It would appear that such comparisons can be inconclusive and that representative results are not available. This might be expected given the potential variations in the type of road vehicle, engine design, technical modifications, driving conditions, etc. Additionally, as illustrated by Table 5, some studies report substantial variations in tailpipe emission results for the same type of vehicle under that same test conditions (Ref. 6). The explanation for such variability and the subsequent effects on comparisons between tailpipe emissions for biodiesel and conventional diesel is that, apart from CO_2 emissions, only trace amounts of pollutants are being measured.

Table 4 Tailpipe Emissions from Road Vehicles using Biodiesel and Ultra Low Sulphur Diesel for Australia (Ref. 6)

Vehicle	Fuel	CO_2 (g/km)	CO (g/km)	HC[(a)] (g/km)	NO_x (g/km)	PM[(b)] (g/km)
Bus	Ultra Low Sulphur Diesel	1406	1.41	0.53	14.32	0.16
Bus	Biodiesel	0[(c)]	7.68	0.86	17.20	0.60

Notes

(a) HC = methane and non-methane volatile organic compounds (NMVOC).

(b) PM = particulate emissions.

(c) Net CO_2 emissions; tailpipe emissions of CO_2 from vehicles using biodiesel balanced by take up of CO_2 during growth of oilseed rape crop.

Table 5 Variability of Tailpipe Emissions in Road Vehicle Tests (Ref. 6)

Vehicle	Fuel	Variation[(a)]	CO_2 (g/km)	CO (g/km)	VOC[(b)] (g/km)	NO_x (g/km)	PM[(c)] (g/km)
Bus	Conventional Diesel	Minimum	-17%	-68%	-38%	-46%	-92%
		Maximum	+33%	+275%	+35%	+73%	+124%
Bus	Biodiesel	Minimum	(d)	-43%	-22%	-62%	-50%
		Maximum	(d)	+55%	+19%	+39%	+114%

Notes

(a) Variation about an average value.

(b) VOC = volatile organic compounds.

(c) PM = particulate emissions.

(d) Net CO_2 emissions; tailpipe emissions of CO_2 from vehicles using biodiesel balanced by take up of CO_2 during growth of oilseed rape crop.

Despite this, pollutants other than CO_2 emissions can be significant considerations. Since PM emissions have been linked with human respiratory diseases, it has been suggested that the specific use of biodiesel in urban environments may offer important advantages. This may be one reason why some countries have promoted biodiesel use in buses and taxis in inner city areas. Additionally, it has been concluded that biodiesel itself is **non-toxic** and has no apparent health risks (Ref. 6). Furthermore, it is **biodegradable** which is a particularly attractive feature when such fuel is involved in incidental and accidental spillages (Ref. 6). Since there is only relatively limited experience of the regular use of biodiesel, it is not possible to make final conclusions about its ease of use. Some initial problems were reported from transport fleets using biodiesel in terms of the softening or failure of engine components made of rubber, rubber compounds or elastomers (Refs. 6 and 8). However, it would seem that such problems can be avoided by replacing these components selectively in older engines with parts made of more compatible materials now used in new engines. Although the distinctive smell of biodiesel has been noted by some users, this does not appear to present a significant obstacle to its widespread use. So far, no other important issues have been reported which would prevent biodiesel being used as an alternative to conventional diesel for road transport.

Whereas it can be argued that lower PM emissions of biodiesel and its biodegradability confer notable advantages of the use of this transport fuel over conventional diesel, these advantages may be regarded as relatively small. Indeed, apart from one particular consideration, it can be concluded that there is no clear consensus on conclusive differences of direct consequences in the use of biodiesel and conventional low sulphur and ultra low sulphur diesel. However, this one particular consideration is significant since it concerns CO_2 and total GHG emissions. As shown in Tables 2 and 3, there are no effective direct CO_2 emissions associated with the use of biodiesel. Obviously, as a carbon-based fuel, biodiesel releases CO_2 when burnt. However, such CO_2 emissions balance the CO_2 absorbed by the OSR crop which is the source of the biomass feedstock used to produce biodiesel. As such, biodiesel is frequently referred to as a "**carbon neutral**" transport fuel. Although such a description may seem appropriate from this somewhat limited perspective, it would be incorrect to assume that there are zero CO_2 emissions associated with the use of biodiesel. Consequently, it cannot be assumed that significant CO_2 and GHG savings, equivalent to avoided CO_2 and GHG emissions of conventional diesel use, as indicated by the results illustrated in Table 2, can automatically be achieved by using biodiesel as an alternative transport fuel. The well-known reason for this is that fossil fuels are consumed in the production of biodiesel and this involves the release of CO_2 over and above the CO_2 absorbed by the growing OSR crop. In order to determine the relative CO_2 savings, as well as relative fossil fuel depletion and other environmental impacts, it is necessary to compare all aspects of the life cycles of biodiesel and conventional diesel. This can only be accomplished by means of life cycle assessment.

3. LIFE CYCLE ASSESSMENT

3.1 Basic Principles

Life cycle assessment is an established technique for quantifying the total environmental impacts of the provision of a product or service from original resources to final disposal, or so-called "cradle-to-grave". Its background can be traced back at least as far as the development of energy analysis in the 1970's. During this particular time when concern about **fossil fuel resource depletion** was increasing due to the first oil shock, energy analysis emerged as a means of calculating the total energy required to provide products and services. Many of the approaches and conventions incorporated into life cycle assessment have their roots in the principles of energy analysis. Broader environmental concerns and implementation of environmental management have resulted in increased interest in life cycle assessment. Amongst numerous reasons for conducting life cycle assessment studies is the possibility of comparing the **total environmental impacts** of alternative products or services. As such, life cycle assessment is a potential tool for assisting policy analysis and decision-making. Its practical use in this and other applications has been considerably enhanced by the creation of an official framework for life cycle assessment in the form of the **International Standard ISO 14040 series** (Refs. 10 to 13). This framework establishes the definitions and conventions of life cycle assessment, and provides practical advice on methods of calculation.

In total, life cycle assessment is composed of six major stages, consisting of goal and scope definition, life cycle inventory analysis, life cycle impact assessment, life cycle interpretation, reporting and critical reviewing. The **goal** of a life cycle assessment establishes the intended application of subsequent results, the reasons for generating these results and the expected audience for these results. The **scope** of a life cycle assessment provides full specification of the study and the product or service which is being examined. In particular, the scope indicates the "**functional unit**" which is being investigated by providing a clear, full and definitive description of the product or service which enables subsequent results to be interpreted correctly and compared with other results in a meaningful manner. In relation to this study, the functional unit could be a kilogram or litre of biodiesel or conventional diesel. Alternatively, the functional unit could be an amount of energy available, typically a MJ (mega joule or 10^6 joules), when either fuel is burnt, or a given distance travelled by a road vehicle using either fuel. Life cycle **inventory analysis** involves quantifying relevant inputs and outputs of the life cycle of a product or service. This is a significant activity in life cycle assessment since it usually requires considerable data collection and analysis. Various life cycle inputs and outputs must be quantified, including energy resources, such as fossil fuels, and emissions to atmosphere, such as CO_2 and other GHG. The purpose of **life cycle impact assessment** is to evaluate the significance of potential impacts from the life cycle of the product or service. This is achieved by **classification**, which involves assigning life cycle inputs and outputs to impact categories, **characterisation**, which consists of combining results within impact categories, and **weighting**, which incorporates further aggregation of results, where possible. All the findings are brought together in life cycle interpretation prior to **reporting** and **critical reviewing** which are the final major stages of life cycle assessment.

In this study, the relevant aspects of life cycle assessment are the first two stages; goal and scope definition, and life cycle inventory analysis. From the perspective of the aims established in Section1.2 and in relation specifically to life cycle assessment, the **goal of this study** consists of evaluating the energy and global warming costs of producing biodiesel from OSR in the UK and comparing results with those of other relevant "green" fuels and relevant energy saving measures. This goal is set within the context of current government policy and, hence, the audience is composed of policy-makers and those who have a particular interest in the development of the biodiesel industry in the UK. The major aspect of the **scope for this study** is the functional unit which is taken to be 1 tonne of biodiesel produced from OSR and distributed to relevant sales points for subsequent use in road transport vehicles in the UK. Although results may be presented in terms of other units of weight (kilogram) or volume (litre), it is proposed that the main comparison with conventional diesel, other energy sources and energy efficiency measures is by the unit of energy delivered or saved (MJ). As discussed in Section 1.1, it can be argued that the main issues which must be addressed by life cycle assessment here are energy consumption resulting in **fossil fuel resource depletion** and **global climate change** linked to emissions of CO_2 and other GHG. Consequently, the application of life cycle assessment in this study is strictly limited to these particular inputs and outputs.

3.2 Inputs and Outputs

Since energy, and CO_2 and other GHG emissions are the principal considerations here, it is necessary to provide related definitions to ensure clarity with subsequent results (Ref. 14). The appropriate measure of fossil fuel resource depletion is **primary energy** which consists of the amount of energy available in resources in their natural state, such as coal, natural gas and oil deposits in the ground. As such, it is an indicator of energy resource availability which is greater than the energy provided by fuels and electricity used by consumers, known as **delivered energy,** and the energy services required by these consumers, referred to as **useful energy**. For convenience, energy analysis provides a terminology for deriving and presenting energy results. If the product or service under investigation is specified in physical terms, then the energy result is referred to as the **energy requirement**, which is equal to the total amount of primary energy involved in the provision of a given product or service. Depending on the nature of the product or service, the energy requirement can be measured in different physical units, such as weight (MJ/kg), volume (MJ/l) or energy (MJ/MJ). The total amount of primary energy consists of the sum of the **direct energy** due to the use of fuels and electricity, the **indirect energy** associated with the production of materials, equipment, etc., and the energy contained in any **feedstocks**, such as chemicals and materials derived from fossil fuels. An additional consideration is that the energy requirement of a fuel can also include the calorific value of the fuel, in which case the result is referred to as the gross energy requirement. In this study, an essential comparison needs to be made between the primary energy input to biodiesel production (the energy requirement of biodiesel) and the primary energy input to conventional diesel production (the gross energy requirement of conventional diesel).

The calculation of CO_2 emissions from the provision of a product or service is based, principally, on the evaluation of emissions from the use of fuels and electricity. This is achieved by means of suitable **carbon coefficients**, or combustion emission factors, which indicate the CO_2 emissions produced per unit of energy available when a fuel is burnt or electricity is generated (such as kg CO_2/MJ). Similar coefficients are available for assessing other emissions, including other GHG. Although such carbon coefficients include CO_2 and other GHG emissions from electricity generation, they usually exclude CO_2 and other GHG emissions from other fuel cycle activities, such as the construction, operation and maintenance of infrastructure for processing fuels. In order to clarify the basis of subsequent calculations, the term gross carbon coefficient can be adopted to represent the total CO_2 emissions produced per unit of energy available from fuels or electricity (also measured as kg CO_2/MJ). Elsewhere, this is referred to as the total upstream and combustion emission factor (Ref. 15).

Using these coefficients and factors in life cycle assessment, it is possible to derive the **carbon or GHG requirement** of a product or service which consists of the total CO_2 or GHG emissions associated with the provision of a physical unit of the product or service. The total CO_2 emissions equal the **direct CO_2 emissions** from the combustion of fuels and the **indirect CO_2 emissions** due to the generation of electricity and the manufacture of materials, equipment, etc. In addition to CO_2 emissions from the direct or indirect combustion of fossil fuels, other sources of CO_2 emissions, such as the manufacture of cement and nitrogen fertiliser, are usually taken into account. The matter of feedstocks in such CO_2 calculations is more complicated than in primary energy calculations. Whether any CO_2 emissions arise from feedstocks which store carbon originally derived from fossil fuels depends on the ultimate fate of this carbon. If the carbon always remains stored in the feedstock, then it is excluded from calculations. However, if the feedstock is eventually burnt or decomposes naturally, the CO_2 released must be included. Additionally, the carbon in fossil fuels used as feedstocks in chemical processes may be released as CO_2 emissions as a result of chemical reactions. As can be seen, actual calculation procedures depend on specific circumstances. Similar considerations apply to the evaluation of other GHG emissions.

3.3 Process Chains

The central feature of a life cycle assessment is the **process chain** which summarises the main activities in the provision of a product or service. The process chain reflects the life cycle of the product or service from the original natural resources, or "cradle", through actual use, and on to eventual disposal, or "grave". In the case of a liquid transport fuel, the issue of eventual disposal is irrelevant since it is almost entirely consumed during its use. Some disposal activities may be considered as a result of incidental and accidental spillages. Even so, under normal circumstances, the majority of the fuel should be consumed in combustion processes. However, this does not mean that disposal does not, effectively occur since most of the combustion products, which are exhaust gases, are released into the environment. Fortunately, life cycle assessment recognises these as outputs which are accounted along with other outputs and inputs to the process chain.

For a product such as a liquid transport fuel, the process chain consists of a sequence of activities, starting with the provision of the basic raw material and ending with a suitable product, distributed and available for use in suitable road transport vehicles. It should be noted that the actual use of the fuel in a vehicle could be included in the process chain and subjected to life cycle assessment. Clearly, vehicle emissions must be taken into account but, apart from these, it is usually assumed that no significant engine modifications are required for the use of a fuel such as biodiesel. Hence, when comparing biodiesel with conventional diesel, this stage can be excluded. For this study, the process chain for biodiesel production consists of OSR cultivation, transportation from farm to mill, drying, storage, solvent extraction of rapeseed oil, refining, esterification, and transportation to points of distribution and sale. The process chain for ultra low sulphur diesel, which is the fuel which biodiesel is most likely to displace, involves exploration and extraction from crude oil deposits, transportation from oilfield to refinery, refining including hydro-cracking, and transportation to points of distribution and sale.

3.4 System Boundaries

Life cycle inventory analysis is based, primarily, on **systems analysis** which treats the process chain as a sequence of sub-systems that exchange inputs and outputs. A key feature of systems analysis is the definition of **systems boundaries** which are drawn around complete systems or sub-systems in order to identify inputs and outputs prior to quantification. The application of systems boundaries might, at first, seem like a self-evident and simple exercise. However, even for quite uncomplicated process chains, the issue of systems boundaries is an important and potentially complex consideration. The reason for this is that almost any activity requires inputs, ranging from raw materials to sophisticated machinery. These must be provided by other activities or, from the perspective of systems analysis, other systems. In an industrial economy, there are links, immediately or remotely, between any one activity and all the other activities in the economy. Hence, when preparing a life cycle inventory, it is, in theory, necessary to trace all these connections in order to account for all the accumulated inputs and outputs.

For instance, when producing a life cycle inventory of the primary energy inputs to oilseed rape cultivation, it is necessary to consider the farm machinery as well as the fuel used by these machines. Primary energy is consumed as a result of the fuels and electricity used in the factories which manufacture agricultural equipment. Such factories also require raw materials such as steel which itself involves the consumption of further primary energy through the fuels and electricity used in the steelworks. This process continues indefinitely and it may seem to present insurmountable problems for the calculation of total primary energy inputs and, similarly, with CO_2 and other GHG outputs. Fortunately, there is a practical solution to this which, in effect, involves checking the relative contribution of successively removed systems in the process chain. In general, successive contributions diminish in relative magnitude and it is often possible to draw the systems boundary around a fairly small group of systems connected to the main process chain. For example, it might be found that the primary energy inputs of fuels and agrochemical used in cultivation are very important, whereas those of farm machinery manufacture and maintenance are considerably less significant. The method for tracing and accounting for each connected system within a process chain is referred to as **process analysis**, whereas another method called **statistical analysis**, which is based on input-output analysis of complete economic systems, provides a way of deriving approximate results that incorporate the effects of all the connections (Ref. 14).

3.5 Reference Systems

One particular aspect of life cycle assessment which needs to be considered for the production of biodiesel from OSR is the matter of **reference systems**, which are used to determine **credits** for alternative activities that are avoided or displaced by the main process under investigation. It should be noted that reference systems and their resulting credits must be taken into account for any aspect of the process chain which will have an alternative use if not involved in providing the product or service in question. Land is a typical aspect which attracts the use of reference systems in life cycle assessment. For example, the land which is used for growing OSR could be used for some other purpose. At one extreme, it could be left fallow, under current set-aside regulations, so that only relatively small primary energy inputs and associated CO_2 and GHG emissions would arise due to occasional mowing. At the other extreme, the land could be used for growing an energy-intensive crop which would result in relatively high primary energy inputs and associated CO_2 and GHG emissions. In the former case, the primary energy, CO_2 and GHG credits would be fairly small and, in the latter, they might be quite significant. Hence, having accepted the need to apply reference systems and subsequent credits, it is necessary to determine which is should be chosen. Although there is no absolute rule, it is important to take into account the broader implications and policy considerations of any choice of reference system. If OSR for biodiesel production is, in current circumstances, most likely to be grown on set-aside land which will be left fallow, then this is clearly the appropriate reference system. If the economic conditions exist for expanding biodiesel production dramatically so that OSR is grown on land normally used for cultivating energy-intensive crops, then this might seem to indicate the correct choice of reference system. However, this then raises the question of whether such energy-intensive crops are still in demand and, therefore, where they will be produced. This concern applies particularly to food crops, which are essential over the long term, even if temporary surpluses exist in certain areas. As such, this would require the introduction of broader and more complex considerations into policies towards biodiesel production. Above all, the eventual choice of reference systems and subsequent credits should reflect current economic reality.

3.6 Allocation Procedures

Process chains which involve the provision of more than one product or service present an important issue for life cycle assessment. This is because it is necessary to divide inputs and outputs between each product or service. The ways in which this might be achieved are referred to as **allocation procedures** and considerable attention is devoted to the nature of these procedures in the literature, especially ISO 14041 (Ref. 11). It is important to recognise at the very beginning that there is no single allocation procedure which is appropriate for all circumstances. In economics, the problem is resolved, mainly, by using prevailing market prices determined by relevant demand to allocate costs between different products and services from a single process. In relation to products specifically, economic distinctions are drawn, effectively, between the **main product** which attracts the greatest revenue, **co-products** which receive equal revenues, **by-products** which result in smaller revenues, and **waste products** which provide little or no revenue. Although this approach to allocation can be adopted in life cycle assessment, it is not necessarily the automatic choice. The reasons for this are, chiefly, due to concerns about the fundamental effects of relative price fluctuations on the results of life cycle assessment and an inclination to base allocation procedures on relatively fixed physical rather than varying economic relationships between multiple products or services.

Consequently, various allocation procedures are available in life cycle assessment. Most are based on a common feature which is shared by the multiple products or services. For example, the mass, volume or calorific value of products can be used, although such simple bases for allocation need to be justified satisfactorily. In cases where all the products are fuels, such as petroleum products produced by an oil refinery, allocation by relative output and calorific value can be regarded as appropriate. However, allocation by this means for products which might have calorific values but are not, in fact, used as fuels is quite tenuous and not really suitable. Of course, most allocation procedures are applied in instances where multiple products or service share no common feature. Hence, it would appear that the most preferred allocation procedure is the one which uses a **substitution approach**. This involves identifying the main process for producing a co-product, by-product or, even, a waste product. The inputs and outputs of this main process are then treated as effective credits which are subtracted from the life cycle inventory of the process chain under investigation. This allocation procedure recognises that the co-products, by-products or waste products are, in practice and in economic terms, substituting for the equivalent product derived from its main source. Although this allocation procedure increases the amount of work required to undertake a life cycle assessment study, it is fundamentally sound and widely adopted. Unfortunately, the main drawback with the substitution approach is that it cannot be used when co-products, by-products or waste products are not produced by any main process. In other words, such products are always regarded as co-products, by-products or waste products. In such difficult cases, it is necessary to revert to simpler allocation procedures, of which allocation by market price and subsequent revenue may be the most appropriate.

It should be noted that the choice of allocation procedures for the life cycle assessment of biodiesel produced from OSR is a major consideration. This is because of the numerous co-products, by-products and waste products generated by this means of biodiesel production. In addition to raw rapeseed harvested from cultivation, rape straw is also produced. Whilst this straw is mainly treated as a waste product, it could be used in a variety of ways including combustion as a fuel, whereby displacing energy derived from fossil fuels. During the extraction of crude rapeseed oil from dried rapeseed, rape meal or cake is produced. This is a marketable co-product which is used mainly as cattle feed. Hence, the crude rapeseed oil and the rape meal have two different and distinct uses with few shared properties. In terms of allocation, soya meal could be regarded as a substitute for rape meal but this approach can be complicated by the possible use of soya as an alternative source of biodiesel. Finally, crude glycerine is also obtained when biodiesel is produced by esterification of refined rapeseed oil. Currently, crude glycerine is a valuable co-product and allocation might seem appropriate using the substitution approach. Unfortunately, the main source of glycerine is currently as a by-product of soap manufacture and this precludes the use of the substitution approach. Hence, there are some challenging choices for the application of allocation procedures in the life cycle assessment of biodiesel production from OSR. The main guidance with these important choices is that they must be consistent with the wider evaluation of the costs and benefits of biodiesel and should reflect the reality of the circumstances in which this fuel is being considered.

4. EXISTING STUDIES

4.1 Collection of Studies

Many studies, which have adopted a life cycle or related approach, have been conducted for evaluating the energy inputs and/or CO_2 and GHG outputs of the production of biodiesel from OSR. Whilst some of these take the form of complete or partial life cycle assessments, others are more specific, thereby influencing the comparability of results. Despite such potential diversity, the interest in this topic is, perhaps, a reflection of findings of all these studies which indicate that the estimated primary energy inputs and associated CO_2 or GHG outputs of such biodiesel production are not insignificant in comparison with many other renewable sources of energy. Such interest has clearly been

Table 6 Abbreviated and Complete Titles of Existing Studies

Abbreviated Title	Complete Title
ETSU 1992	"A Review of the Potential of Biodiesel as a Transport Fuel" by F. Culshaw and C. Butler, ETSU-R-71, Energy Technology Support Unit, United Kingdom, September 1992 (Ref. 5)
AFAS 1993	"Technikfolgenabschaatzung zum Thema Nachwachsende Rohstoffe" (Technical Process Assessment of Renewable Energy Raw Materials) by D. Wintzer, B. Furniss, S. Klein-Vielhauer, L. Leible, E. Nieke, Ch. Rosch and H. Tangen, Abteilung für Angewandte Systemanalyse Kernforschungszentrum Kahlsruhe GmbH (Division for Applied Systems Analysis, Nuclear Research Centre), Germany, 1993 (Ref. 16)
ETSU 1996	"Alternative Road Transport Fuels – A Preliminary Life-Cycle Study for the UK" by M. P. Gover, S. A. Collings, G. S. Hitchcock, D. P. Moon and G. T. Williams, Report R92, Volume 2, Energy Technology Support Unit, United Kingdom, March 1996 (Ref. 17)
VITO 1996	"Comparative Life-Cycle Assessment of Diesel and Biodiesel" by C. Spirinckx and D. Ceuterick, Vlaamse Instelling voor Technologisch Onderzoek (Flemish Institute for Technological Research), Belgium, 1996 (Ref. 18)
IFEU 1997	"Nachwachsende Energieträger – Grundlagen, Verfaben, Ökologische Bilanzierung" (Renewable Energy Sources, Basis, Processes and Ecological Balance) by M. Kaltschmitt and G. A. Reinhardt (eds), Vieweg, Institut für Energie- und Umweltforschung Heidelberg GmbH (Institute for Energy and Environmental Research), Germany,1997 (Ref. 9)
ECOTEC 1999	"Financial and Environmental Impact of Biodiesel as an Alternative to Fossil Diesel in the UK" ECOTEC Research and Consulting Ltd., United Kingdom, November 1999 (Ref. 19)
Levington 2000	"Energy Balances in the Growth of Oilseed Rape and of Wheat for Bioethanol" by I. R. Richards, Levington Agriculture Ltd., United Kingdom, June 2000 (Ref. 20)
ECOTEC 2000	"Emissions from Liquid Biofuels" ECOTEC Research and Consulting Ltd., United Kingdom, 2000 (Ref. 21)
ECOTEC 2001	"Lifecycle Greenhouse Gas Assessment of RME – Comparative Emissions from Set-aside and Wheat" ECOTEC Research and Consulting Ltd., United Kingdom, 2001 (Ref. 22)
CSIRO 2002	"Comparison of Transport Fuels: Life-Cycle Emissions Analysis of Alternative Fuels for Heavy Vehicles" by. T. Beer, T. Grant, G. Morgan, J. Lapszewicz, P. Anyon, J. Edwards, P. Nelson, H. Watson and D. Williams, Commonwealth Scientific and Industrial Research Organisation, Australia, 2002 (Ref. 6)
ECOTEC 2002	"Analysis of Costs and Benefits from Biofuels Compared to Other Transport Fuels" ECOTEC Research and Consulting Ltd., United Kingdom, 2002 (Ref. 23)

stimulated by concerns about the likely magnitude of net savings in primary energy and CO_2 or GHG emissions which might be achieved by replacing conventional diesel with biodiesel produced from OSR. In order to identify relevant studies, a full literature search was conducted using library and internet facilities in the period leading up to the consultation period on the Draft Report which was released in May 2002. A number of organisations assisted with this activity, most notably the British Association for Bio Fuels and Oils (BABFO) which provided copies of specific studies it has commissioned. In total, fourteen relevant studies were identified produced for diverse purposes by various authors from organisations in Austria, Australia, Belgium, France, Germany and the UK. Information on a small number of these studies was found to be too brief and their contents too limited for subsequent detailed evaluation. Instead, evaluation was concentrated on the remaining eleven studies which were available in published form, with supplementary information, where relevant, so that realistic evaluation could be conducted. For convenience, each study is referred to here by an abbreviated title with date and these are summarised in Table 6 where complete titles and other details are provided. It should be noted that two further studies, prepared by Shell Global Solutions (Ref. 24) and L-B-Systemtechnik GmbH (Ref. 25), became available after the end of the consultation period on the Draft Report and, hence, could not be evaluated here.

4.2 Qualitative Evaluation

Each of the eleven chosen studies was subjected to critical reviews, the main outcomes of which are presented in Appendix A. The principal concerns of these reviews were to determine the relevance of the studies to the UK, and to establish their coverage and transparency regarding the estimation of inputs of primary energy and outputs of associated carbon dioxide and other GHG for the production of biodiesel from OSR. From this perspective, the CSIRO 2002 study is not relevant because it provides results appropriate for the cultivation of OSR in Australia. All the studies attempt to consider the full process chain for biodiesel production from oilseed rape, but not necessarily in a detailed or independent manner. The AFAS 1993 study concentrates mainly on cultivation and treats processing with much less detail. This is due to the specific aims of the AFAS 1993 study which are concerned with the investigation and comparison of different agricultural practices. It is important to point out that the ETSU 1996 study updates and extends the ETSU 1992 study. The ECOTEC 1999 study is partly a critique of the ETSU 1996 study and subsequently modified results are mainly used in the Levington 2000 study. The ECOTEC 2000 study updates and extends the ECOTEC 1999 study and takes into account the work of the Levington 2000 study. Further updating is undertaken in the ECOTEC 2001 study which examines other considerations including the use of a reference system based on growing wheat. The ECOTEC 2002 study uses the results of earlier life cycle assessment to investigate the comparative monetary values of costs and benefits of biofuels with other transport fuels.

The studies display varying degrees of transparency in regard of basic data, assumptions and methods of calculation, especially allocation procedures. The ETSU 1992 study presents an adequate level of detail for the primary energy calculations but not for the CO_2 calculations. Furthermore, a crucial assumption concerning the CO_2 emissions from nitrogen fertiliser manufacture is not explained. As already mentioned, the AFAS 1993 study only deals with processing in a fairly cursory manner and it does not present full results for all the different cultivation methods considered, even though these are considered in some detail. The ETSU 1996 study presents considerable detail for both primary energy and CO_2 calculations, and corrects some of the deficiencies of the ETSU 1992 study. Although the VITO 1996 study is a complete life cycle assessment, full details of the basic data, assumptions and calculations could not be found in the relevant papers which have been published in English. The appropriate level of detail may be provided in the original work in Flemish but this was not accessible. Additionally, estimates of CO_2 emissions are aggregated into total GHG emissions and cannot be separated out.

The IFEU 1997 study is extremely detailed with various options in the calculations being considered in a very open manner. Although there is some lack of clarity in the quoted data for primary energy and CO_2 data for the manufacture of nitrogen fertiliser, an original reference provides more detail (Ref. 23). Since the ECOTEC 1999 study is mainly a critique of the ETSU 1996 study, only certain data are discussed and, hence, it cannot be considered as a full study. The Levington 2000 study does not address processing in sufficient detail, although this is partly rectified in the ECOTEC 2000 study and the ECOTEC 2001 study. Unfortunately, the ECOTEC 2000 study does not explain the chosen allocation procedures. Although this deficiency is corrected in the ECOTEC 2001 study, results are presented only in "per kilometre" terms which cannot be readily translated into other bases for meaningful comparison. Additionally, the basis of many calculations is not apparent and estimates of CO_2 emissions are aggregated into total GHG emissions. The CSIRO 2002 study is quite confusing over its organisation of data, explanation of assumptions and description of calculations which are, in part, based on the results of the VITO 1996 study. Estimates of CO_2 emissions are also aggregated into total GHG emissions.

The conclusions of this qualitative evaluation of existing studies can be summarised as follows:

- The ETSU 1992 study contains some uncertainties, is not totally transparent and has been superseded.
- The AFAS 1993 study is somewhat incomplete, is not totally transparent and has been superseded.
- The ETSU 1996 study is very detailed and quite transparent.
- The VITO 1996 study is not transparent in terms of all data, assumptions, calculations and results.
- The IFEU 1997 study is very detailed and transparent in almost every regard apart from certain results.
- The ECOTEC 1999 study is mainly a critique and cannot be regarded as a complete assessment.
- The Levington 2000 study is not wholly complete nor transparent especially concerning certain results.
- The ECOTEC 2000 study is not wholly complete nor transparent.
- The ECOTEC 2001 study is not transparent in relation to the presentation of results.
- The CSIRO 2002 study is not relevant to the UK nor is it wholly transparent.
- The ECOTEC 2002 study repeats the results of earlier studies and, hence, is not transparent in relation to the presentation of results.

On the basis of this qualitative evaluation of the studies which have been reviewed, it would seem that the most relevant, complete and transparent work available currently is the IFEU 1997 study. This suggests that the IFEU 1997 study could be used for deriving representative results for the production of biodiesel from OSR in the UK since it might enable data to be updated, assumptions to be modified and methods of calculation to be adjusted, where necessary, with relative ease and confidence.

4.3 Quantitative Evaluation

Since it is apparent that the existing studies which have been selected for reviewing have been conducted using diverse data, assumptions and methods of calculation, it is not surprising that they generate different results. In order to compare these results in a meaningful manner and to understand some of the key differences in how they have been derived, summary sheets were prepared for each study. These summary sheets, which are provided in Appendix B, contain the source of the study (full reference), the specifications of the rape methyl ester (RME) or biodiesel (assumed density and energy content), the main cultivation details (type of cultivation and yield, nitrogen fertiliser input, energy requirement and carbon requirement, total energy input and carbon output, and reference system energy and carbon credits), the main processing details (methanol input, energy requirement and carbon requirement, energy inputs and carbon outputs of drying, extraction and refining, and total energy inputs and carbon outputs of processing), details of allocation procedures, final results (unadjusted and adjusted energy and carbon results in terms of energy content and weight of biodiesel), reference fuel data (density, energy content, gross energy requirements per unit energy and weight, and carbon requirements per unit energy and weight), and estimated savings (unadjusted and adjusted net energy and carbon savings per unit energy and weight). The existing studies use a variety of means for presenting results. However, to assist with basic comparison, these have been converted, mainly by means of data provided in each study, into a similar basis of per unit energy (MJ), per unit weight (kg) and per unit volume (l) of biodiesel. These results are shown in Table 7 which presents results in their so-called adjusted forms that take into full account all assumptions, methods of calculation and allocation procedures adopted by the original studies. It should be noted that some studies provide a range of results based on a selection of different assumptions and allocation procedures. In such instance, it has been necessary to choose particular results as the most representative of those available.

Table 7 Comparison of Energy and Carbon Requirements for Biodiesel Based on the Results of Existing Studies[(a)]

Study	Main Cultivation Considerations	Energy Requirement MJ			Carbon Requirement kg CO_2		
		per MJ	per kg	per l	per MJ	per kg	per l
ETSU 1992	Winter oilseed rape with straw used as fuel	0.33	12.30	10.82	-0.091	-3.39	-2.98
ETSU 1992	Spring oilseed rape with straw used as fuel	0.33	12.30	10.82	0.036	1.33	1.17
AFAS 1993	Winter oilseed rape	0.47	17.52	15.41	0.036	1.34	1.18
ETSU 1996	Winter oilseed rape with no straw used as fuel	0.89	33.17	29.19	0.032	1.19	1.05
ETSU 1996	Winter oilseed rape with straw used as fuel	0.66	24.60	21.65	0.020	0.75	0.66
ETSU 1996	Spring oilseed rape with no straw used as fuel	0.88	32.80	28.86	0.032	1.19	1.05
ETSU 1996	Spring oilseed rape with straw used as fuel	0.66	24.60	21.65	0.020	0.75	0.66
VITO 1996	Winter oilseed rape	0.55	20.50	18.04	?	?	?
IFEU 1997	Winter oilseed rape	0.39	14.54	12.79	0.030	1.12	0.98
Levington 2000	Winter oilseed rape with straw ploughed in	0.54	20.13	17.71	0.012	0.45	0.39
Levington 2000	Winter oilseed rape with straw used as fuel	0.55	20.50	18.04	0.014	0.52	0.46
CSIRO 2002	Winter oilseed rape with straw used as fuel	0.43	16.03	14.10	?	?	?

Note

(a) Assuming standard biodiesel specifications of density of 0.88 kg/l and net calorific value of 37.27 MJ/kg throughout.

From Table 7, it can be seen that there are some significant differences between results provided by the existing studies. In terms of the energy requirement of biodiesel, the lowest results are those from ETSU 1992 study and the highest are those from the ETSU 1996 study. This outcome is not translated fully into the carbon requirements of biodiesel. Oddly, the ETSU 1992 study offers both the lowest and highest results. However, the main reason for the lowest (negative) carbon requirements obtained in the ETSU 1992 study is that all co-products (glycerine), by-products (rape meal) and waste products (rape straw) are, in effect, assumed to be burnt as fuels, giving substantial energy and CO_2 emissions credits. Leaving aside the negative carbon requirements from the ETSU 1992 study, it can be seen that the next lowest results are those presented in the Levington 2000 study. However, the results of the Levington 2000 study are presented in an ambiguous manner and it is possible that they may only refer to OSR cultivation. It should be noted that carbon requirements for biodiesel from the VITO 1996 study and CSIRO 2002 study are not included in this comparison due to a lack of transparency. In particular, these studies aggregate all GHG emissions so that CO_2 emissions cannot be considered separately. Additionally, the results of the ECOTEC 2000 and 2001 studies could not be incorporated since these are reported in terms of per kilometre travelled by vehicles using biodiesel and conventional diesel. Due to lack of transparency, such results could not be converted into forms similar to those presented in Table 7. Despite such limitations, it is apparent that basic data, assumptions and methods of calculation are responsible for the relatively wide variation of results recorded in Table 7.

It is helpful to consider some of the differences in the most important data, assumptions and methods of calculation for the existing studies. In particular, this provides a sound basis for deriving representative results for biodiesel production from oilseed rape in the UK. However, this further quantitative evaluation of the existing studies should not be seen as an attempt to reconcile differences and synthesise agreement in the results. By examining the studies, it is possible to identify common factors which usually exert considerable influence over the final results which they produce. These factors are the nitrogen fertiliser input and the subsequent rapeseed yield, the energy and carbon requirements of nitrogen fertiliser, total energy inputs and CO_2 outputs of oilseed cultivation, reference systems for oilseed cultivation, oilseed processing data, and allocation procedures. Comparisons of these factors are summarised in Tables 8 to 13. Largely due to the occasional lack of transparency, it has not been possible to compare every factor for all the studies. Additionally, it has been necessary to qualify the use of some of these factors depending on details provided in the original studies.

Considerable variations in nitrogen fertiliser inputs and rapeseed yields can be seen in Table 8. The fertiliser input quoted in the CSIRO 2002 study can be discounted because there is confusion over the data reported and because such data reflect Australian rather than European farming conditions. Despite this, a factor of two variation in nitrogen fertiliser input is still apparent for conventional agricultural practices in western Europe. Similar variations can be observed in the rapeseed yield, although these are not linked simply to variations in nitrogen fertiliser inputs. Indeed, the highest yield is reported by the Levington 2000 study and yet the nitrogen fertiliser input is amongst the lowest quoted. It is known that these results were obtained from field trials. In contrast, it appears that the other studies have attempted to adopt nitrogen fertiliser inputs and rapeseed yields which reflect typical agricultural practice, normally on a national scale. However, this comparison needs to be tempered somewhat since a general lack of definition in rapeseed yields was encountered in many studies. In particular, most studies did not specify whether the quoted yield was for raw rapeseed (typically with a moisture content of 15%) or dried rapeseed (typically with a moisture content 9%). This undermines simple comparison of these factors and can have a noticeable influence on subsequent results.

Most studies recognise that the primary energy consumption and CO_2 emissions of manufacturing nitrogen fertiliser play a prominent role in the calculation of the energy and carbon requirements of biodiesel produced from oilseed rape. However, a number of studies do not address this issue explicitly and, hence, only limited comparison could be achieved in Table 9. For those studies which do report these factors, considerable variations in the assumed energy and carbon requirements of nitrogen fertiliser were found. For the energy requirement of nitrogen fertiliser, the lowest value used was in the Levington 2000 study and the highest in the ETSU 1996 study. The Levington 2000 study also used the lowest value for the carbon requirement of nitrogen fertiliser, although only the average value from a quoted range of 0.45 to 2.08 kg CO_2/kg N. The highest value for the carbon requirement of nitrogen fertiliser is adopted in the IFEU 1997 study. Unfortunately, full details of the derivation of the energy and carbon requirements for nitrogen fertiliser are only provided in a few instances. In particular, the Resources Research Unit (RRU) of Sheffield Hallam University provided the data for the values, subsequently modified, in the ETSU 1992 study, and the values, not modified, in the ETSU 1996 study. However, it is now recognised that these values refer to older practices for the manufacture of ammonium nitrate fertiliser. The IFEU 1997 study uses values obtained from another detailed report (Ref. 26), although this is not wholly transparent. The general issues raised by the use of these very influential values for the energy and carbon requirements of nitrogen fertiliser include whether they reflect typical or best practice in fertiliser manufacturing, and how account has been taken of the energy content of hydrocarbon feedstock (usually natural gas) and recovered CO_2 in fertiliser production. These considerations have a fundamental effect on subsequent results for biodiesel production from OSR.

Table 8 Nitrogen Fertiliser Input and Rapeseed Yield in Existing Studies

Study	Cultivation Details	Nitrogen Fertiliser Input (kg N/ha.a)	Rapeseed Yield[(a)] (t/ha.a)
ETSU 1992	Winter oilseed rape	260	3.200
ETSU 1992	Spring oilseed rape	150	2.200
AFAS 1993	Winter oilseed rape – high intensity	180	3.110
AFAS 1993	Winter oilseed rape – nitrogen conserving	134	2.950
AFAS 1993	Winter oilseed rape – mainly organic	83	2.540
ETSU 1996	Winter oilseed rape	185	3.200
ETSU 1996	Spring oilseed rape	120	2.200
VITO 1996	Winter oilseed rape	?	3.500
IFEU 1997	Winter oilseed rape	146	3.165
ECOTEC 1999	Winter oilseed rape	290	3.200
Levington 2000	Winter oilseed rape	180	4.080
ECOTEC 2000	Winter oilseed rape	180	4.080
ECOTEC 2001	Winter oilseed rape	188	3.200
CSIRO 2002	?	20	?

Note

(a) Rapeseed yield may be quoted in terms of raw rapeseed with a moisture content of 15%, dried rapeseed with a moisture content of 9%, or unspecified in the existing studies.

Table 9 Nitrogen Fertiliser Energy and Carbon Requirements in Existing Studies

Study	Nitrogen Fertiliser	
	Energy Requirement (MJ/kg N)	Carbon Requirement (kg CO_2/kg N)
ETSU 1992	59.70	1.87
ETSU 1996	65.30	2.26
VITO 1996	45.00	?
IFEU 1997	47.10	2.47
Levington 2000	38.00	1.14

Obviously, the primary energy consumption and CO_2 emissions from the manufacture of nitrogen fertiliser make significant contributions to the total energy inputs and CO_2 outputs of conventional OSR cultivation. These totals include the consumption of diesel fuel by farm machinery engaged in various activities, and the production of other fertilisers, herbicides, pesticides, etc. A comparison of the total energy inputs and CO_2 outputs of cultivation is presented in Table 10. This shows that, apart from the lowest and highest values of total energy input which are reported in the ECOTEC 1999 study and the ETSU 1992 study, there is a degree of similarity with the energy results. This is not reflected in the CO_2 results, which indicate almost a factor of three variation between the lowest value, given by the ETSU 1996 study, and the highest value, recorded by the ETSU 1992 study. Complete comparison is not possible since results are missing for certain studies due to the aggregation of CO_2 emissions into total GHG emissions.

Table 10 Total Energy Inputs and Carbon Dioxide Outputs of Cultivation in Existing Studies

Study	Cultivation Details	Cultivation	
		Total Energy Input (MJ/ha.a)	Total CO_2 Output (kg CO_2/ha.a)
ETSU 1992	Winter oilseed rape	21,167	877
ETSU 1992	Spring oilseed rape	14,600	671
AFAS 1993	Winter oilseed rape – high intensity	14,930	?
AFAS 1993	Winter oilseed rape – nitrogen conserving	12,620	?
ETSU 1996	Winter oilseed rape	18,131	521
ETSU 1996	Spring oilseed rape	12,162	314
IFEU 1997	Winter oilseed rape	10,015	544
ECOTEC 1999	Winter oilseed rape	4,600	421
Levington 2000	Winter oilseed rape – straw ploughed in	13,254	626
Levington 2000	Winter oilseed rape – straw used as fuel	13,911	751

Significantly different approaches are taken to the use of reference systems in the existing studies, as demonstrated in Table 11. The ETSU 1992 and 1996 studies, and the Levington 2000 study do not adopt a reference system for their calculations. The maintenance of fallow set-aside is assumed in most of the AFAS 1993 study, the IFEU 1997 study and the ECOTEC 2001 study. However, differences in the estimated energy and CO_2 credits are apparent, although these cannot be compared in a meaningful way because of the partial reporting of results in these studies. The largest credit, at least in terms of CO_2 emissions, is derived by the ECOTEC 2001 study which examines the proposed option of replacing wheat production with the cultivation of OSR for biodiesel. In terms of the other studies, this is an extreme approach to the issue of reference systems and subsequent credits.

Table 11 Reference Systems and Credits in Existing Studies

Study	Reference System Details	Energy Credit (MJ/ha.a)	CO2 Credit (kg CO_2/ha.a)
ETSU 1992	No reference system	0	0
AFAS 1993	Fallow set-aside vs high intensity	5,520	?
AFAS 1993	Fallow set-aside vs nitrogen conserving	7,074	?
ETSU 1996	No reference system	0	0
IFEU 1997	Fallow set-aside	1,024	75
Levington 2000	No reference system	0	0
ECOTEC 2001	Fallow set-aside	?	58
ECOTEC 2001	Wheat cultivation	?	389

Only a few studies provide adequate detail on the data, assumptions and calculations used to derive estimates of the primary energy inputs and CO_2 outputs of processing rapeseed to produce biodiesel, or rape methyl ester (RME). As shown in Table 12, only limited comparison is possible, although it reveals important differences. First, different processing methods, involving the extraction stage specifically, can be considered. Extraction consists of either cold pressing and solvent treatment using hexane, as assumed in the VITO 1996 study and the IFEU 1997 study, or hot pressing and crushing, as assumed in the ETSU 1992 and 1996 studies, and the Levington 2000 study. However, very different results are derived the crushing method. As pointed out in the ECOTEC 1999 study, which is referenced by the Levington 2000 study, the ETSU 1992 and 1996 studies over-estimate the energy required by crushing significantly. Second, there are basic differences in energy and carbon requirements of methanol which is used in the esterification stage. The ECOTEC 1999 study and the subsequent Levington 2000 study do not account for the use of methanol in calculations. However, this is rectified in the ECOTEC 2001 study. Different values are taken for the energy and carbon requirements of methanol. As pointed out in the VITO 1996 study, this is important because, apart from its use in esterification, the methanol effectively contributes primary energy and carbon from fossil fuels to a not inconsiderable fraction of the biodiesel. Finally, as result of all these different data and assumptions, it is hardly surprising that there are substantial differences between the estimates of total primary energy input and CO_2 output of biodiesel processing. However, such is the complexity and lack of transparency of most studies, that it is impossible to resolve the sources of these differences totally.

Table 12 Biodiesel Processing Data in Existing Studies

Study	Extract Method	Extraction		Methanol		Total Processing	
		Energy (MJ/kg RME)	CO_2 (CO_2/kg RME)	Energy (MJ/kg methanol)	CO_2 (CO_2/kg RME)	Energy (MJ/kg RME)	CO_2 (CO_2/kg RME)
ETSU 1992	Crushing	3.47	?	19.70	?	9.60	0.67
ETSU 1996	Crushing	8.52	0.48	33.00	?	20.92	0.97
IFEU 1997	Solvent	2.78	0.16	38.09	2.72	11.43	0.75
Levington 2000	Crushing	0.43	?	0	0	11.43	?

Fundamentally dissimilar allocation procedures have been adopted by the existing studies. These apply to the division of primary energy inputs and CO_2 outputs between rapeseed and rape straw, between crude rapeseed oil and rape meal, and between biodiesel and crude glycerine. The procedures adopted are summarised in Table 11.

Some studies adopt no allocation procedures, either fully, as in the case of the ECOTEC 1999 study and, possibly, the ECOTEC 2000 study, or partially, as in the case of the ETSU 1996 study and, possibly the ECOTEC 2001 study. However, the ETSU 1996 study does assume substitution of rape meal by soya meal to address the allocation issue for cultivation and extraction, whilst the ECOTEC 2001 study used market prices for allocation between biodiesel and crude glycerine. Only one study, the VITO 1996 study, adopts mass as a basis for allocation and, then, only for allocation between rapeseed and rape straw. The ETSU 1992 study uses energy content as a basis for all allocation procedures, as may the Levington 2000 study and the CSIRO 2002 study. Although the attraction of this approach is probably its simplicity, there is little justification for it since none of the co-products, by-products and waste products are actually used as fuels in current practice. It should be noted that, although the main results from the IFEU 1997 study are based on an allocation procedure using energy content, this work also examines the effect of other allocation procedures in some detail. These include the use of mass and price, completely or in different combinations.

Table 13 Allocation Procedures in Existing Studies

Study	Main Allocation Procedures		
	Rapeseed: Rape Straw	Crude Rapeseed Oil: Rape Meal	Biodiesel: Crude Glycerine
ETSU 1992	Energy content	Energy Content	Energy Content
ETSU 1996	No allocation	Substitution by soya meal	No allocation
VITO 1996	Mass	Market price	Market price
IFEU 1997	No allocation	Energy content	Energy content
ECOTEC 1999	No allocation?	No allocation?	No allocation?
Levington 2000	Energy content?	Energy content?	Energy content?
ECOTEC 2000	No allocation?	No allocation?	No allocation?
ECOTEC 2001	No allocation?	No allocation?	Market price
CSIRO 2002	Energy content?	Energy content?	Energy content?

Based on this quantitative evaluation, the principal critical observations which can be made about the existing studies are as follows:

- The ETSU 1992 study uses over-estimated extraction data and unjustified allocation procedures.

- The AFAS 1993 study does not provide the data and assumptions for the complete process chain.

- The ETSU 1996 study uses over-estimated extraction data and does not apply allocation procedures to all the by-products and waste products.

- The VITO 1996 study does not provide adequate data and assumptions for the complete process chain.

- The IFEU 1997 study provides very detailed data and assumptions which enable a range of results to be derived.

- The ECOTEC 1999 study does not provide adequate data and assumptions for the complete process chain.

- The Levington 2000 study adopts an extremely high rapeseed yield, extremely low energy and carbon requirements for nitrogen fertiliser and, possibly, unjustified allocation procedures.

- The ECOTEC 2000 adopts an extremely high rapeseed yield, probably assumes extremely low energy and carbon requirements for nitrogen fertiliser and does not use any allocation procedures.

- The ECOTEC 2001 study adopts an extremely favourable reference system and does not apply allocation procedures to all the co-products and waste products.

- The CSIRO 2002 study does not provide adequate data and assumptions for the complete process chain.

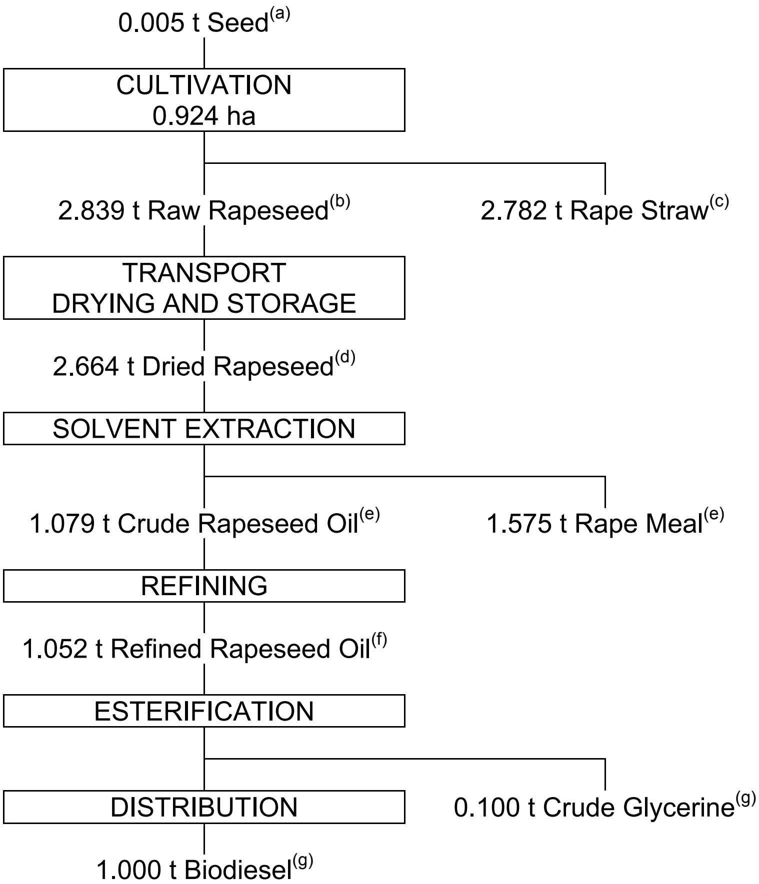
It can be concluded that results from none of the existing studies can be used as wholly representative of biodiesel production from OSR in the UK. Many suffer from lack of detail and transparency which means that they cannot be readily modified to provide representative results. However, it can be suggested that two studies could be used in this way: the ETSU 1996 study and the IFEU 1997 study. Of these two studies, the IFEU 1997 study provides more detail, not only in terms of considerable transparency in the data and assumptions used, but also in relation to the investigation of different processing options and methods of calculation. Even so, further work is required to derive representative results using the IFEU 1997 study.

5. REPRESENTATIVE RESULTS

5.1 Conventional Production

Although the IFEU 1997 study can provide substantial data for producing representative energy and carbon requirements of biodiesel, a considerable amount of other information has to be taken into account to ensure that the results reflect typical production of biodiesel from OSR in the UK. The first step is to prepare a flow chart which illustrates the process chain for biodiesel production with typical UK values for all the principal raw materials, products, co-products, by-products and waste products involved. It should be noted that flow charts are rarely provided in the existing studies and often information on key aspects of the process chain is ambiguous, vague or opaque The flow chart used in this study is presented in Figure 1. The values summarised in this flow chart are normalised in terms of the production of one tonne of biodiesel for distribution, sale and use. Best practice from the Agricultural Development and Advisory Service (ADAS) was used to determine the annual oilseed sowing rate (Ref. 27). The latest four year average for total annual rapeseed production, from both set-aside and non-set-aside land, published by the Department for Environment, Food and Rural Affairs (DEFRA), was used as the source of typical rapeseed yields (Ref. 28). It should be noted that these published yields are quoted, originally, in terms of dried rapeseed with a moisture content of 9%. Hence, these data were converted, accordingly, into terms of raw rapeseed with a typical moisture content of 15% (Ref. 18). Furthermore, these yields incorporate the sum of both spring and winter OSR output for the UK in order to be consistent with the average fertiliser application rates derived from national statistics. This enables subsequent results to reflect current national circumstances rather the specific individual farming conditions or possible future productivity improvements derived from selective field trials. Various ratios between the production of raw rapeseed and rape straw are quoted in the existing studies but the most typical appears to be a value of 1:0.98 (Ref. 20). The amount of dried rapeseed obtained from raw rapeseed is based on German drying data (Ref. 9). Similarly, German data are used for the solvent extraction of crude rapeseed and rape meal (Ref. 9). As will be shown later, this is consistent with the assumed energy consumption of mechanical extraction. Flemish data are adopted for the refining of rapeseed oil (Ref. 18) and German data provide the basis for the production of biodiesel from unrefined

Figure 1 Flow Chart for the Conventional Production of Biodiesel from OSR in the UK with Solvent Extraction



Notes

(a) Annual sowing rate of 5 kilograms of seed per hectare based on ADAS Best Practice (Ref. 27).

(b) 4 year average between 1997 and 2000 for total annual UK rapeseed production (set-aside and non-set-aside) of 2900 kilograms of dried rapeseed with 9% moisture content per hectare (Ref. 28), giving a yield of 3074 kilograms of raw rapeseed with 15% moisture content per hectare (Ref. 18).

(c) Dried rape straw with 10% moisture content based on a raw rapeseed to rape straw ratio of 1:0.98 (Ref. 20).

(d) 3165 kilograms of raw rapeseed with 15% moisture content provides 2970 kilograms of dried rapeseed with 9% moisture (Ref. 9).

(e) 1000 kilograms of dried oilseed gives 405 kilograms of crude rapeseed oil and 591 kilograms of rape meal (Ref. 9).

(f) 1000 kilograms of crude rapeseed oil provides 975 kilograms of refined rapeseed oil (Ref. 18).

(g) 100 kilograms of crude glycerine is produced along with every 1000 kilograms of biodiesel (Ref. 4).

(h) 1203 kilograms of unrefined rapeseed oil gives 1143 kilograms of biodiesel (Ref. 9).

rapeseed oil (Ref. 9). Finally, typical UK data are used for the amount of crude glycerine derived with each tonne of biodiesel (Ref. 4).

Using the flow chart shown in Figure 1 and data provided by appropriate sources, representative primary energy inputs and CO_2 outputs for biodiesel production from OSR in the UK were calculated (see Appendix D). The results are presented in Table 14 which provides a breakdown between nitrogen fertiliser use, all other inputs to cultivation less credits for fallow set-aside as a reference system, transport, drying and storage of raw rapeseed, crude rapeseed oil extraction, refining and esterification, and distribution of biodiesel to sales outlets. Average values for results are given in Table 14, qualified by error bars derived from calculated standard deviations, where possible, or estimated using typical levels of ± 15% uncertainty (Ref. 6). Key assumptions and specific data incorporated into the calculation of the results given in Table 14 can be summarised as follows. The application rate for nitrogen fertiliser of 196 kg N/ha.a is based on a 4 year average for England and Wales between 1997 and 2000, inclusive (Ref. 29). This particular average was adopted for consistency with the rapeseed yield assumed in Figure 1 (Ref. 28).

Table 14 Representative Primary Energy Inputs and Carbon Dioxide Outputs for Conventional Production of Biodiesel from OSR with Solvent Extraction in the UK

Activity	Primary Energy Input		Carbon Dioxide Output	
	(MJ/t biodiesel)	(%)	(kg CO_2/t biodiesel)	(%)
Cultivation				
- nitrogen fertiliser	3,962 ± 556	24	186 ± 27	20
- other inputs less fallow set-aside	1,845 ± 239	11	93 ± 13	10
Transport	511 ± 22	3	33 ± 1	5
Drying	566 ± 85	4	41 ± 6	4
Storage	214 ± 18	1	17 ± 2	2
Extraction	2,394 ± 242	15	113 ± 13	12
Refining	411 ± 34	3	26 ± 2	3
Esterification	5,706 ± 607	35	368 ± 40	40
Plant Construction and Maintenance	162 ± 21	1	7 ± 1	1
Distribution	498 ± 21	3	32 ± 1	3
Totals	**16,269 ± 896**	**100**	**916 ± 52**	**100**

Energy and carbon requirements for nitrogen fertiliser were based on data, presented in Appendix C, which reflect recent average production in the EU. It should be emphasised that these results for nitrogen fertiliser used here have been modified for the joint production of ammonium nitrate and the recovery of carbon dioxide as an industrial gas. Previous results did not take into account the subsequent use of carbon dioxide gas and, consequently, allocated all primary energy inputs and CO_2 outputs, including the recovered CO_2, to the nitrogen fertiliser. However, it can be argued that this approach is not correct since the recovered CO_2 has industrial applications which should be responsible for a share of the primary energy inputs and CO_2 outputs. Hence, the current energy and carbon requirements of nitrogen fertiliser reflect an allocation procedure based on the market price of ammonia used in the production of ammonium nitrate and the market price of recovered CO_2 as an industrial gas. This allocation procedure was adopted because all other methods are inappropriate. In particular, the most favoured approach involving substitution cannot be used because CO_2 is mainly obtained as a recovered by-product from various industrial processes. In practice, the results are only modified slightly by this allocation procedure due to the high the price of ammonia of £8.44/kg N (Ref. 30) compared to the price of recovered CO_2 of £0.21/kg CO_2 (Ref. 31). It has been assumed that, although this recovered gas has other industrial uses, all the CO_2 is ultimately released into the atmosphere. However, as a result of adopting this approach, 93% of these eventual CO_2 emissions are associated with the production of ammonium nitrate and only 7% is, effectively, allocated to the subsequent uses of CO_2 as an industrial gas. The justification for this is that, without the original production of ammonium nitrate fertiliser, the CO_2 would not have been available for recovery and use. Hence, the ammonium nitrate should be responsible for a significant proportion of CO_2 emissions derived from the initial natural gas feedstock as well as those directly involved in nitrogen fertiliser production.

In contrast to earlier estimates of the energy and carbon requirements of nitrogen fertiliser derived by the RRU, updated values of 40.61 ± 5.70 MJ/kg N and 1.90 ± 0.27 kg CO_2/kg N were used here (see Appendix C). These values reflect recent average European production of nitrogen fertiliser. In general, there has been a considerable of transparency and consistency in the evaluation of the energy, carbon and GHG requirements of nitrogen fertiliser. This may be partly due to issues of commercial confidentiality within the fertiliser manufacturing industry. However, with appropriate correction and modification it was possible to obtain updated values using extensive data published in one particular detailed study (Ref. 32). In order to derive values which could be used with confidence, it was necessary to adjust the data in this original study for the fact that only delivered energy consumption (direct energy inputs) seems to have been considered, for the omission of primary energy inputs and carbon dioxide outputs for capital plant manufacture, packaging and transport, and for allocation between ammonia and recovered carbon dioxide in nitrogen fertiliser production. These updated energy and carbon requirements for nitrogen fertiliser are lower than the values of 47.10 MJ/kg N and 2.47 kg CO_2/kg N adopted in the IFEU 1997 study and higher than the values of 38.00 MJ/kg N and 1.14 kg CO_2/kg N used in the Levington 2000 study.

The IFEU 1997 study was the initial source of data on all the other inputs to OSR cultivation, including ploughing, sowing, spreading, spraying and harvesting, seeds, other fertilisers and soil conditioners, herbicides, pesticides, for the representative results. The sowing rate was modified for typical UK practice (Ref. 27) and average UK application rates for agrochemical were incorporated where appropriate (Refs. 33 and 34). A reference system of fallow set-aside was assumed and the IFEU 1997 study provided estimates the primary energy inputs and CO_2 outputs as the source of estimates for this. All the estimates for cultivation were adjusted for the standard land area of 0.924 hectares per tonne of biodiesel indicated in Figure 1. It should be noted that no credits have been calculated for any benefits from OSR cultivation derived by following crops such as wheat. In particular, this concerns any reductions in fertiliser needs by following crop cultivation. There are two major reasons why subsequent credits have not been included here. First, it would be necessary to determine average national savings in fertilisers arising from OSR cultivation. Second, it would be necessary to devise a justifiable and consistent means of allocating these credits between OSR and all other following crops. Significant problems would occur with this due to differences in the use of OSR and following crops. Apart from extending the assumptions which need to be incorporated into this study, this would have expanded considerably the cultivation scenarios accommodated in subsequent results. Furthermore, if such benefits are substantial, it would have been necessary to assume that specific cultivation patterns would always be adopted to ensure that resulting primary energy and CO_2 credits would be routinely achieved.

UK data were used to calculate the primary energy input and CO_2 output of raw rapeseed transportation by bulk road carrier (Ref. 15). An average round trip distance of 260 kilometres was taken from the ETSU 1996 study. Estimates of the primary energy inputs and CO_2 outputs of raw rapeseed drying and storage were adopted from the IFEU 1997 study adjusted for an assumed rate of 2.664 tonnes of dried rapeseed per tonne of biodiesel illustrated in Figure 1. Unlike the IFEU 1997 study, it is assumed that dried rapeseed would be stored at the plants where extraction, refining and esterification might occur in the UK. Hence, transportation over an average round trip distance of 240 kilometres in Germany between the dried rapeseed store and the biodiesel processing plant is avoided.

As shown in Table 12, there are considerable differences between estimates in the primary energy inputs and CO_2 outputs of rapeseed oil extraction. Principal differences arise due to the method of oil extraction. Although the main results of the IFEU 1997 study are based on cold pressing and hexane solvent extraction, the ETSU 1996 and ECOTEC 1999 studies confirm that mechanical extraction would probably be the most likely method of processing in the UK. The ETOTEC 1999 study notes a considerable overestimate of the primary energy input to mechanical extraction in the ETSU 1992 and 1996 studies. However, as shown in Table 15, results are available from the IFEU 1997 study which imply that the ECOTEC 1999 study underestimates the primary energy input to mechanical oil extraction. Unfortunately, the ECOTEC 1999 study does not clarify whether the quoted energy input is given in terms of electricity consumed in the oil mill or primary energy used to generate this electricity. The estimate from the IFEU 1997 study, which is used here for producing representative results, suggests that the former interpretation may be relevant. The additional differences in the extraction efficiencies adopted by the different studies, illustrated in Table 15, should also be noted. Although earlier estimates in the Draft Report for this study assumed mechanical extraction of rapeseed oil, it is noted that solvent extraction, involving cold pressing and hexane, is the most prominent processing technique currently used in the UK and is, therefore, most likely to form the basis of future biodiesel production from OSR. Consequently, relevant data from the IFEU 1997 study were adopted in this study. In particular, this included productivity figures of 0.405 tonnes of crude rapeseed oil and 0.591 tonnes of rape meal per tonne of dried rapeseed. The IFEU 1997 study also provided the estimates of primary energy inputs and CO_2 outputs for refining and esterification. This includes data for the use, and energy and carbon requirements of methanol, as presented in Table 12. UK data were used for estimating the primary energy input and CO_2 output of distribution of biodiesel to sales outlets by bulk road carrier (Ref. 15). An average round trip distance of 450 kilometres was assumed based on data contained in the ETSU 1996 study.

Table 15 Energy Estimates of Mechanical Extraction of Rapeseed Oil

Study	Energy Estimate		Energy Input (MJ/t rapeseed oil)	Extraction Efficiency (t rapeseed oil per tonne dried rapeseed)
	Electricity	Primary Energy		
ETSU 1992		✓	8,520	0.370
ETSU 1996		✓	8,520	0.370
IFEU 1997		✓	1,406	0.332
ECOTEC 1999	?		426	0.420

The basis of all the allocation procedures applied in the derivation of representative results here was price. The reason that price was chosen was that the more favoured approach using substitution could not be adopted. In particular, rape straw is generally regarded as a waste product which has no alternative means of production. Where demand exists, it can be sold and a market price of £25 per tonne was assumed here based on data provided in the ETSU 1996 study. This compares with an average price for raw rapeseed of £152 per tonne derived from annual average prices in the UK between 1997 and 2000 (Ref. 4). Given typical production rate of 0.98 tonnes of rape straw per tonne of raw rapeseed (Ref. 20) incorporated in Figure 1, this resulted in allocation of 86% of all primary energy inputs and CO_2 outputs of cultivation to raw rapeseed. It has been suggested that soya meal could be taken as a substitute for rape meal produced in oil mills. However, this does not resolve the allocation problem between rape meal and crude rapeseed oil since soya meal is also a by-product from soya bean processing. Hence, substitution is not appropriate and, again, price was used for allocation here. Average prices of £323 per tonne of crude rapeseed oil and £84 per tonne of rape meal were derived from UK data between 1997 and 2000 (Ref. 4). This resulted in the allocation of 72% of the primary energy inputs and CO_2 outputs of cultivation, transportation, drying, storage and extraction to crude rapeseed oil. Finally, price was used as a basis of allocation between biodiesel and crude glycerine because the latter is also a by-product of soap manufacture so that a substitution approach is not applicable. Average prices of £268 per tonne of biodiesel and £388 per tonne of crude glycerine were obtained from UK data between 1997 and 2000 (Ref. 4). These prices were combined with a production rate of 0.1 tonnes of crude glycerine per tonne biodiesel (Ref. 4). This resulted in the allocation of 87% of the primary energy inputs and CO_2 outputs of all stages in cultivation and production apart from final distribution to biodiesel.

In addition to CO_2 emissions, other GHG emissions, such as methane (CH_4) and nitrous oxide (N_2O), can be released from activities such as the production of biodiesel from OSR. These gases contribute to the greenhouse effect and are, therefore, also implicated in global climate change. The relative contributions of these gases depends on the amount released and their so-called "global warming potential" (GWP). For convenience, values of GWP can be used to convert CH_4 and N_2O into equivalent amounts of CO_2. Hence, 1 kilogram of CH_4 equals 24.5 kilograms of CO_2 equivalent (kg eq CO_2) and 1 kilogram of N_2O equals 320 kilograms of CO_2 equivalent. There are a number of different sources for CH_4 and N_2O emissions in the production of biodiesel from OSR. Most significantly, N_2O emissions arise during the production of nitrogen fertiliser and, subsequently, as a result of its application to soil during and after the cultivation of OSR. Due to the variety of factors influencing the behaviour of nitrogen in cultivated soils, there is considerable uncertainty about the magnitude of N_2O emissions. However, it is beyond the scope of this study to resolve such uncertainties. Instead, it is possible to provide an illustration of the estimated total GHG emissions based on the most representative data available from existing studies. This involves adopting a similar approach to that taken in the calculation of representative CO_2 emissions above. In particular, the same flow chart given in Figure 1 was used as the basis for producing biodiesel from OSR in the UK. In general, the IFEU 1997 study provided the majority of the GHG emissions data, supplemented with information from other studies, where necessary (Ref. 14). Additionally, UK transport and distribution information were used (Refs. 8, 15 and 17). The results of subsequent calculations are presented in Appendix D and summarised in Table 16.

Table 19 Representative Total Greenhouse Gas Emissions from the Conventional Production of Biodiesel from Oilseed Rape with Solvent Extraction in the UK

Activity	Greenhouse Gas Output	
	(kg eq CO_2 /t biodiesel)	(%)
Cultivation - nitrogen fertiliser - other inputs less fallow set-aside	 766 ± 76 96 ± 13	 51 6
Transport	33 ± 1	2
Drying	41 ± 6	3
Storage	18 ± 2	1
Extraction	120 ± 13	8
Refining	27 ± 2	2
Esterification	376 ± 40	25
Plant Construction and Maintenance	7 ± 1	-
Distribution	32 ± 1	2
Totals	**1,516 ± 88**	**100**

It is apparent from Table 16 that the most significant contribution to total GHG emissions from the production of biodiesel from OSR in the UK is due to nitrogen fertiliser. The manufacture of nitrogen fertiliser is responsible for the majority of these GHG emissions. An updated value of 6.70 ± 0.276 kg eq CO_2/kg N was adopted here, compared with a value of 5.56 kg eq CO_2/kg N used in the IFEU 1997 study. Assuming an application rate of 196 kg N/ha.a, this gives total GHG emissions from nitrogen fertiliser manufacture of 1,313 kg eq CO_2/ha.a. Additionally, GHG emissions arise from the application of nitrogen fertiliser to soil during and after cultivation of oilseed rape. In particular, N_2O is released through increases in the denitrification rate of the soil due to artificial fertiliser, the decomposition of crop residues and changes in biological nitrogen fixation. In total, it is estimated in the IFEU 1997 study that 36 grams of N_2O are released for every kilogram of nitrogen fertiliser applied, resulting in GHG emissions of 226 kg eq CO_2/ha.a. By comparing Tables 14 and 16, it can be seen that, by accounting for all GHG emissions, the total equivalent CO_2 output from the production of biodiesel from oilseed rape increases by 66% over the estimated CO_2 emissions alone.

On the basis of these assumptions and chosen values of data, the representative results were derived for the conventional production of biodiesel from OSR. Representative energy, carbon and GHG requirements for biodiesel are presented in Tables 17 to 19, respectively. It will be seen that these results are provided in terms of "per MJ" energy output, "per kilogram" and "per litre". It should be noted that the "per MJ" output is measured here relative to the net calorific value of biodiesel.

Table 17 Representative Energy Requirements for the Conventional Production of Biodiesel[(a)]

Fuel	Energy Requirement		
	MJ/MJ	MJ/kg	MJ/l
Biodiesel	0.44 ± 0.02	16.27 ± 0.90	14.32 ± 0.79

Note

(a) Assuming standard biodiesel specifications of density of 0.88 kg/l and net calorific value of 37.27 MJ/kg.

Table 18 Representative Carbon Requirements for the Conventional Production of Biodiesel[(a)]

Fuel	Carbon Requirement		
	kg CO_2/MJ	kg CO_2/kg	kg CO_2/l
Biodiesel	0.025 ± 0.001	0.92 ± 0.05	0.81 ± 0.05

Note

(a) Assuming standard biodiesel specifications of density of 0.88 kg/l and net calorific value of 37.27 MJ/kg.

Table 19 Representative Greenhouse Gas Requirements for the Conventional Production of Biodiesel[(a)]

Fuel	Greenhouse Gas Requirement		
	kg CO_2 eq/MJ	kg CO_2 eq/kg	kg CO_2 eq/l
Biodiesel	0.041 ± 0.002	1.52 ± 0.09	1.33 ± 0.08

Note

(a) Assuming standard biodiesel specifications of density of 0.88 kg/l and net calorific value of 37.27 MJ/kg.

5.2 Modified Production

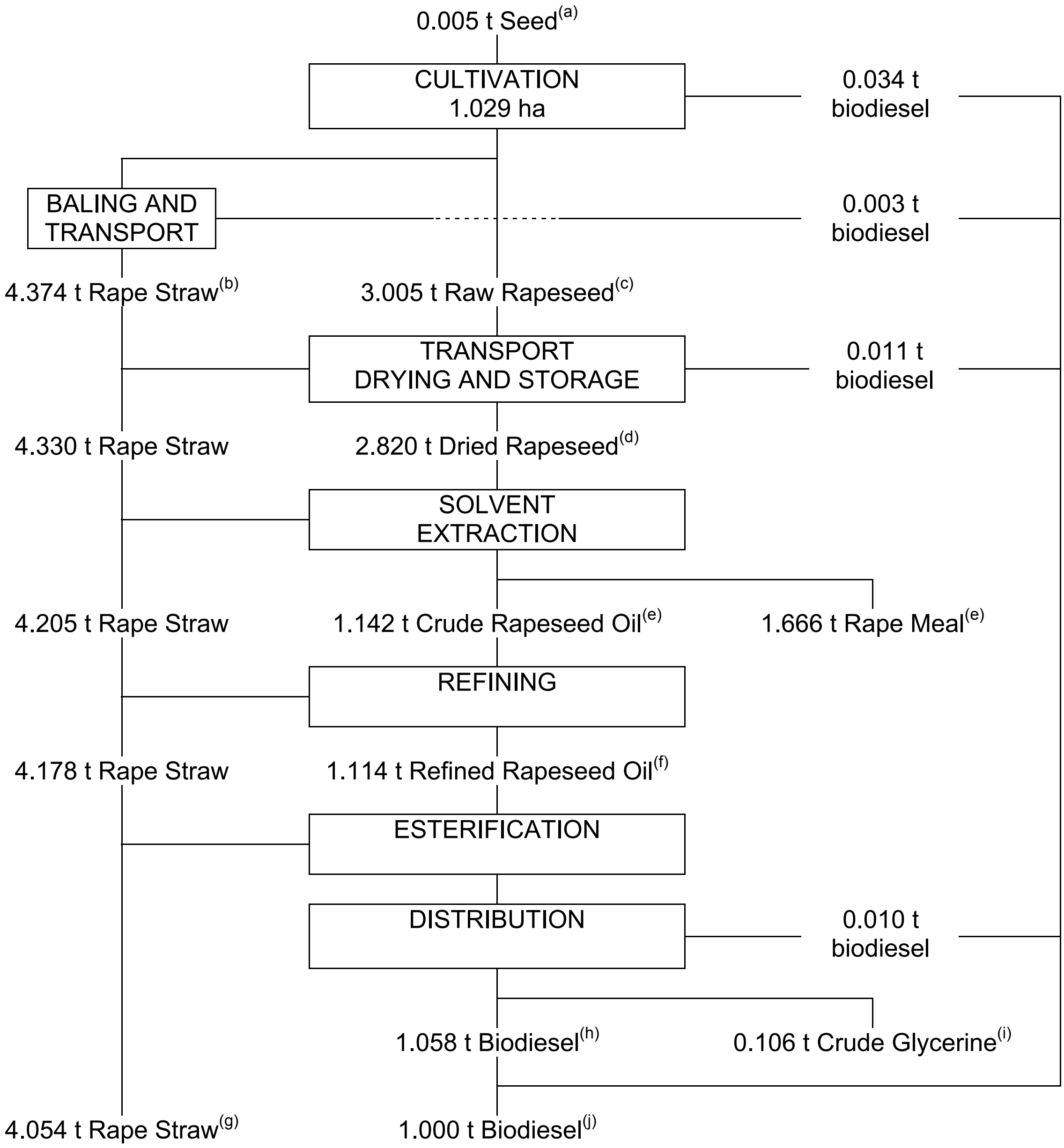
Partly as a consequence of the consultation over the Draft Report for this study, it was decided that the potentially-beneficial effects of realistic modifications to the production process on the energy, carbon and GHG requirements of biodiesel from OSR should be investigated. Based on options outlined in existing studies and from feedback received during the consultation period, a modified production process was formulated. This is modified production process assumes the following:

- low-nitrogen methods of cultivation which reduce the application of nitrogen fertiliser, other fertilisers, fungicides, herbicides and pesticides,
- rape straw utilisation to replace natural gas, and light and heavy fuel oil, as process heating fuels in drying, solvent extraction, refining and esterification, and
- biodiesel utilisation to replace conventional diesel in agricultural machinery used for OSR cultivation, and in bulk road vehicles for transporting raw rapeseed from the farm to the biodiesel processing plant and from the biodiesel processing plant to the point of distribution.

The flow chart for this modified production process is illustrated in Figure 2. This is based on a low-nitrogen cultivation method which decreases the application of nitrogen fertiliser to 81 kg N/ha.a, other fertilisers to 57% of previous values, fungicides, herbicides and pesticides to 94% of previous values, with a resulting reduction in annual yield to 2.740 tonnes of dried (9% moisture content) OSR per hectare (Ref. 16). Under these conditions, it was assumed that an average yield of 4.250 tonnes of dried (10% moisture content) rape straw would be achieved (Ref. 19). On the basis that the calorific value of dried rape straw is 17.00 MJ/kg (Ref. 5) and with an assumed thermal efficiency of a straw-fired boiler of 60%, it was estimated that 1 kilogram of dried rape straw could replace 12.75 MJ of direct energy provided by natural gas, or light and heavy fuel oil normally consumed in conventional boilers with assumed thermal efficiencies of 80%. In total, 0.320 tonnes of dried rape straw could be used to displace fossil fuels in heating applications for the production of 1.000 tonnes of biodiesel available for sale. This would leave 4.054 tonnes of surplus dried rape straw for sale, as previously assumed, at a market price of £25 per tonne. It should be noted that it was not assumed that all the rape straw available from OSR cultivation is used as an alternative heating fuel. This is because, due to its effective economic value of about £42 per tonne as a replacement for natural gas, it would have to be regarded as a co-product with biodiesel. This would significantly alter the life cycle assessment of biodiesel through the allocation procedure as well as its economic and strategic evaluation.

On the basis of the calorific values for biodiesel and conventional diesel given in Table 1, it was determined that 0.0268 kilograms of biodiesel could replace 1 MJ of direct energy provided conventional diesel in agricultural machinery and bulk road transport vehicles. This results in the requirement of 58 kilograms of biodiesel for these applications for every tonne of biodiesel available for sale to other consumers. In terms of all other flow chart data for this modified method of production, the values remain the same as those assumed in conventional production, as summarised previously in Figure 1. Additionally, the same market prices for surplus rape straw, rape meal, crude glycerine and biodiesel are adopted here for allocation. However, because of change in yield due to the low-nitrogen cultivation of OSR, the allocation of related primary energy inputs and CO_2 and other GHG outputs to saleable biodiesel via raw rapeseed (15% moisture content) is now 82%. Other allocation factors are the same as for the conventional production of biodiesel, as are the relevant energy, carbon and other GHG requirements of items used in the process chain.

Figure 2 Flow Chart for the Modified Production of Biodiesel from OSR in the UK with Low-Nitrogen Cultivation, Straw Replacing Heating Fuel and Biodiesel Replacing Diesel Fuel



Notes

(a) Annual sowing rate of 5 kilograms of seed per hectare based on ADAS Best Practice (Ref. 24).

(b) Estimated annual yield of 4250 kilograms of dried rape straw with 10% moisture content per hectare from low-nitrogen cultivation (Ref. 16).

(c) Estimated annual yield of 2740 kilograms of dried rapeseed with 9% moisture content per hectare from low-nitrogen cultivation, giving an annual yield of 2920 kilograms of raw rapeseed with 15 % moisture content per hectare (Refs. 9 and 16).

(d) 3165 kilograms of raw rapeseed with 15% moisture content provides 2970 kilograms of dried rapeseed with 9% moisture (Ref. 9).

(e) 1000 kilograms of dried oilseed gives 405 kilograms of crude rapeseed oil and 591 kilograms of rape meal (Ref. 9).

(f) 1000 kilograms of crude rapeseed oil provides 975 kilograms of refined rapeseed oil (Ref. 18).

(g) Assuming dried 316 kilograms of rape straw with 10% moisture content and a calorific value of 17.0 MJ per kilogram (Ref. 9) used in boilers with thermal efficiencies of 60% replaces natural gas and fuel oil used in boilers with thermal efficiencies of 80% for drying (42 kilograms of rape straw), solvent extraction (125 kilograms of rape straw), refining (27 kilograms of rape straw) and esterification (124 kilograms of rape straw).

(h) 1203 kilograms of unrefined rapeseed oil gives 1143 kilograms of biodiesel (Ref. 9).

(i) 100 kilograms of crude glycerine is produced along with every 1000 kilograms of biodiesel (Ref. 4).

(j) Assuming 58 kilograms of biodiesel replaces 1,256 MJ of diesel in cultivation and harvesting (34 kilograms of biodiesel), 128 MJ of rape straw baling and transport (3 kilograms of biodiesel), 401 MJ of raw rapeseed transport (11 kilograms of biodiesel), and 390 MJ of biodiesel distribution (11 kilograms of biodiesel).

Subsequent detailed calculations are presented in Appendix E. The primary energy inputs, and carbon and total GHG outputs of the modified production of biodiesel from OSR are summarised in Tables 20 and 21. Resulting energy, carbon and GHG requirements are shown in Tables 22 to 24, respectively. These results indicate that, as a consequence of the modifications considered here, the energy, carbon and GHG requirements of biodiesel could be reduced by between 52% and 54%. Although these potential reductions are significant, it should be noted that their possible realisation depends on certain major assumptions. In particular, it would be necessary for all farmers who produce OSR for biodiesel production to adopt low-nitrogen cultivation practices. Additionally, the effective utilisation of rape straw would have to be demonstrated and routinely undertaken on a commercial scale. In order to achieve this, a number of practical considerations would have to be addressed. First, apparent difficulties in collecting rape straw from fields would have to be overcome. Specifically, these problems relate to both "green" rape straw, which apparently tends to obstruct baling machinery, and dried rape straw, which can be extremely brittle and, hence, difficult to collect. Second, the disadvantages of rape straw as a commercial heating fuel need to be resolved. These disadvantages seem to relate to its brittle and potentially-dusty nature, and its high nitrogen content, both of which mean that it may be an unattractive heating fuel for consumers. Finally, the use of biodiesel in all agricultural machinery and processors' bulk road transport vehicles must become commonplace and complete. Only when all these criteria are achieved can the substantial reductions in the energy, carbon and GHG requirements of biodiesel be realised in practice.

Table 20 <u>Representative Primary Energy Inputs and Carbon Dioxide Outputs for Modified Production of Biodiesel from OSR with Low-Nitrogen Cultivation, Straw Replacing Heating Fuel and Biodiesel Replacing Diesel Fuel</u>

Activity	Primary Energy Input		Carbon Dioxide Output	
	(MJ/t biodiesel)	(%)	(kg CO_2/t biodiesel)	(%)
Cultivation - nitrogen fertiliser - other inputs less fallow set-aside	 1,739 ± 244 243 ± 115	 22 3	 82 ± 12 - 13 ± 6	 19 - 3
Transport	140 ± 17	2	8 ± 1	2
Storage	227 ± 19	3	11 ± 2	2
Extraction	760 ± 58	10	34 ± 5	8
Refining	59 ± 6	1	4	1
Esterification	4,274 ± 574	55	296 ± 40	67
Plant Construction and Maintenance	172 ± 22	2	7 ± 1	2
Distribution	136 ± 13	2	8 ± 1	2
Totals	**7,750 ± 638**	**100**	**437 ± 42**	**100**

Table 21 Representative Total Greenhouse Gas Emissions for Modified Production of Biodiesel from OSR with Low-Nitrogen Cultivation, Straw Replacing Heating Fuel and Biodiesel Replacing Diesel Fuel

Activity	Greenhouse Gas Output	
	(kg eq CO_2 /t biodiesel)	(%)
Cultivation - nitrogen fertiliser - other inputs less fallow set-aside	 336 ± 33 - 11 ± 6	 48 - 1
Transport	8 ± 1	1
Storage	12 ± 2	1
Extraction	36 ± 15	5
Refining	4	1
Esterification	302 ± 40	43
Plant Construction and Maintenance	7 ± 1	1
Distribution	8 ± 1	1
Totals	**702 ± 53**	**100**

Table 22 Representative Energy Requirements for the Modified Production of Biodiesel[a]

Fuel	Energy Requirement		
	MJ/MJ	MJ/kg	MJ/l
Biodiesel	0.21 ± 0.02	7.75 ± 0.64	6.82 ± 0.56

Note

(a) Assuming standard biodiesel specifications of density of 0.88 kg/l and net calorific value of 37.27 MJ/kg.

Table 23 Representative Carbon Requirements for the Modified Production of Biodiesel[a]

Fuel	Carbon Requirement		
	kg CO_2/MJ	kg CO_2/kg	kg CO_2/l
Biodiesel	0.012 ± 0.001	0.44 ± 0.04	0.38 ± 0.04

Note

(a) Assuming standard biodiesel specifications of density of 0.88 kg/l and net calorific value of 37.27 MJ/kg.

Table 24 Representative Greenhouse Gas Requirements for the Modified Production of Biodiesel[a]

Fuel	Greenhouse Gas Requirement		
	kg CO_2 eq/MJ	kg CO_2 eq/kg	kg CO_2 eq/l
Biodiesel	0.019 ± 0.001	0.70 ± 0.05	0.62 ± 0.05

Note

(a) Assuming standard biodiesel specifications of density of 0.88 kg/l and net calorific value of 37.27 MJ/kg.

5.3 Sensitivity Analysis

From the review of existing studies and foregoing derivation of the primary energy inputs and CO_2 outputs of the production of biodiesel from OSR, it is apparent that certain factors could have a significant influence on subsequent results. Consequently, sensitivity analysis was performed on the assumed values of the following factors; OSR yield, nitrogen fertiliser energy and carbon requirements, the cultivation reference system, and the price ratios of raw rapeseed to rape straw, rapeseed oil to rape meal and biodiesel to crude glycerine. The effects of varying the values of these factors on the energy and carbon requirements of biodiesel, derived for the earlier Draft Report of this study, are demonstrated in Figures 3 and 4, respectively. It should be noted that these earlier results assume older estimates of the energy and carbon requirements of nitrogen fertiliser and mechanical extraction of rapeseed oil. Despite differences with current results, the general conclusions of this sensitivity analysis remain valid. In particular, this shows that the assumed OSR yield and the assumed energy and carbon requirements of nitrogen fertiliser have the most pronounced influence on results. In terms of the OSR yield, it is falling rather than rising values which have, proportionately, the greatest impact. For example, although the Levington 2000 study incorporates an OSR yield of 4.08 tonnes per year, which is 41% higher than the recent average UK value adopted here, it only reduces the representative energy and carbon requirements of biodiesel by 15% and 14%, respectively. In contrast, the lowest average UK OSR yield observed between 1997 and 2001 of 2.60 tonnes per year (Ref. 25) reflects a 10% reduction in yield which produces a 6% increase in representative energy and carbon requirements of biodiesel. As illustrated in Figures 2 and 3, this effect increases with lower OSR yields.

As indicated in Table 14, nitrogen fertiliser makes the largest single contribution to the total primary energy input of biodiesel production from OSR. Hence, it is hardly surprising that the energy and carbon requirements of biodiesel are relatively sensitive to the energy and carbon requirements of nitrogen fertiliser. Figures 2 and 3 show that the relationship is linear. It is also possible to investigate the effect of different allocation procedures for CO_2 recovered during the manufacture of nitrogen fertiliser. Allocating all the recovered CO_2 to the nitrogen fertiliser increases its carbon requirement by 8% but only raises the carbon requirement of biodiesel by 3%. Alternatively, excluding the recovered CO_2 from the carbon requirement of nitrogen fertiliser reduces its carbon requirement by 31%, although this only decreases the carbon requirement of biodiesel by 11%. It can be seen from Figures 3 and 4 that the choice of reference systems does not seem to have much impact on the representative energy and carbon requirements for biodiesel. In particular, if no primary energy and CO_2 credits are assumed for a reference system, the representative energy and carbon requirements for biodiesel increase by just 3% and 4%, respectively. However, it would be wrong to conclude that reference systems have little effect on the representative results in all circumstances. In the ECOTEC 2001 study, an extreme case is examined in which wheat cultivation is adopted as the reference system. This increases the primary energy and CO_2 credits by 1277% compared to that assumed in the representative results and the energy and carbon requirements of biodiesel fall by 38% and 31%, respectively. However, the replacement of wheat cultivation for food by OSR cultivation for biodiesel used in transport has wider implications which would need to be recognised and accommodated before this approach could be justified in these calculations. Of more relevance for the representative results produced here are the effects of relative prices assumed in the allocation procedures. Figures 3 and 4 demonstrate that the representative energy and carbon requirements of biodiesel are most sensitive to the price ratio of crude rapeseed oil to rape meal. By considering the fluctuations in this ratio in the UK between 1990 and 2000 from – 47% (£240 per tonne of crude rapeseed oil to £117 per tonne of rape meal) to + 33% (£385 per tonne of crude rapeseed oil to £75 per tonne of rape meal) have been observed (Ref. 4). These cause

Figure 3 Sensitivity of the Energy Requirement of Biodiesel Produced from OSR in the UK

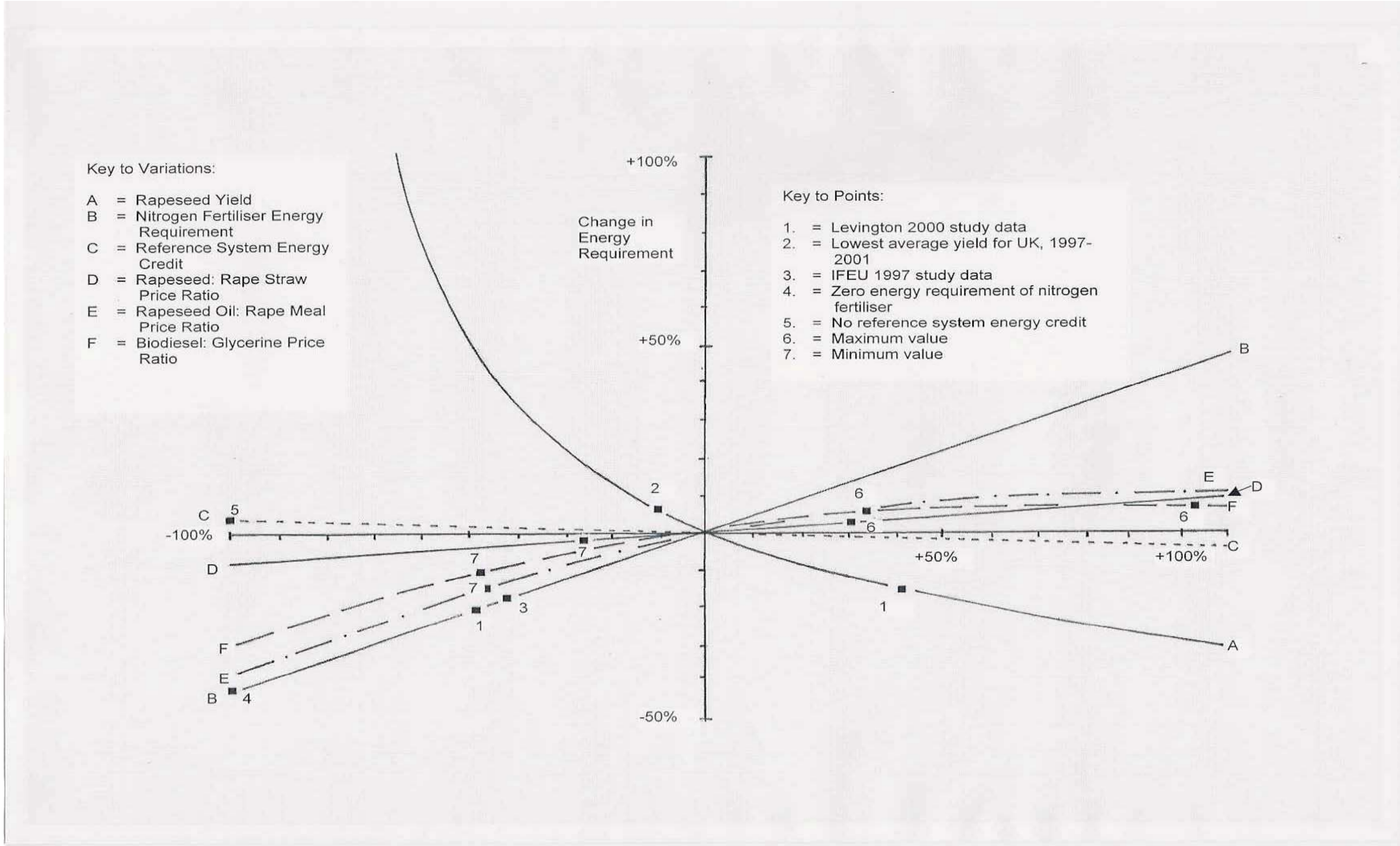
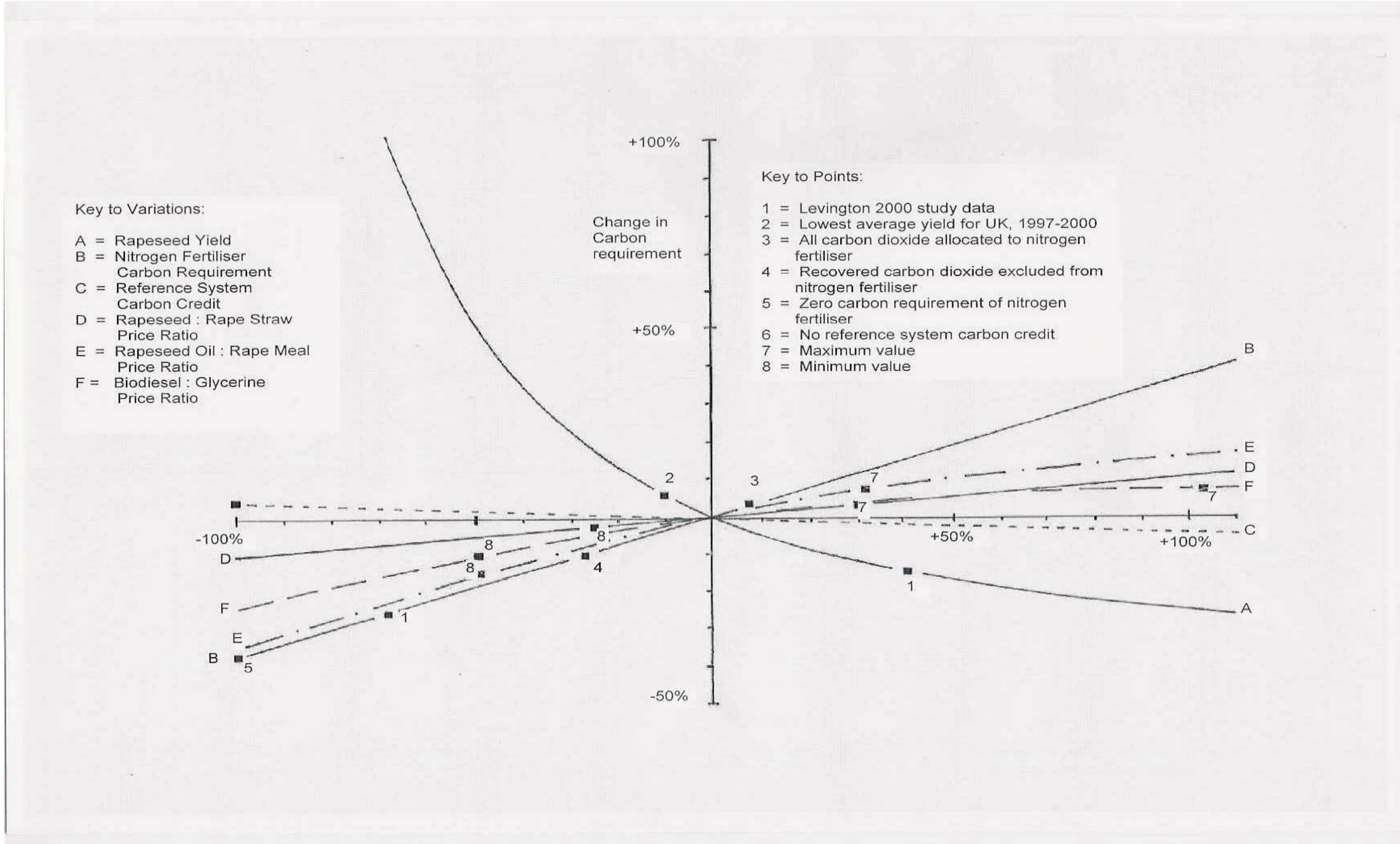


Figure 4 Sensitivity of the Carbon Requirement of Biodiesel Produced from OSR in the UK



subsequent changes in the representative energy and carbon requirements of biodiesel from – 15% to + 6%. The influence of variations in the price ratios for raw rapeseed to rape straw and biodiesel to crude glycerine are less pronounced. The source of data for these price ratio variations is again observed values in the UK between 1990 and 2000 (Ref. 4). Variations in the ratio of the price of biodiesel to the price of crude glycerine from – 48% (£240 per tonne of biodiesel to £667 per tonne of crude glycerine) to + 103% (£286 per tonne of biodiesel to £204 per tonne of crude glycerine) only produce changes in the representative energy and carbon requirements of biodiesel from – 10% to + 7%. Fluctuations in the ratio of raw rapeseed to the price of rape straw from – 26% (£112 per tonne of raw rapeseed to £25 per tonne of rape straw) to + 30% (£197 per tonne of raw rapeseed to £25 per tonne of rape straw) only result in changes in the representative energy and carbon requirements of biodiesel from – 3% to + 2%.

6. COMPARATIVE COSTS AND BENEFITS

6.1 Comparative Primary Energy Resource Depletion

The relative depletion of primary energy resources by the production of different road transport fuels can be determined by comparing respective energy requirements, as shown in Table 25. The representative energy requirements of biodiesel obtained by conventional and modified production from OSR in the UK are provided from Tables 17 and 22, respectively. These indicate the total amount of primary energy resources, mainly in the form of fossil fuels, used in biodiesel production. It should be noted that the amounts of actual energy contained in the original source material and in the biodiesel are not incorporated in this energy requirement. This is not the case for the energy requirements of the other fuels presented in Table 25. These fuels, consisting of low sulphur diesel, ultra low sulphur diesel and compressed natural gas (CNG), are all derived from fossil fuel sources and, hence, the energy contained is included in the relevant energy requirements as indicators of primary energy resource depletion. The energy requirements for these particular fuels were derived from standard data for the UK in 1996 (Ref. 14) modified for specific processes used in their production (Ref. 6). In particular, it is assumed that hydro-desulphurisation provides the means to produce low sulphur diesel, that hydro-cracking is the main process for obtaining ultra low sulphur diesel and that CNG is compressed using electricity from national supplies in the UK. All subsequently modified energy requirements are based on the extraction and processing of crude oil or natural gas from the North Sea. Hence, these results reflect relatively recent experience in supplying these fuels in the UK.

As might be expected, the production of biodiesel uses less primary energy than that involved in the manufacture of conventional road transport fuels derived from fossil fuels. In particular, the total primary energy required for the conventional production of biodiesel from OSR is about 63% lower than that needed for ultra low sulphur diesel. A similar reduction is apparent in comparison with CNG. Even larger reductions, of around 83%, can be achieved when modified production of biodiesel is considered. Although there is a clear advantage for biodiesel in terms of primary energy resource depletion, it can be seen that the amount of primary energy used to produce this alternative road transport fuel is not insignificant. Indeed, the energy requirement of biodiesel is very high in comparison with most other renewable energy sources (Ref. 35). Comparison with other biomass forms of renewable energy, referred to as **biofuels**, may be relevant. For example, updating earlier results (Ref. 36) with data from a recent study (Ref. 15) gives an energy requirement of 0.29 MJ/MJ for electricity generated by gasification of wood chips derived from short rotation coppice (SRC).

Table 25 Comparison of Energy Requirements

Fuel	Energy Requirement			
	MJ/MJ		MJ/kg	MJ/l
	net[(a)]	gross[(b)]		
Biodiesel:				
- Conventional Production	0.44 ± 0.02	0.43 ± 0.02	16.27 ± 0.90	14.32 ± 0.79
- Modified Production	0.21 ± 0.02	0.20 ± 0.02	7.75 ± 0.64	6.82 ± 0.56
Low Sulphur Diesel	1.21	1.13	51.34	43.64
Ultra Low Sulphur Diesel	1.26	1.17	53.23	44.18
Compressed Natural Gas	-	1.14	-	-

Notes

(a) Per net calorific value of the fuel.

(b) Per gross calorific value of the fuel.

6.2 Comparative Carbon Dioxide Emissions

The relative amounts of CO_2 emitted during the production of biodiesel from OSR and other road transport fuels in the UK can be established by comparing relevant carbon requirements, as demonstrated in Table 26. The representative carbon requirements for the conventional and modified production of biodiesel were taken from Tables 18 and 23, respectively. The carbon requirements for low sulphur diesel, ultra low sulphur and CBG diesel were again obtained by using a combination of information (Refs. 6 and 14) to reflect production in 1996 in the UK. It can be seen that CO_2 emissions from biodiesel production are lower than those from the manufacture of other road transport fuels derived from fossil fuels. It should, of course, be noted the carbon requirement of biodiesel excludes direct CO_2 emissions during combustion since these are absorbed during the cultivation of the oilseed rape. In contrast, direct CO_2 emissions are included in the carbon requirements of the other road transport fuels. On these terms, savings in total CO_2 emissions of 57% and 72% can be achieved by using biodiesel derived by conventional production instead of CNG and ultra low sulphur diesel, respectively. In relation to biodiesel obtained by modified production, saving of 80% and 86% are possible in comparison with CNG and ultra low sulphur diesel, respectively. The carbon requirement of biodiesel is comparable with, or better than the carbon requirements of some other biofuels. For example, the carbon requirement of electricity generated by the gasification of wood chips produced from SRC is 0.024 kg CO_2/MJ (Refs. 15 and 36).

Table 26 Comparison of Carbon Requirements

Fuel	Carbon Requirement			
	kg CO_2/MJ		kg CO_2/kg	kg CO_2/l
	net[(a)]	gross[(b)]		
Biodiesel:				
Conventional Production	0.025 ± 0.001	0.024 ± 0.001	0.916 ± 0.052	0.806 ± 0.046
Modified Production	0.012 ± 0.001	0.011 ± 0.001	0.437 ± 0.042	0.385 ± 0.037
Low Sulphur Diesel	0.084	0.078	3.559	3.025
Ultra Low Sulphur Diesel	0.087	0.081	3.674	3.049
Compressed Natural Gas	-	0.056	-	-

Notes

(a) Per net calorific value of the fuel.

(b) Per gross calorific value of the fuel.

6.3 Comparative Greenhouse Gas Emissions

Table 27 illustrates the comparison between the total GHG emissions from the production of biodiesel from OSR and the production of other road transport fuels from fossil fuels. The representative GHG requirement for biodiesel was obtained from Table 19 and a combination of information was used to derive the GHG requirements for low sulphur diesel, ultra low sulphur diesel and CNG (Refs. 6 and 14). As before, direct CO_2 emissions from the combustion of biodiesel are excluded from its GHG requirement but the direct CO_2 emissions from the combustion of the other road transport fuels are included in the GHG requirements shown in Table 27. It can be seen that, on this basis, biodiesel has lower total GHG emissions than those of conventional road transport fuels derived from fossil fuels. However, relative savings in total GHG emissions are less than those for total CO_2 emissions indicated in Table 26. In particular, total GHG emissions from the conventional production of biodiesel are only 31% of those for CNG and 56% of those for ultra low sulphur diesel. With the modified production of biodiesel, savings in total GHG emissions of 67% and 80% are estimated in comparison with those of CNG and ultra low sulphur diesel, respectively. Only limited comparisons can be made between

Table 27 Comparison of Greenhouse Gas Requirements

Fuel	Greenhouse Gas Requirement			
	kg eq CO_2/MJ		kg eq CO_2/kg	kg eq CO_2/MJ
	net[(a)]	gross[(b)]		
Biodiesel: Conventional Production Modified Production	 0.041 ± 0.002 0.019 ± 0.001	 0.040 ± 0.002 0.019 ± 0.001	 1.516 ± 0.088 0.702 ± 0.053	 1.334 ± 0.077 0.618 ± 0.047
Low Sulphur Diesel	0.091	0.085	3.876	3.295
Ultra Low Sulphur Diesel	0.095	0.088	4.012	3.330
Compressed Natural Gas	-	0.058	-	-

Notes

(a) Per net calorific value of the fuel.

(b) Per gross calorific value of the fuel.

the GHG requirements of biodiesel and other biofuels due to lack of detailed studies. However, using the results of the IFEU 1997 study with UK data (Refs. 15 and 36), a GHG requirement of 0.036 kg CO_2 eq/MJ was estimated for electricity generated by gasification from SRC wood chips.

6.4 Comparative Energy and Global Warming Benefits

Using the results presented in Sections 6.1 to 6.3, it is possible to derive net savings which arise when one particular source of energy is displaced by another. For example, fossil fuel savings due to biodiesel displacing ultra low sulphur diesel can be estimated using the energy requirements of these two road transport fuels given in Table 25. These results indicate that the displacement of ultra low sulphur diesel by biodiesel from conventional or modified production would produce fossil fuel savings of 65% or 83%, respectively. This can be compared with the fossil fuel savings of other biofuels, for example SRC wood chips used to generate electricity by means of gasification. The comparative fossil fuel savings of such SRC-generated electricity are based on the displacement of average electricity supplies in the UK which have an energy requirement of 3.09 MJ/MJ (Ref. 14). On this basis, fossil fuel savings of 91% can be achieved by means of this particular biofuel. Similar calculations can be performed for assessing net savings of CO_2 emissions. Given the carbon requirements presented in Table 26, the displacement of ultra low sulphur diesel by biodiesel from conventional or modified production would result in 71% or 86% net savings of CO_2 emissions, respectively. Comparison with the displacement of average UK electricity supplies, with a carbon requirement of 0.150 kg CO_2/MJ (Ref. 14), by SRC-generated electricity results in 84% net savings in CO_2 emissions. Likewise, net savings of GHG can be estimated. Using the GHG requirements summarised in Table 27, net savings in GHG emissions of 57% or 86% can be achieved when ultra low sulphur diesel is displaced by biodiesel from conventional or modified production, respectively. In comparison, 78% net savings of GHG emissions arise when SRC-generated electricity displace average UK electricity supplies with a GHG requirement of 0.162 kg CO_2 eq/MJ (Ref. 14).

6.5 Cost Effectiveness

For completeness, it is necessary to take into account the relative costs as well as the relative benefits of biodiesel production from OSR in the UK. There are various types of relative costs which can be considered. In this study, the costs which are examined are the government subsidies that effectively support a variety of options for reducing CO_2 and GHG emissions. It should be noted that such government subsidies are not being considered here as specific mechanisms for internalising environmental externalities since, in reality, they encompass a range of diverse policy aims. In this context, the relative costs and benefits of these options can be compared by means of **net CO_2 or GHG saving cost effectiveness**, which is equal to the ratio of the net CO_2 or GHG savings and the financial subsidy for the option under consideration. The net CO_2 or GHG savings equal the total CO_2 or GHG emissions avoided or displaced by using a given option less the total CO_2 or GHG emissions associated with the production and/or use of the option. The avoided CO_2 or GHG emissions of an option are calculated in relation to the CO_2 or GHG emissions which arise from the production and/or use of the conventional means of providing a particular product or service such as electricity, heat, etc. This basis for assessing the savings of an option is referred to here as the **comparative reference**.

Indicative results for net CO_2 and GHG saving cost effectiveness of a range of options, including biodiesel produced from OSR, are shown in Tables 28 and 29, respectively. Due to the substantial data requirements of necessary calculations, only a limited range of options could be examined in this study. Additionally, the results presented in Tables 28 and 29 are referred to as indicative because of the significant assumptions and variations which have to be accommodated by the actual estimation of net CO_2 or GHG saving cost effectiveness. Hence, only general comparisons should be drawn from the results given here. The calculation of the net CO_2 or GHG saving costs effectiveness for biodiesel produced from OSR was based on the representative carbon and GHG requirements, provided in Tables 26 and 27, respectively. It was assumed that biodiesel was a potential replacement for ultra low sulphur diesel. The effective subsidy for biodiesel consists of the current fuel duty reduction of 20 pence per litre relative to ultra low sulphur diesel (Ref. 2) or an increased derogation of 40 pence per litre (Refs. 4 and 37) and an Arable Area Payment of £239 per hectare in 2002 (Ref. 38) which, based on the standard data incorporated in the flow chart shown in Figure 1, amounts to a further 19 pence per litre.

Carbon and GHG requirements for heat and electricity produced from SRC wood chip were estimated using a combination of data (Refs. 9, 15 and 36). It was assumed that SRC cultivation would receive the current initial establishment grant of £1,000 per hectare under the Energy Crop Scheme plus annual set-aside payments of £239 per hectare in 2002 (Ref. 39). It was not possible to determine the likely effect on net CO_2 and GHG saving cost effectiveness of new capital grants which are now available for schemes that produce electricity or heat from wood chip. This is because the outcome of such grants cannot be estimated, currently, because of their competitive nature. The net CO_2 saving

Table 28 Indicative Net Carbon Dioxide Saving Cost Effectiveness for a Range of Options

Option	Comparative Reference	Net CO_2 Saving Cost Effectiveness (kg CO_2/£)
Compressed Natural Gas	Ultra Low Sulphur Diesel	2.4
Biodiesel from OSR by Conventional Production - Increased Derogation[(a)]	Ultra Low Sulphur Diesel	3.4
Biodiesel from OSR by Modified Production - Increased Derogation[(a)]	Ultra Low Sulphur Diesel	4.2
Biodiesel from OSR by Conventional Production - Current Derogation[(b)]	Ultra Low Sulphur Diesel	5.2
Biodiesel from OSR by Modified Production - Current Derogation	Ultra Low Sulphur Diesel	6.3
Heat from SRC Wood Chip	Heat from Natural Gas	18.2
Electricity from SRC Wood Chip	Average Electricity, UK 1996	19.6
Heat from Condensing Gas Boiler	Heat from Conventional Gas Boiler	34.4
Glass Fibre Loft Insulation	No Loft Insulation	478.5

Notes

(a) Based on 40 pence per litre reduction in fuel excise duty (Refs. 4 and 38).

(b) Based on 20 pence per litre reduction in fuel excise duty (Ref. 2).

Table 29 Indicative Net Greenhouse Gas Saving Cost Effectiveness for a Range of Options

Option	Comparative Reference	Net GHG Saving Cost Effectiveness (kg CO_2 eq/£)
Compressed Natural Gas	Ultra Low Sulphur Diesel	2.9
Biodiesel from OSR by Conventional Production - Increased Derogation[(a)]	Ultra Low Sulphur Diesel	3.0
Biodiesel from OSR by Modified Production - Increased Derogation[(a)]	Ultra Low Sulphur Diesel	4.2
Biodiesel from OSR by Conventional Production - Current Derogation[(b)]	Ultra Low Sulphur Diesel	4.5
Biodiesel from OSR by Modified Production - Current Derogation[(b)]	Ultra Low Sulphur Diesel	6.5
Heat from SRC Wood Chip	Heat from Natural Gas	17.4
Electricity from SRC Wood Chip	Average Electricity, UK 1996	19.6
Glass Fibre Loft Insulation	No Loft Insulation	506.1

Notes

(a) Based on 40 pence per litre reduction in fuel excise duty (Refs. 4 and 38).

(b) Based on 20 pence per litre reduction in fuel excise duty (Ref. 2).

cost effectiveness of heat from a domestic condensing natural gas-fired boiler was evaluated in comparison with heat from a conventional natural gas-fired boiler. Suitable data were not available to determine the net GHG saving cost effectiveness for this option. The effective subsidy was based on a current grant of £150 per boiler (Ref. 40). Finally, the net CO_2 saving cost effectiveness of glass fibre loft insulation was based on carbon and GHG requirements for glass wool (Ref. 14) and estimates of energy savings from the installation of 250 millimetres thickness of glass wool to an uninsulated loft in a domestic dwelling which is heated by natural gas (Ref. 41). Although various grants are available depending on specific circumstances, the effective subsidy was based on a 20% discount on a typical cost of £240 for installation by a contractor (Ref. 40).

Some general observations can be drawn from the comparison of indicative values of net CO_2 and GHG saving cost effectiveness shown in Tables 28 and 29, respectively. First, it can be seen that, with the current level of derogation, conventionally-produced biodiesel is more cost effective in reducing CO_2 and GHG emissions than CNG as a replacement for ultra low sulphur diesel. It should, however, be noted that level of derogation applied to CNG may reflect other considerations such as its comparatively large resource potential and its relative ease of introduction as an immediate alternative to conventional road transport fuels, as well as significant benefits in terms of low noise and tailpipe emissions (Ref. 42). Second, it is apparent that biodiesel from OSR is clearly less cost effective as a measure for mitigating CO_2 and GHG emissions than a comparable biofuel in the form of SRC wood chip for either heat or electricity production. One particular reason for this is that SRC cultivation is less intensive in terms of agricultural operations and agrochemical use, especially artificial fertilisers which are not needed by this crop. Additionally, SRC wood chip requires considerably less processing for use as a renewable energy source in comparison with biodiesel produced from oilseed rape. Third, biodiesel is even less cost effective than a typical energy efficiency measure such as a condensing gas boiler. Finally, biodiesel is a substantially less cost effective means of reducing net CO_2 and GHG emissions than fabric energy efficiency measures, as represented by glass fibre loft insulation. Obviously, further and more detailed examination of comparative net CO_2 and GHG saving cost effectiveness for a wider range of options would be needed to establish their relative importance as measures supported by government to address commitments to the Global Climate Change Convention. However, it can be seen from this preliminary investigation that it is possible to place biodiesel produced from OSR in the UK in relative context to some alternative options.

7. IMPACTS ON THE RURAL ECONOMY

The impacts on the rural economy of producing biodiesel from OSR in the UK can, in theory, be determined by evaluating the cash flow which enters and propagates through farming communities as a result of cultivating this particular crop. There are two specific elements to the potential flow of money into the rural economy; direct cash flow from the net income of farming and indirect cash flow generated locally by the subsequent spending of this **net income** which is equal to the total revenue, including any subsidies, received for the crop less all off-farm expenditure on purchases, including fertilisers, pesticides, fuel, machinery, etc. Generally, it is assumed that money spent on such purchases does not enter the rural economy. Hence, the net income reflects the combination of profits to the farmer and the salaries of farm labourers. As such, the net income represents the money available to the farmer and farm labourers which could, possibly, be spent in the local community. The secondary impact of this spending depends on the **multiplier effect** which measures the additional spending, income and employment that it generates as cash flows through the economy. In order to set the total impact on the rural economy of growing OSR for biodiesel production in an appropriate context, it must be compared with the economic impact of alternative uses of the land. In terms of this study, comparison with the cultivation of SRC would seem to be most relevant since this is an alternative energy crop which might be grown by farmers on certain types of land.

Although the basis for assessing and comparing the impacts on the rural economy might appear to be quite simple, the actual means of quantification are affected by a number of significant considerations. The first of these is the evaluation of the net income from OSR and SRC cultivation. Very few comprehensive studies seem to have been conducted on the comparative economics of OSR and SRC cultivation. This is presumably due to the relative novelty of SRC cultivation, especially in the UK. Those studies which have been completed have very particular purposes such as the economic comparison of SRC cultivation with sheep production in upland area (Ref. 43). However, one study has been conducted on the comparative economics of growing SRC and OSR, as well as spring barley and winter wheat (Ref. 44). This would appear to provide the most suitable information for this assessment, although some qualification is necessary. In particular, the **gross margin** for OSR is calculated by subtracting annual variable costs from annual revenue. This is compared, in Table 26, with the **equivalent annual value** for SRC derived by **discounted cash flow analysis** to adjust for a crop with a three year cutting cycle over a plantation life of up to twenty four years. It should be noted the estimation of this value, which enables a long duration crop to be compared with an annual crop, also includes some capital costs.

The standard yield incorporated in the flow chart, illustrated Figure 1, and used for calculating the representative primary energy inputs and CO_2 and GHG outputs is 2.90 tonnes of dried rapeseed per hectare per year. Assuming that the yields given in Table 30 also refer to dried rapeseed, then the appropriate estimate of annual net income for winter OSR with subsidy is between £506 and £586 per hectare. For consistency with the sources of energy, CO_2 and GHG data on SRC (Refs. 9 and 36), a yield of 9.00 tonnes of oven dried wood chip per hectare per year can be assumed for SRC production in the UK. Hence, the comparative annual net income for SRC with subsidy is between £197 and £287 per hectare. This indicates a significant economic advantage, in terms of direct cash flow into the local community, from OSR over SRC.

Table 30 <u>Comparison of the Gross Margin of OSR and the Equivalent Annual Value of SRC</u> (Ref. 43)

Crop	Yield (t/ha.a)	Annual Net Income[a] (£/ha.a)	
		Without Subsidy	With Subsidy
Winter Oilseed Rape	2.7[b]	181	506
Winter Oilseed Rape	3.2[b]	261	586
Winter Oilseed Rape	3.7[b]	341	666
Short Rotation Coppice	8.0[c]	7	197
Short Rotation Coppice	10.0[c]	97	287
Short Rotation Coppice	12.0[c]	188	378

<u>Notes</u>

(a) Gross margin for OSR and equivalent annual value for short rotation coppice.

(b) Assumed to be dried rapeseed.

(c) Oven dried wood chip.

This simple comparison of direct cash flow into the rural community must be qualified in a number of aspects. The calculation of the gross margin for a crop, by subtracting variable costs from revenue, means that a large proportion of costs, including capital and other joint costs, are not allocated to specific crops. The sum of gross margins will, therefore, exceed the income of farmers. Income from farming is divided into income from employment, rents and interest, and the residual available to farmers, known as the **total income from farming** (TIFF). It should be noted that the TIFF is very sensitive to agricultural prices and subsidies because many of the farmer's costs are not avoidable in the short run. This argument can also be applied to the yield, at a given price, with improvements in agricultural output resulting in improved TIFF. This will particularly be the case if the increased output is for a new market, such as biodiesel or SRC wood chip, with less likelihood of a downward pressure on the final product. However, the price of any co- or by-products, such as glycerine, may fall as a consequence. Because of the relatively fixed nature of farming costs, particularly in the short to medium term, it is reasonable to regard the gross margin of an additional output, such as winter OSR grown on set-aside land, as a proxy for the net local benefit to the rural economy. This measure of direct cash flow has certain advantages when compared to the measures derived from **input-output analysis**, since the latter assume average values between inputs and outputs, whereas, in this case, it is the marginal value which is relevant. In addition, input-output measures have been developed in a national or regional context to assess economic impacts of policy at these levels of government, which does not match the distinction between rural and urban economies required in this study.

Certain reservations may be made against the use of the gross margin as a measure of direct cash flow into the local economy. It does not include the variable costs of contracting and casual labour which, on average, amounted to £38 per hectare for OSR grown in England and Wales in 1996 (Ref. 45). Some other costs are also incurred, such as plant maintenance, which are not included as variable costs in the standard approach to calculating gross margins. However, these costs will often represent income in the rural economy. Given the absence of more detailed information on these relatively minor points, the gross margin for OSR of between £506 and £586 per hectare is taken to be an appropriate measure of annual direct cash flow in this study. There are also some problems with using the equivalent annual value of SRC as a measure of direct cash flow into the local economy. The method for calculating the equivalent annual value, being essentially an investment appraisal technique, includes capital items and some labour items excluded from the estimation of gross margin. The greater gross margin of winter OSR is not necessarily evidence of a greater impact in the rural economy. Even so, the cultivation of winter OSR could represent better use of existing equipment rather than investment in further capital for growing SRC, thus retaining more of the cash benefit within the rural economy. Specialist equipment may be needed to harvest SRC wood chip (Ref. 43), thereby causing a leakage of cash from the rural economy. On the other hand, the possibility of siting wood-fired power stations in rural area where SRC is grown could improve the flow of cash directly into the rural economy.

In summary, the use of the gross margin for growing OSR on set-aside land seems to be a reasonable proxy for the benefit to rural incomes because of its local, marginalist approach. In contrast, the input-output approach is considered to be less useful because this methodology entails regional and average cost measures. At first sight, it might appear inappropriate to compare the gross margin for growing OSR with the equivalent annual value for SRC cultivation. However, the specific nature of the machinery used in SRC cultivation may require inclusion of the cost of such machinery in the marginalist approach. In this case, such a consideration supports the comparison of equivalent annual value with the gross margin. It should be stressed that this argument holds in the short- to medium-term rather than in the long-term when all costs should be taken into account. Given the urgency of regeneration of the rural economy in the UK, it is reasonable to adopt the approach outlined here as appropriate for this shorter timescale.

Determination of indirect effects on the rural economy depends on evaluating appropriate values for the multiplier effect, or **multipliers**. The economic impact of any new activity can be assessed by first looking at the direct employment, or income effects of the activity, and, secondly, by calculating the indirect employment or income effects of the activity. This second calculation is based on the concept of the Keynesian multiplier which is the ratio of the increase in income to the initial expenditure which brought it about. The multiplier was first introduced as part of Keynesian macro-economic analysis and it derives from the additional expenditures of workers and shareholders in the new activity. These expenditures create, in turn, more new jobs and, therefore, further new incomes. This process could be continued indefinitely but, at each stage of the process, some money is not passed on as expenditure because it is saved, collected in taxes, or spent on imports which benefit other economies. The value for the multiplier is higher for an economy, as a whole, than it is for local communities because, at a local level, much expenditure will be on goods and services produced in other areas of the country. A second version of the multiplier was introduced following the development of input-output analysis. Rather than concentrating on the consumption activities of workers and shareholders, this approach explores the production relationships between different parts of the economy. For example, the production of OSR is also associated with employment in the fertiliser manufacturing and oilseed industries. An increase in the production of OSR will also result in higher employment in these related industries. Identification of the proportion of outputs of one industry which are inputs in another allows the calculation of so-called "Type I multipliers" both for employment and income. The effects of the Keynesian multiplier, which represents the impact of subsequent expenditure, can then be added to this, resulting in what are referred to as "Type II multipliers".

Multipliers based on input-output analysis produce a measure of the interconnectedness of a particular activity with the surrounding economy. Unless a detailed local survey is undertaken, the location of such effects is difficult to determine. The split between rural and urban effects, which is needed to assess the extent of benefits to the rural economy of growing crops, such as OSR or SRC, requires detailed investigation which could not be attempted here. However, some progress can be made in estimating the range of likely outcomes based on existing studies. It is important to note that the use of multipliers in this manner has attracted criticism from neoclassical economists, who currently represent the dominant paradigm in economics, because of concentration on output effects and neglect of price effects. The implicit assumption of both the Keynesian and input-output multiplier analyses is that the removal of an activity will not result in its replacement with another activity. This implies that, if, for example, OSR production is reduced, then no other agricultural production will take place and workers losing jobs in the related fertiliser and oilseed milling industries will not find alternative employment. Neoclassical economists, on the other hand, would argue that these changes in output would affect prices and wages which would alter the allocation of resources, creating new employment and output. While it is clear that the market does not work perfectly to effect such changes, it is also apparent that the loss of employment in one industry may allow a new industry to expand in its place, although some time may be needed to achieve this transition. As a consequence, neoclassical approaches to modelling the economy result in lower values for multipliers. The same economists also reject a basic assumption of input-output analysis that the ratios between inputs and outputs remain the same whatever the level of output is considered. This restriction of input-output analysis presents particular difficulties for its use in the present study.

One estimate of the employment impact of growing OSR for biodiesel production in the UK suggests a ratio of on-farm jobs to total jobs of about 1.56 (Ref. 37). This is based, in part, on the results of an agricultural input-output model of the Grampian region (Ref. 46), although it is not clear how the changing technical coefficients and input-output relationships implied by a shift to biodiesel production, rather than other uses of OSR, could be incorporated in such a calculation. Additionally, this multiplier includes employment in the oilseed milling industry which may not be strictly located in rural areas. Excluding these jobs reduces the ratio to 1.53. Furthermore, it is likely that jobs in the fertiliser and agricultural supplies industries are still included in this revised ratio which, therefore, overestimates the actual multiplier. Instead, it can be argued that a Keynesian multiplier should be used but, given considerable leakages from the local rural economy, this is unlikely to be more than 1.20 or 1.30. A study of the costs and benefits of SRC in the Netherlands infers an employment multiplier of 1.43 (Ref. 47). This is not inconsistent with employment multipliers for forestry operations in England and Wales of between 1.29 and 1.49 (Refs. 48 and 49), but lower than the values of between 1.77 and 1.80 reported for forestry activities in Scotland (Ref. 50). It should be noted, however, that the study of SRC in the Netherlands does not distinguish between effects in rural and urban economies. On this basis, it would seem that the multipliers for both OSR and SRC are generally similar but may overestimate the indirect effects on rural cash flow.

Having established feasible estimates for net annual income and multiplier effects, it is possible to evaluate the impact on the rural economy of growing OSR for biodiesel production and SRC wood chip for heat and electricity generation. This can be achieved by calculating the **cost effectiveness of rural economic impact** which is the ratio of the total benefit to the rural economy from a given crop to the total subsidy for that crop arising directly or indirectly from government policy. The total benefit to the rural economy is the product of the net annual income of the given crop and the relevant multiplier. Subsequent results are presented in Table 31. Estimates of net annual income from different yields of OSR and SRC are extrapolated from Table 30 to obtain values equivalent to annual yields of 2.90 tonnes of dried OSR per hectare and 9.00 tonnes of oven dried wood chip per hectare. The direct government subsidy for OSR is based on the Arable Area Payments scheme rate of £239 per hectare for the UK in 2002 (Ref. 38). It should be noted that such Arable Area Payments must be incorporated into the current analysis since it is an actual subsidy for OSR cultivation, even if it is also available for other crops, and because meaningful comparison can be achieved if its is selectively excluded. The direct government subsidy for SRC is a combination of the Arable Area Payments scheme rate of £239 per hectare for energy crops in the UK in 2002 (Ref. 38) and the establishment grant of £1,000 annualised at a discount rate of 5% over an assumed 30 year life for the plantation (Ref. 39). An indirect government subsidy arises for OSR from the derogation of fuel excise duty on biodiesel. The increased level of 40 pence per litre (Refs. 4 and 37) translates into an indirect government subsidy of £170 per tonne of dried rapeseed based on the data specified in Figure 1. With an annual yield of 2.90 tonnes of dried rapeseed per hectare, this translates into an indirect subsidy of £492 per hectare.

It can be argued that there is an indirect subsidy for SRC used to generate electricity which occurs through the Renewable Energy Obligation (REO). As part of current government policy, REO sets a target on utilities of 10% electricity generation from renewable sources by 2010 (Ref. 51). Although this measure is beginning to create a market in renewable electricity, it is probably too early to determine the average price of such electricity for the purposes of this study. However, REO also fixes a penalty of 3 pence per kWh on utilities which do not fulfil the target (Ref. 51), thereby establishing a likely maximum price for renewable electricity. This provides a basis for the effective indirect subsidy promoted by government policy. The magnitude of this subsidy depends on the average price which the market would bear for electricity generated from any source if REO were not in place. This is difficult to determine currently due to the introduction of the New Electricity Trading Arrangements (NETA) which were introduced on 27 March 2001. However, an indication of the relevant price can be estimated using the previous Pool Purchase Price for which the last weighted average in March 2001 was

Table 31 Comparison of the Cost Effectiveness of Rural Economic Impact of OSR for Biodiesel Production and SRC Wood Chip for Electricity Generation

Crop	Yield (t/ha.a)	Annual Net Income (£/ha.a)	Subsidy (£/ha.a)		Multiplier	Cost Effectiveness of Rural Economic Impact (£/£)
			Direct	Indirect		
Winter Oilseed Rape	2.90[a]	458[c]	239[e]	492[g]	2.67[i]	1.67
Short Rotation Coppice	9.00[b]	307[d]	254[f]	145[h]	2.67[j]	2.05

Notes

(a) Assumed to be dried OSR.

(b) Assumed to be oven dried wood chips.

(c) Annual net income without subsidy of £219/ha.a for an dried OSR yield of 2.90 t/ha.a extrapolated from economic assessment (Ref. 44) plus an Arable Area Payments Scheme rate of £239/ha.a for OSR in the UK in 2002 (Ref. 38).

(d) Annual net income without subsidy of £53/ha.a for an oven dried wood chip yield of 9.00 t/ha.a extrapolated from economic assessment (Ref. 44), plus an establishment grant from the Energy Crops Scheme of £1,000/ha (Ref. 39) annualised at a discount rate of 5% over 30 years to £15/ha.a, plus an Arable Area Payments Scheme rate of £239/ha.a for energy crops on set-aside land in the UK in 2002 (Ref. 38).

(e) Arable Area Payments Scheme rate of £239/ha.a for OSR in the UK in 2002 (Ref. 38).

(f) Establishment grant from the Energy Crops Scheme of £1,000/ha (Ref. 39) annualised at a discount rate of 5% over 30 years to £15/ha.a plus an Arable Area Payments Scheme rate of £239/ha.a for energy crops on set-aside land in the UK in 2002 (Ref. 38).

(g) Based on an effective subsidy of fuel duty derogation of 40 p/l assuming an OSR yield of 2.90 t/ha.a and a resulting biodiesel production rate using solvent extraction of 1,230 l/ha.a.

(h) Based on an effective subsidy of 1 p/kWh equal to a price of 3 p/kWh for the initial level of payments as a means of discharging the renewables obligation (Ref. 51) less the weighted average pool purchase price of 2 p/kWh in March 2001 (Ref. 52), an oven dried wood chip yield of 9.00 t/ha.a and electricity generation of 1,616 kWh/t oven dried wood chips by means of gasification with a thermal efficiency of 35% (Ref. 36).

(i) Type II income multiplier for OSR based on cereal data (Ref. 53).

(j) Type II income multiplier for short rotation coppice assumed similar to the Type II income multiplier for cereal crops (Ref. 53).

2 pence per kWh (Ref. 52). Hence, the effective indirect subsidy is equal to the 1 pence per kWh based on the difference between the REO penalty and the Pool Purchase Price. It should be noted that this estimate is currently a maximum value and that this is likely to vary as the NETA and renewable electricity markets develop. Assuming an annual yield of 9.00 tonnes of oven dried SRC wood chip which can be used to generate 1,616 kWh of electricity per tonne in a power station using gasification at 35% thermal efficiency (Ref. 36), this results in an indirect subsidy of £145 per hectare. Due to expected similarities in the expenditure of farming incomes regardless of the particular crop, the appropriate Type II income multiplier for OSR and SRC might be based on a value of 2.67 derived for cereal crops (Ref. 53). The results shown in Table 31 indicate that, on this basis, there is an approximately 23% greater benefit to the rural economy per £ of total subsidy from SRC cultivation for electricity generation than from growing OSR for biodiesel production.

8. CONCLUSIONS AND RECOMMENDATIONS

This study addresses the need to provide an independent, comprehensive and rigorous evaluation of the comparative energy, global warming and socio-economic costs and benefits of producing biodiesel from OSR in the UK within the context of current debate concerning fuel excise duty derogation. Given the commissioned framework for this study, a completely new evaluation of these issues has not been undertaken. Instead, the study has involved identifying, assessing and using existing work as a basis for deriving representative results and formulating appropriate conclusions to assist policy-makers. A considerably diverse collection of work has been consulted. By necessity, the study has focused on specific aspects of the essential issues. In particular, the effects on fossil fuel depletion have been considered by examining primary energy inputs. Environmental concerns have concentrated on tailpipe emissions, and total CO_2 and GHG emissions. Both energy and environmental benefits have been interpreted in terms of net savings. Socio-economic issues have concerned total impact on the rural economy where benefits may arise from the generation of extra local income. The main costs regarded in the study are taken to be total government subsidies. Subsequent comparisons have been made between biodiesel, ultra low sulphur diesel and CNG, along with SRC wood chip as a major potential biofuel and a sample of common energy efficiency measures. These comparisons have been selected to represent important means available in the UK for mitigating CO_2 and GHG emissions.

Investigation of published test results indicated that consistent comparisons between non-CO_2 tailpipe emissions were not available due to differences in types of road vehicle, driving conditions, engine design and fundamental variability in observed measurements. Most reported differences in non-CO_2 emissions were found to be marginal. However, even significant differences were not necessarily conclusive since, in general, measurements involved trace amounts of tailpipe emissions. Given the inconclusive nature of existing published comparisons of tailpipe emissions data, it is recommended that further clarification should be based on any new tests which provide results, qualified by actual variability, for biodiesel and other fully specified road transport fuels. Despite the numerous shortcomings of existing test data, these clearly demonstrate significant savings in net CO_2 emissions which take into account the well-established fact that tailpipe emissions of CO_2 from vehicles using biodiesel are balanced by CO_2 absorbed during the growth of the oilseed rape crop.

Acknowledgement of effective net zero CO_2 tailpipe emissions of biodiesel underlines the need to evaluate the total CO_2 and GHG emissions, as well as primary energy inputs, of the production of biodiesel from OSR. The basis of this essential evaluation has been established by thorough review of ten existing life cycle assessment or related studies. This has shown significant variations amongst many studies, especially in terms of differences in the complete or partial process chains examined, methods of calculation, definitions, assumptions, etc. Additionally, different degrees of detail and transparency were encountered. As a consequence, substantial differences in results and interpretations of their relevance were apparent. On the basis of qualitative and quantitative assessment, it was concluded that work, referred to as the IFEU 1997 study, provided the most suitable basis for deriving representative results for biodiesel production from OSR in the UK. This conclusion was formed on the basis of the extent of coverage, the level of detail and the clarity of this particular existing work.

Detailed estimates, which incorporate data chosen to reflect typical current conditions in the UK, have been obtained for the total primary energy input (16,269 $\pm$ 896 MJ/tonne of biodiesel), total CO_2 output (916 $\pm$ 52 kg CO_2/tonne of biodiesel) and total GHG output (1,516 $\pm$ 88 kg eq CO_2/tonne of biodiesel). Various activities and inputs to the production of biodiesel contribute to these results. In particular, it has been found that the largest single contribution is associated with the manufacture of nitrogen fertiliser which, alone, accounts for 24% of the total primary energy input, 20% of the total CO_2 output and 51% of the total GHG output. The next most significant contribution is due to the use of methanol in esterification, accounting for 22% of the total primary energy input, 28% of the total CO_2 output and 17% of the total GHG output.

The effect of possible modifications to the conventional production of biodiesel using solvent extraction from OSR has been examined. These modifications consist of growing OSR with low-nitrogen methods, using rape straw to replace natural gas and fuel oil for heating in the biodiesel production process, and using biodiesel as a replacement for conventional diesel in all agricultural machinery and road transport vehicles. Although there are some concerns regarding the practical realisation of these modifications, it is demonstrated that substantial reductions in primary energy inputs, and CO_2 and GHG outputs, might be achieved if such changes are feasible. In particular, it was estimated that the primary energy input could fall by 52% (to 7,750 ± 638 MJ/tonne of biodiesel), the total CO_2 output could decrease by 52% (to 437 $\pm$ 42 kg CO_2/tonne of biodiesel), and the total GHG output could be reduced by 54% (to 702 $\pm$ 53 kg eq CO_2/tonne of biodiesel).

The relative importance of nitrogen fertiliser has been emphasised further by the outcome of subsequent sensitivity analysis. This has also demonstrated the sensitivity of results to OSR yield. In particular, lower rather than higher assumed values of yield have been shown to exert a relatively greater influence on results. It has been noted that the effects of nitrogen fertiliser application rates and yield may be linked and that values for these factors have to be chosen on the basis of consistency and typical practice rather than special trials. It has been concluded that results have to be based on average instead of extreme circumstances in order to reflect national circumstances and, thereby, inform realistic debate and assist policy-makers. Other factors considered by the sensitivity analysis include the effect of the credits arising from applied reference systems for OSR cultivation, and the consequences of variations on the relative prices of rapeseed and rape straw, rapeseed oil and rape meal, and biodiesel and glycerine. It was found that, within realistic limits, these factors have relatively less impact on results than nitrogen fertiliser and OSR yield.

The representative energy requirement, or total primary energy input per unit of energy in biodiesel from OSR in the UK, has been estimated as 0.44 ± 0.02 MJ/MJ (net) for conventional production, and 0.21 ± 0.02 MJ/MJ (net) assuming modified production. These values are at the lower extreme of the range of energy requirements from 0.33 to 0.89 MJ/MJ reported by the earlier studies which have been reviewed here. As would be expected, biodiesel represents a saving of primary energy compared with transport fuels derived from fossil fuel sources. In particular, reductions of 63% to 83% in primary energy input can be achieved in comparison with ultra low sulphur diesel for biodiesel from conventional or modified production, respectively. Similarly, reductions of between 62% and 82% are possible in comparison with CNG. However, the quantity of primary energy used in the conventional production of biodiesel from OSR is somewhat higher than that needed for energy derived from some other biofuels. For example, an energy requirement of 0.29 MJ/MJ of electricity generated from the gasification of SRC wood chip results in a 91% saving of primary energy when such electricity displaces average electricity supplies in the UK.

Calculation of the representative carbon requirement, or total CO_2 output per unit of energy in biodiesel derived from OSR by conventional production in the UK obtained a value of 0.025 $\pm$ 0.001 kg CO_2/MJ (net). This value was found to be towards the higher extreme of the range of values of carbon requirements obtained in previous studies, which vary between - 0.091 and 0.036 kg CO_2/MJ. The carbon requirement of 0.012 $\pm$ 0.001 kg CO_2/MJ (net) for biodiesel obtained using modified production from OSR is about at midrange of these values. In similarity with the expected benefits for fossil fuel depletion, CO_2 emissions savings, amounting to 72% and 86%, were estimated as achievable by biodiesel from conventional or modified production, respectively, in comparison conventional diesel. Likewise, reductions in CO_2 emissions of between 57% and 80% for biodiesel produced from conventional or modified methods were determined relative to CNG. However, there is more similarity between biodiesel and other biofuels in terms of total CO_2 emissions. For example, the carbon requirement of electricity generated from the gasification of SRC wood chip is 0.024 kg CO_2/MJ. If used to displace average electricity supplies in the UK, electricity produced from SRC wood chip would result in 84% net CO_2 emissions savings which are marginally higher than those savings which might be achieved by replacing ultra low sulphur diesel with conventionally-produced biodiesel from OSR.

Further evaluation derived a representative GHG requirement, or total GHG output per unit of energy in biodiesel from OSR in the UK of 0.041 ± 0.002 kg eq CO_2/MJ (net) for conventional production and 0.019 ± 0.001 kg eq CO_2/MJ (net) for modified production. This results in net GHG savings of between 56% and 80%, respectively, over ultra low sulphur diesel and between 31% and 67%, respectively, relative to CNG. The GHG requirement for conventionally-produced biodiesel is slightly higher than that of 0.036 kg CO_2 eq/MJ for electricity generated by the gasification of SRC wood chip. This translates into 78% net savings of GHG emissions when such electricity displaces average electricity supplies in the UK. It is recognised that the comparison of energy, carbon and GHG requirements of biodiesel with those of other biofuels, such as bioethanol, as well as estimated net savings, would probably be helpful. Hence, it is recommended that results from future life cycle assessment and related studies of such biofuels should be taken into account as these become available.

Indicative estimates of the net CO_2 and GHG saving cost effectiveness of biodiesel have been derived. These estimates compare the amounts of CO_2 and GHG emissions saved by biodiesel in comparison with ultra low sulphur diesel per £ value of government subsidies, directly from current and increased levels of fuel excise duty derogation and indirectly through Arable Area Payments to farmers. Assuming conventional production of biodiesel from OSR, values of 5.2 kg CO_2/£ and 4.5 kg eq CO_2/£ were obtained for the current level of derogation of 20 pence per litre, and 3.4 kg CO_2/£ and 3.0 kg eq CO_2/£ for an increased level of derogation of 40 pence per litre. This demonstrates that biodiesel from OSR is more cost effective as a means of saving net CO_2 and GHG emissions that CNG as an alternative road transport fuel. However, it was found that biodiesel is significantly less cost effective than SRC, as an alternative energy crop, and a sample of other CO_2 and GHG emissions mitigation measures. In particular, values of 18.2 kg CO_2/£ and 17.4 kg eq CO_2/£ were derived for heat produced from SRC wood chip and 19.6 kg CO_2/£ and 19.6 kg eq CO_2/£ for electricity generated from gasification of SRC wood chip. Additionally, values of 34.4 kg CO_2/£ for condensing gas boilers, and 478.5 kg CO_2/£ and 506.1 kg eq CO_2/£ glass fibre loft insulation were estimated. From this limited comparison, it is suggested that estimates of cost effectiveness for a wider range of measures might be considered so that these might be set within a comprehensive, complementary and coherent framework of CO_2 and GHG emissions mitigation for the UK.

The relative impact of biodiesel production from OSR on the rural economy has been examined by calculating net annual incomes, equalling total farm revenue less off-farm expenditures, and the relevant rural multiplier, as an indicator of additional income from cash flow through the economy. Detailed examination was constrained by the limited number of existing assessments of net annual incomes from OSR and other crops, their lack of detail and problems with appropriate comparisons. Furthermore, no simple consensus was apparent on values for rural multipliers. Consequently, only general analysis of impact on the rural economy was possible. This undertaken by producing estimates of the cost effectiveness of rural economic impact as the ratio of total benefit to the rural economy from a given crop to the total government subsidy, both directly and indirectly, for that crop. This analysis suggest a possible advantage for SRC grown for electricity generation, with a value 2.05 £/£, compared with 1.67 £/£ for OSR cultivated for biodiesel production. It is recommended, however, that further developments concerning the comparative economics of these particular crops, evaluation of the rural multiplier and the effect of more recent indirect subsidies, such as new grants for wood fuel schemes, might be evaluated accordingly.

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APPENDIX A: Reviews of Studies

This appendix contains single page reviews of all the major published studies which contain results for the energy inputs and carbon dioxide outputs of biodiesel production. These studies have been produced for a variety of purposes. Although some focus on particular issues to provide specific results, others undertake complete life cycle assessments with fully classified, characterised and normalised results. However, their essential commonality is that they incorporate or present relevant data and results. To varying degrees, these studies address, explicitly or implicitly, key considerations which can have a fundamental effect on the results derived. In particular, these considerations include oilseed rape yield, nitrogen fertiliser application and the energy and carbon requirements of nitrogen fertiliser production, cultivation reference systems, and allocation procedures for oilseed and rape straw from oilseed rape cultivation, for rapeseed oil and rape meal from oilseed rape crushing, and for biodiesel and glycerine from esterification. Particular attention is given to these considerations in the following reviews which are intended to examine their transparency and consistency, and to establish their strengths and weaknesses.

These reviews are presented in the chronological order of the publication of the respective studies which, for convenience, referred to by the following abbreviated titles:

ETSU 1992
AFAS 1993
ETSU 1996
VITO 1996
IFEU 1997
ECOTEC 1999
Levington 2000
ECOTEC 2000
ECOTEC 2001
CSIRO 2002
ECOTEC 2002

ETSU 1992 Study

A Review of the Potential of Biodiesel as a Transport Fuel

F. Culshaw and C. Butler

ETSU-R-71,
Energy Technology Support Unit,
Harwell,
Oxfordshire OX11 0RA,
UNITED KINGDOM.

September 1992

This study represents an early attempt in the United Kingdom to evaluate the energy inputs and carbon dioxide outputs from the production of biodiesel from oilseed rape. Fairly detailed and transparent energy balances are presented for biodiesel production from winter and spring oilseed rape. Less detailed and transparent carbon savings are given for biodiesel production from winter oilseed rape only.

Cultivation assumptions appear to be based on information provided by the former Ministry of Agriculture, Fisheries and Food in 1991. No reference system for cultivation is used in the calculations. The main energy input to biodiesel production is nitrogen fertiliser and the energy requirement used is relevant to the level of information available at the time. There is one odd though minor point in the energy balance which is the assumption that the energy requirement of the seed is based on the calorific value of its oil content.

More importantly, the effective allocation of energy inputs between biodiesel and the by-products, consisting of straw, meal and glycerine, is based on their respective calorific values. There is no convincing explanation of this approach which cannot be justified since only one product, biodiesel, will actually be consumed in combustion for its energy content. Although the straw may also be burnt for energy purposes, it might also be disposed of by alternative means. Furthermore, the meal and glycerine have very specific, non-energy uses.

This allocation procedure is also inconsistent with that which is, effectively, used in the estimation of carbon dioxide savings. Assumptions about the possible combustion of straw, meal and glycerine are not wholly justified. Additionally, any savings in carbon dioxide, due to the use of these by-products as alternative energy sources to coal, are added to net carbon dioxide savings derived from the replacement of conventional diesel with biodiesel. This is not the same as the allocation procedure for the energy balance. Instead, for consistency, it would be necessary to divide carbon dioxide outputs from biodiesel production between this main product and its by-products pro-rata by energy content.

There are two other problems with the carbon dioxide calculations. First, the important assumption that 62.6% of the carbon dioxide associated with nitrogen fertiliser production is allocated to this particular product is not explained. Second, it is assumed, incorrectly, that the carbon dioxide outputs of all other aspects of biodiesel production are based on the emission factor for oil. As a consequence, the carbon dioxide savings presented in this study cannot be recommended for subsequent use without careful qualification. Additionally, the results of the energy balance are only meaningful if the effects of the inappropriate allocation procedure are corrected.

AFAS 1993 Study

Technikfolgenabschaatzung zum Thema Nachwachsende Rohstoffe
(Technical Process Assessment of Renewable Energy Raw Materials)

D. Wintzer, B. Furniss, S. Klein-Vielhauer, L. Leible, E. Nieke, Ch. Rosch and H. Tangen

Abteilung für Angewandte Systemanalyse Kernforschungszentrum Kahlsruhe GmbH,
(Division for Applied Systems Analysis, Nuclear Research Centre)
GERMANY.

1993

This book looks into details in agricultural practices and the effect of the use of fertilisers on yields, primary energy input and emissions to the atmosphere, such as carbon dioxide, nitrous oxide, etc., for several biofuels including winter rapeseed. It considers, in depth, the following three practices of using fertilisers:

> Hohe Intensität (high intensity) cultivation: using a high input of nitrogen fertilisers (180 kg N/ha.a)
> N-Angabe (nitrogen-conserving) cultivation: using a mixture of organic and mineral fertilisers (135 kg N/ha.a)
> WSG cultivation: using organic fertilisers in compliance with German Water Protection Act.

Results are produced from 1987 data, representing then-current circumstances, as well as projections for 2005, when technological improvements in technology have occurred and when it is assumed that the burning of oilseed rape straw would be commonplace so that this can be accounted as an energy credit.

The primary energy input to the manufacturing of fertilisers is given as a total of all fertilisers grouped together. Unfortunately, this lack of transparency means that it is not possible to determine and compare specific primary energy inputs for each type of fertiliser. However, the primary energy inputs of 11.32 GJ/ha.a and 9.06 GJ/ha.a for the production of fertilisers used in Hohe Intensität and N-Angabe cultivation, respectively, are comparable to other studies published during the same period.

No detailed calculations are carried out for the conversion processes (oil extraction and esterification). Instead, the process energy input is given as a percentage (47%) of the calorific value of the ultimate product which is biodiesel. It is not very clear what basis is applied for allocating energy inputs between this main product and the resulting by-products.

For carbon dioxide emissions, a comparison is carried out between biodiesel and conventional diesel. Again, the basis of calculations is not sufficiently transparent as results are only presented in terms of total, process and net carbon dioxide emissions. However, these results seem to be comparable to other studies for the same period (for example, the ETSU 1992 Study).

ETSU 1996 Study

Alternative Road Transport Fuels – A Preliminary Life-cycle Study for the UK

M. P. Gover, S. A. Collings, G. S. Hitchcock, D. P. Moon and G. T. Wilkins

R92, Volume 2,
Energy Technology Support Unit,
Harwell,
Oxfordshire OX11 0RA,
UNITED KINGDOM.

March 1996

This study evaluates the primary energy inputs and airborne emissions, including carbon dioxide, of the production and use of a range of road transport fuels, including biodiesel from oilseed rape. Other airborne emissions consist of carbon monoxide, hydrocarbons, oxides of nitrogen, sulphur dioxide and particulates. The other transport fuels comprise conventional petrol and diesel, liquefied petroleum gas, natural gas, electricity, biomethanol and bioethanol. Subsequent results for biodiesel represent updates of those derived in the ETSU 1992 Study. These results are presented in considerable detail, important assumptions are explained and various options are investigated. As before, the cultivation of both winter and spring oilseed rape is considered. However, in this instance, revised estimates of the primary energy input and carbon dioxide output for the manufacture of ammonium nitrate fertiliser are incorporated. The possibility of using straw, obtained during harvesting, as an alternative fuel to natural gas in oilseed rape processing is considered as an optional energy credit in the calculations.

Although the ETSU 1992 Study is the source of data in the calculations for oilseed crushing, results for this specific activity do not seem be comparable, possibly as a consequence of the units used in reporting. In general, estimated primary energy inputs and carbon dioxide and other emission outputs appear for oilseed crushing, oil refining and esterification appear to be considerably higher than the ETSU 1992 Study. Additionally, it is unclear whether oilseed drying has been taken into account. The allocation procedure for rapeseed oil and rape meal is based on the substitution of rape meal with soya meal, thereby resulting in an energy credit. Unlike the ETSU 1992 Study, an energy credit for glycerine is not used as a basis for the allocation procedure in oil refining and esterification. In fact, no allocation procedure is applied because it is recognised that substitution or replacement is not an option since all other sources of glycerine are also by-products of "other processes such as soap manufacture". Although this presents obvious difficulties, it is not appropriate to ignore glycerine completely in these calculations.

A series of results are presented in the form of different options depending on cultivation, and the treatment of straw and rape meal in calculations. Options concerning the use of straw as a fuel and the substitution of rape meal by soya meal are discussed and these are set in the context of current circumstances and realistic future possibilities. It appears that the recommended results are based on the assumption that natural gas, rather than straw, is used in biodiesel processing, so that no energy credit given for straw, and that an energy credit for rape meal is incorporated, based on substitution by soya meal.

VITO 1996 Study

Comparative Life-Cycle Assessment of Diesel and Biodiesel

C. Spirinckx and D. Ceuterick

Vlaamse Instelling voor Technologisch Onderzoek,
(Flemish Institute for Technological Research)
Mol,
BELGIUM.

1996

The purpose of this assessment is to compare the environmental impacts of biodiesel with "fossil" diesel. As such, the established principles of life cycle assessment are applied rigorously. Subsequent results have been reported in numerous papers. Unfortunately, the actual details of the calculations are only partly described in these papers. In some instances, quite detailed assumptions and background data are presented in full, whilst in other instances, only limited information is provided. The basis of the calculations is, however, set out completely. The goal, scope, functional unit and systems boundaries are all defined with care. In particular, it is specified that the source of the biodiesel is winter oilseed rape grown in Belgium. Additionally, it is noted that rapeseed oil extraction is based on treatment by hexane as a solvent as an alternative to crushing.

The initial seed input, yield, straw production and the fuel consumption of all agricultural operations are specified but resulting primary energy inputs and associated carbon dioxide emissions are not presented. The energy requirement of nitrogen fertiliser is stated but neither the application rate nor the carbon requirement are quoted. The consumption of specific inputs, such as electricity, steam and hexane for rapeseed oil extraction, and electricity and steam for esterification and refining are summarised but the conversion into primary energy inputs and carbon dioxide emissions is not presented. However, the allocation procedures for the by-products are described in adequate detail. In particular, the energy and emissions of cultivation are divided between oilseed and straw on the basis of mass, whilst the energy and emissions of processing are partitioned between rapeseed oil and rape meal, and between biodiesel and glycerine on the basis of their prices. The effects of other allocation procedures, involving the use of relative energy contents or prices throughout, are examined.

Results are presented in considerable detail but not in a format which is totally helpful for subsequent comparison. In keeping with the principles of life cycle assessment, results are subjected to classification, characterisation and normalisation. Unfortunately, this leads to the aggregation of results at a very early stage, so that important details are lost. It is possible to identify the estimated total primary energy input but total carbon dioxide emissions are subsumed within combined GHG emissions, measured in terms of equivalent carbon dioxide output.

IFEU 1997 Study

Nachwachsende Energieträger - Grundlagen, Verfahren, Ökolgische Bilanzierung
(Renewable Energy Sources, Basis, Processes and Ecological Balance)

M. Kaltschmitt and G. A. Reinhardt (eds)

Institut für Energie- und Umweltforschung Heidelberg GmbH,
(Institute for Energy and Environmental Research)
GERMANY.

1997

This is a very thorough study which examines, in detail, the life cycles, consisting of cultivation and conversion, of several biomass energy sources, including rapeseed oil and biodiesel; rape methyl ester (RME). Primary energy inputs of cultivation include energy inputs for fertilisers, pesticides, agricultural machinery, storage and transport of products. Conversion processes include drying, oil extraction, refining and esterification.

A detailed derivation of the energy requirement for producing of ammonia, calcium ammonium nitrate and urea is carried out. In particular, weighted averages for the energy and carbon requirements of German nitrogen-based fertilisers are based on their nitrogen content and country of origin (47.1 MJ/kg N, including transport but excluding infrastructure and packaging). The resulting carbon requirement is 2.468 kg CO_2/kg N. These are considered to be a rather low figures compared with those of other studies. A reference system of fallow set-aside with occasional mowing is assumed in cultivation calculations.

Assessment of primary energy inputs and equivalent carbon dioxide emissions in the processes of oil extraction and esterification is very detailed. This takes into account primary energy inputs to produce methanol (38.08 MJ/kg) and hexane (52.05 MJ/kg), and a range of other chemicals as well as thermal and electrical energy required for the processes. Oil extraction and esterification are found to account for about 75% of the total primary energy inputs to biodiesel production. A sensitivity analysis is conducted on the following allocation procedures:

> energy content of rapeseed oil, rape meal, glycerine and biodiesel,
> mass of rapeseed oil, rape meal, glycerine and biodiesel,
> price of rapeseed oil, rape meal, glycerine and biodiesel,
> mass of rapeseed oil and rape meal, energy content of glycerine and biodiesel,
> price of rapeseed oil and rape meal, and energy content of glycerine and biodiesel,

Additionally, the effects of burning rape meal in other plants, thereby providing an energy credit, and of allocating all inputs and emissions to biodiesel, are considered. The burning of rape meal results in the highest energy and emission savings, followed by allocation on the mass-energy basis. Allocation on the basis of energy content gives similar results to those for price-energy and energy-mass allocation. The lowest energy and emissions savings occur when all inputs and emissions are allocated to biodiesel alone.

Comparisons are made with net energy gains from other biofuels. Combustion of wheat (whole plant), miscanthus and wood chips from poplar give the highest net energy gains (150 GJ/ha.a), followed by the combustion of other cereals, such as triticale, barley and rye, (whole plant), reed and willow (110 GJ/ha.a), then cocksfoot grasses and rape straw used in heating plants, and ethanol production from sugarbeet and wheat (50 - 100 GJ/ha.a). Biodiesel, rapeseed oil, ethanol from potato and use of forest residues, such as spruce wood, beech and grass cuttings result in the lowest net energy gains (35 GJ/ha.a). Similarly, liquid biofuels demonstrate the lowest net equivalent carbon dioxide savings, with 70 kg CO_2/GJ for biodiesel.

ECOTEC 1999 Study

Financial and Environmental Impact of Biodiesel as an Alternative to Fossil Diesel in the UK

ECOTEC Research and Consulting Ltd

Priestly House,
28-34 Albert St,
Birmingham B4 7UD,
UNITED KINGDOM

November 1999

This study was commissioned by the British Association for Bio Fuels and Oils (BABFO) to review selected parts of the ETSU 1996 Study. Throughout, figures are based on this study and ETSU 1998 field trials data, with updates derived from information from BABFO and Cargill plc, and with adjustments to assumptions and the method of calculation. Results are aggregated and expressed as "greenhouse gas" and converted into "per kilometre" terms, which reflects the variations in energy content and fuel efficiency during fuel combustion in the vehicle.

The main sources of deviation from the ETSU 1996 Study are as follows. Using data from Cargill Plc, it is suggested that the ETSU 1996 Study greatly overestimates the energy requirement for crushing oilseed; and this is reduced from 238 MJ/GJ to 12 MJ/GJ. Additionally, it is proposed that the energy estimates for agricultural machinery are too high, and it is assumed that mowing still needs to be carried out on set-aside land in order to keep it in fit condition if it is not used to grow oilseed rape.

Although it is stated that the assumed yield is 3.2 tonne of rape methyl ester (RME)/ha.a, it would appear that this figure should be given in terms of tonnes of rape oilseed, which would be consistent with the data used in the ETSU 1992 Study. No total nitrogen fertiliser input to the land is stated explicitly, although a total fertiliser input of 290 kg/ha.a is quoted. Since energy inputs and carbon dioxide outputs are not provided on a "per tonne of nitrogen" basis, effective comparison is limited.

Apparently in relation to the use of a reference system, it is stated that “it has been assumed set-aside practices will require a quarter of the diesel used in growing rape”. The source of this assumption is given as BABFO. Hence, it would appear that this assumption is reflected in the eventual results, although the calculations are insufficiently transparent in many areas to establish whether and, if so, how this has been achieved.

Methanol, which is required in biodiesel production, is not accounted and the allocation of by-products is not discussed in terms of the biodiesel production. Therefore, it would seem that no allocation is carried out, even though the allocation energy inputs and GHG emissions for diesel is carried out on an energy content basis.

LEVINGTON 2000 Study

Energy Balances in the Growth of Oilseed Rape for Biodiesel and of Wheat for Bioethanol

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Levington Park,
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Suffolk IP10 0LU,
UNITED KINGDOM.

June 2000

This study concentrates on the agricultural inputs for the cultivation of oilseed rape. Although some data are presented on processing and biodiesel production, these are drawn primarily from an ECOTEC 1999 Study. The main crop examined, for the purposes of this review, is winter oilseed rape. Two agricultural options are considered; the first assumes the rape straw is ploughed in after the oilseed has been harvested, while the second assumes rape straw is utilised as an energy crop in an energy generation facility within 30 miles distance of the field.

Considerable attention is given to the issue of oilseed rape yields. A key variable in determining these yields is the rate of nitrogen fertiliser application, and the study concludes that the most efficient rate is 180 kg N/ha.a which, based on field trials in the period 1994-8, produced an average yield of 4.08 tonnes of oilseed/ha.a. The fertiliser application rate is close to current actual rates, but the yield figure is high compared to both those used in other studies and to those then-currently achieved in the United Kingdom. Average rapeseed yields are more typically around 3 t/ha and have not risen dramatically over the last 2 decades, so it is unclear whether the yields observed in the Levington trials could realistically be expected on a large scale, particularly given that set-aside land generally produces lower than average yields.

A total of five applications of agrochemicals are assumed to be required. No lime application is mentioned. Fertiliser applications are calculated and, for nitrogen, data for emissions from a modern fertiliser manufacturing complex are presented, derived from the European Fertilizer Manufacturers' Association in 1997. These suggest a major reduction in energy inputs and GHG outputs compared to previous studies, including the ETSU 1992 Study. A mean figure for carbon dioxide emissions of 1.14 kg CO_2/kg N is adopted, with a quoted range of 0.45 to 2.08 kg CO_2/kg N. However, the stochiometric relationships for ammonium nitrate production from natural gas alone suggests that the minimum amount of carbon dioxide generated is 1.57 kg CO_2/kg N. This implies that only part of the carbon dioxide requirement is likely to have been accounted for, and/or the authors have assumed that a large fraction of the carbon dioxide might be recovered for subsequent use. While industrial recovery of carbon dioxide from this process is commonplace, there is every possibility that this is eventually released into the atmosphere.

The processing and biodiesel production process figures, based on the ECOTEC 1999 Study, do not mention drying nor methanol inputs, although the former may be included in the processing data. An energy requirement figure is presented for each of the straw options (0.561 MJ/MJ for plough-in and 0.573 MJ/MJ for straw utilisation). No allocation procedure for biodiesel and its by-products is used, although it is suggested that this should be based on their energy content.

ECOTEC 2000 Study

Emissions from Liquid Biofuels

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UNITED KINGDOM

2000

The purpose of this report was to update and extend the ECOTEC 1999 Study, which was based on the ETSU 1992 and 1996 Studies, and the 1998 field trials. Specifically, this update was undertaken in the light of the Levington 2000 Study, which derived a detailed energy balance for biodiesel (and bioethanol) production.

This report indicates that there are "many differences in the values of parameters in the ETSU and Levington studies", and selects three of them; a rise in oilseed rape yield, different energy efficiency and emissions data for fertiliser production, and higher nitrous oxide emissions from the fertiliser manufacture process.

Regarding oilseed rape cultivation, the report cites the following yields; 3.20 t/ha.a for the ETSU 1992 and 1996 Studies; 3.60 t/ha.a from the Agricultural Budgeting and Costing Standard Pocketbook 1999, and 4.08 t/ha for the Levington 2000 Study. It concludes that the latter is "most up to date". However, there appears to be insufficient justification from the Levington trials data for assuming current national yields on set-aside land could be expected to average 4.08 t/ha.a. In fact, figures published by the Department for Environment, Food and Rural Affairs for actual yields for 2001 were 2.6 t/ha.a on non-set-aside land and 2.5 t/ha.a on set-aside land. Despite some lack of transparency in the calculations, it is clear from the text that the report establishes that the figures for carbon dioxide emissions for fertiliser in the ETSU 1992 Study are under-estimated.

Regarding oilseed rape processing, the report shows that, on a per hectare basis, energy inputs and carbon dioxide outputs are increased in the Levington 2000 Study compared to the earlier ETSU 1992 Study. In fact, it is stated that "the higher yields of rape from the land are partly balanced by increased emissions from the use of tractors". However, on a per tonne of biodiesel produced basis, processing inputs are lower using data from the Levington 2000 Study.

No allocation of energy inputs and carbon dioxide outputs between biodiesel and associated by-products is discussed. Although the energy content of rape straw and cake are stated, the data are presented in energy balance terms and, therefore, it appears that all of the calculated emissions associated with oilseed rape and biodiesel production is attributed to the biodiesel.

ECOTEC 2001 Study

Lifecycle Greenhouse Gas Assessment of RME - Comparative Emissions from Set-aside and Wheat

ECOTEC Research and Consulting Ltd

Priestly House,
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Birmingham B4 7UD,
UNITED KINGDOM

2001

This report updates and extends the ECOTEC 1999 and 2000 Studies, which were based on the ETSU 1992 and 1996 Studies, and 1998 field trials. The main purpose of the report is to establish the theoretical basis for using wheat cultivation and set-aside cultivation as reference systems for oilseed rape cultivation, and to identify the GHG implications of these alternatives in relation to rape methyl ester (RME) production. As with the earlier ECOTEC Studies, figures are aggregated and expressed as "greenhouse gas emissions" and converted into "per kilometre" terms. Since calculations are not fully transparent, the carbon dioxide emissions components of the emissions are not generally explicit.

The logic of using reference systems is not incongruent with life cycle assessment, although it is rarely done because it complicates the study parameters and effectively constrains the relevance of the results to a case or site-specific basis. Assuming that the alternative is fallow set-aside, then any energy input required to maintain set-aside can, theoretically, be subtracted from that for oilseed rape cultivation. However, this is only possible because such set-aside produces no products, and where sufficiently accurate energy inputs and carbon dioxide outputs for set-aside maintenance can be established. Where wheat production is concerned, despite the possibility that the market may currently be saturated with wheat, subtracting the entire energy input of wheat production is problematic. This is because wheat is a traded commodity and it still has a value, and therefore it is unclear which land (if any) would cease to produce wheat if the effect of Common Agricultural Policy measures were removed, or what the effect would be on demand for and production of wheat.

The GHG emissions estimate for wheat cultivation used in the report (106.2 kg C/ha.a) is for farm machinery fuel and was supplied by Cargill plc. As stated in the report, the estimate for maintaining fallow set-aside land was derived as follows: “After phoning a number of agricultural advisers (ADAS, agricultural colleges and a farm energy efficiency centre), we were advised that fuel consumption arising from agricultural operations on set-aside land was typically between 10% and 20% of that on land under cereal.” Applying a factor of 15% to the estimate for wheat cultivation, the report obtains an average of 15.9 kg C/ha.a as the credit for set-aside. However, this is subsequently stated as "15.9 kg C/t RME", suggesting either that it is assumed that 1 tonne of RME is produced per hectare of oilseed rape, or, more likely, that the appropriate conversion has not been applied.

Regarding oilseed rape cultivation and biodiesel production, figures include an assumed oilseed rape yield of 3.20 t/ha.a, with an average fertiliser application rate of 188 kg N/ha.a. The carbon requirement for fertiliser is assumed to be 2.829 kg CO_2/kg N. Processing results include the use of methanol, and a credit for glycerol, based on a market value allocation.

CSIRO 2002 Study

Comparison of Transport Fuels – Life-Cycle Emissions Analysis of Alternative Fuels for Heavy Vehicles

T. Beer, T. Grant, G. Morgan, J. Lapszewicz, P. Anyon, J. Edwards, P. Nelson, H. Watson and D. Williams

CSIRO (Commonwealth Scientific and Industrial Research Organisation) in association with the University of Melbourne , RMIT Centre for Design, Parsons Australia Pty Ltd., and Southern Cross Institute of Health Research,
Aspendale,
Victoria,
AUSTRALIA.

2002

This report consists of a very extensive collection of life cycle assessments of a considerable range of conventional and alternative road transport fuels, including biodiesel, in current or future use in Australia. In general, the report relies on a mixture of new work and modified earlier studies. In particular, the assessment of biodiesel relies quite heavily on the VITO 1996 Study, adjusted to Australia conditions, where necessary. One major modification is the adoption of a typical application rate for nitrogen fertiliser of 20 kg N/ha.a based on Australian statistics. This is considerably less than the application rates observed in the cultivation of oilseed rape in Europe and subsequently adopted in relevant studies. The energy and carbon requirements of nitrogen fertiliser manufacture are not specified. Other data, such as fuel consumption, derived from appropriate Australian agricultural statistics, appear to have been combined with Belgium data in the calculations. Canadian data are also used which implies that rapeseed oil extraction is based on oilseed pressing followed by treatment with hexane solvent. It is unclear whether the use of methanol is accounted for in esterification.

There is discussion of the allocation procedure for dividing the energy inputs and emissions of cultivation between the oilseed and straw based on the VITO 1996 Study and the ECOTEC 1999 Study. However, it would appear that allocation is not required since "In Australia the current practice is to leave the straw and stubble in the field as its quality does not warrant production into straw for feed, and the quantity is not sufficient for field burning". Allocation procedures for biodiesel, rape meal and glycerine are also considered and it seems to be suggested that this was based on some aspect of the energy content of these by-products. Unfortunately, the precise approach adopted is not clarified by discussion of the relative value of these by-products as fuels, which refers to straw as an example, even though this has, apparently, been reasonably dismissed from consideration. Confusingly, it is concluded that "…when calculating upstream emissions, the energy stored in by-products is considered of lower quality than the energy stored in biodiesel or diesel oil".

In general, the report is very wide in its coverage and attempts to provide an extremely comprehensive set of results. However, although considerable detail is given, the lack of complete transparency, certain incoherent explanations, slightly erratic organisation of information, occasional misquotation of data and inconsistencies in terms used present fundamental problems for determining key assumptions and deciphering the basis of calculations. This, combined with the fact that the report explicitly addresses biodiesel production in Australia, limits the comparison of these results with those for European conditions.

ECOTEC 2002 Study

Analysis of Costs and Benefits from Biofuels Compared to Other Transport Fuels

ECOTEC Research and Consulting Ltd., Birmingham, United Kingdom

Priestly House,
28-34 Albert St,
Birmingham B4 7UD,
UNITED KINGDOM.

2002

This study was commissioned by the British Association for Bio Fuels and Oils (BABFO) to compare the environmental and energy security benefits of biodiesel, bioethanol, compressed natural gas, liquefied petroleum gas, ultra-low sulphur diesel and ultra low sulphur petrol. It is mainly concerned with the potential implications of current and potential policy developments on the duty levied on these fuels. It concludes that biofuels offer a range of environmental and energy security benefits which are equivalent to or greater than those offered by road fuel gases.

Throughout, figures relating to life cycle aspects of biodiesel are based on the ECOTEC 2001 study and earlier work by ECOTEC, which generally draws upon ETSU 1996 and Levington 2000 studies. Hence, as with the ECOTEC 2001 study, life cycle impacts results are aggregated and expressed as 'greenhouse gas' and converted into 'per km' terms.

The new work contained within the study is not of direct relevance to the current review work. It involves deriving and applying weights to different tailpipe emissions and aggregating the results. It also attempts to quantify security of supply risks, and uses ExternE figures (the quoted source is "Royal Commission on Environmental Pollution, 1998") to derive monetary values for environmental damage, to provide a valuation in EURO/km for life cycle greenhouse gas emissions. It should be noted that the ExternE study is the most comprehensive external costing study to date and provides a major step forward in terms of producing data for use in valuation. However, the valuation method used is based mainly on drawing generic values from the neo-classical environmental economics literature and applying them to the quantified impacts. Thus, in terms of results, these may be more accurate than those of previous studies, but in terms of efficacy of valuation method, many of the general weaknesses of environmental economics monetisation still apply, with wide ranges of estimates being cited for monetary damages resulting from emissions.

Energy ratios quoted are the same as for the earlier reports as stated above, and the figures are therefore not transparent. The report culminates in a discussion of the case for reducing the duty levied on biodiesel and bioethanol, compared to that for comparative fossil-derived fuels, particularly in the context of diversification of farming into non-food crops, and the idea of taxing road fuels in relative accordance with their global climate change effect. Therefore, while this study may contribute to the wider debate about biofuels, it does not provide any new analysis, evidence or calculations of energy or greenhouse gas associated with biodiesel production.

APPENDIX B: Summary Sheets

The following summary sheets present the key parameters and main results of the prominent published studies which have been reviewed in Appendix A. The key parameters are those which have the greatest influence on the main results. Where necessary, these parameters and subsequent results have been converted into common units to assist with comparison. Additionally, the main results are presented in both adjusted and unadjusted formats. The adjusted format refers to results which do not take into account any credits for a reference system of cultivation nor allocation between main, waste, by- and co-products. As such, adjusted results represent basic estimates which can be, effectively, compared directly with each other. In contrast, the unadjusted results consist of the estimates which are presented in the original studies and, consequently, include any assumptions for reference systems and allocation procedures adopted by these studies. The following notes apply to all the summary sheets:

(a) This is a brief description of the general features of the means of cultivating oilseed rape as a source of rape methyl ester (RME) for biodiesel.

(b) This records the total estimates of primary energy inputs and carbon dioxide outputs of oilseed rape cultivation, which would normally be assumed to include all agricultural operations, all fertiliser applications, and transport from the farm to the processing plant.

(c) The reference system refers to the most likely use of the land if oilseed rape is not grown for biodiesel production. Normally, the primary energy inputs and carbon dioxide outputs for this alternative use of the land are subtracted from those of oilseed rape cultivation for biodiesel production in the calculations.

(d) This is a brief description of the technique used to convert oilseed rape into rape methyl ester for biodiesel production.

(e) This records the total estimates of primary energy inputs and carbon dioxide outputs of oilseed rape processing to derive RME for biodiesel production. This includes drying, crushing and refining, incorporating esterification with methanol. Additionally, transport for the distribution of biodiesel may be included.

(f) This summarises, briefly, the means of partitioning primary energy inputs and carbon dioxide outputs between the products which arise from biodiesel production from oilseed rape. Typical, these products would include oilseed rape straw (a waste product), oilseed meal/feed/cake (a by-product or co-product) and glycerine/glycerol (a by-product or co-product).

(g) The final results consist of two types; total primary energy input or carbon dioxide output per unit energy content of biodiesel, and total primary energy input or carbon dioxide output per unit weight of biodiesel. Furthermore, distinctions are drawn between unadjusted results, which do not take into account credits from the reference system nor allocation between main, waste, by- or co-products, and adjusted results, which do take into account of these considerations according to the approach adopted in the original source.

(h) This is the fuel against which biodiesel is compared.

(i) The savings are those arising from the use of biodiesel instead of the specified reference fuel.

SUMMARY SHEET FOR LIFE CYCLE ASSESSMENT OF BIODIESEL PRODUCTION		
SOURCE: "A Review of the Potential of Biodiesel as a Transport Fuel" by F. Culshaw and C. Butler, ETSU-R-71, Energy Technology Support Unit, Harwell, United Kingdom, September 1992.		
SPECIFICATIONS OF RME:	Density (kg/l) = 0.880	
	Energy Content (MJ/kg) = 37.10 (net)	
CULTIVATION[a]: Winter oilseed rape with a yield of 3200 kg/ha.a		
N Fertiliser:	Input (kg N/ha.a) = 260	
	Yield (kg RME/ha.a) = 1184	
	Energy Requirement (MJ/kg N) = 59.70	
	Carbon Requirement (kg CO_2/kg N) = 1.87	
Totals[b]:	Energy Input (MJ/ha.a)	Carbon Output (kg CO_2/ha.a)
	21,167	877
Reference System[c]:	None	
	Energy Credit (MJ/ha.a)	Carbon Credit (kg CO_2/ha.a)
	0	0
PROCESSING[d]:		
Methanol:	Input (kg methanol/kg RME) = 0.095	
	Energy Requirement (MJ/kg methanol) = 19.70	
	Carbon Requirement (kg CO_2/kg methanol) = ?	
	Energy Input (MJ/kg RME)	Carbon Output (kg CO_2/kg RME)
Drying:	1.43	?
Extracting:	3.47	?
Refining:	1.84	?
Totals[e]:	9.60	0.67
ALLOCATION[f]: It is assumed that the by-products (rape meal, glycerine and straw) could be burnt, so that energy inputs are allocated, effectively equally, by energy content to the energy output of all products. Carbon dioxide emissions avoided by using by-products to replace fossils fuels are added to carbon savings.		
FINAL RESULTS[g]:		
Per Energy	Energy (MJ/MJ)	Carbon (kg CO_2/MJ)
unadjusted:	0.74	0.038
adjusted:	0.27 to 0.40	- 0.047 to - 0.136
Per Weight:	Energy (MJ/kg RME)	Carbon (kg CO_2/kg RME)
unadjusted:	27.48	1.41
adjusted:	9.84 to 14.84	- 1.76 to - 5.06
REFERENCE FUEL[h]:	Density (kg/l) = 0.830 to 0.850	
	Energy Content (MJ/kg) = 42.90 (net)	
	Gross Energy Requirement (MJ/MJ) = 1.17	
	Gross Energy Requirement (MJ/kg) = 59.94	
	Carbon Requirement (kg CO_2/MJ) = 0.069	
	Carbon Requirement (kg CO_2/kg) = 2.97	
ESTIMATED SAVINGS[i]:		
Per Energy	Energy (MJ/MJ)	Carbon (kg CO_2/MJ)
unadjusted:	0.43	0.031
adjusted:	0.77 to 0.90	0.116 to 0.205
Per Weight	Energy (MJ/kg RME)	Carbon (kg CO_2/kg RME)
unadjusted:	24.36	1.16
adjusted:	37.00 to 42.00	4.33 to 7.63

SUMMARY SHEET FOR LIFE CYCLE ASSESSMENT OF BIODIESEL PRODUCTION		
SOURCE: "A Review of the Potential of Biodiesel as a Transport Fuel" by F. Culshaw and C. Butler, ETSU-R-71, Energy Technology Support Unit, Harwell, United Kingdom, September 1992.		
SPECIFICATIONS OF RME:	Density (kg/l) = 0.880	
	Energy Content (MJ/kg) = 37.10 (net)	
CULTIVATION[a]: Spring oilseed rape with a yield of 2200 kg/ha.a		
N Fertiliser:	Input (kg N/ha.a) = 150	
	Yield (kg RME/ha.a) = 814	
	Energy Requirement (MJ/kg N) = 59.70	
	Carbon Requirement (kg CO_2/kg N) = 1.87	
Totals[b]:	Energy Input (MJ/ha.a)	Carbon Output (kg CO_2/ha.a)
	14,600	671
Reference System[c]:	None	
	Energy Credit (MJ/ha.a)	Carbon Credit (kg CO_2/ha.a)
	0	0
PROCESSING[d]:		
Methanol:	Input (kg methanol/kg RME) = 0.095	
	Energy Requirement (MJ/kg methanol) = 19.70	
	Carbon Requirement (kg CO_2/kg methanol) = ?	
	Energy Input (MJ/kg RME)	Carbon Output (kg CO_2/kg RME)
Drying:	1.43	?
Extracting:	3.47	?
Refining:	1.84	?
Totals[e]:	9.60	0.67
ALLOCATION[f]: It is assumed that the by-products (rape meal, glycerine and straw) could be burnt, so that energy inputs are allocated, effectively equally, by energy content to the energy output of all products. Carbon dioxide emissions avoided by using by-products to replace fossils fuels are added to carbon savings.		
FINAL RESULTS[g]:		
Per Energy	Energy (MJ/MJ)	Carbon (kg CO_2/MJ)
unadjusted:	0.74	0.036
adjusted:	0.27 to 0.40	?
Per Weight:	Energy (MJ/kg RME)	Carbon (kg CO_2/kg RME)
unadjusted:	27.53	1.33
adjusted:	9.84 to 14.84	1.33
REFERENCE FUEL[h]:	Density (kg/l) = 0.830 to 0.850	
	Energy Content (MJ/kg) = 42.90 (net)	
	Gross Energy Requirement (MJ/MJ) = 1.17	
	Gross Energy Requirement (MJ/kg) = 59.94	
	Carbon Requirement (kg CO_2/MJ) = 0.069	
	Carbon Requirement (kg CO_2/kg) = 2.97	
ESTIMATED SAVINGS[i]:		
Per Energy	Energy (MJ/MJ)	Carbon (kg CO_2/MJ)
unadjusted:	0.43	0.033
adjusted:	0.77 to 0.90	?
Per Weight	Energy (MJ/kg RME)	Carbon (kg CO_2/kg RME)
unadjusted:	24.36	1.24
adjusted:	37.00 to 42.00	?

SUMMARY SHEET FOR LIFE CYCLE ASSESSMENT OF BIODIESEL PRODUCTION		
SOURCE: "Technikfolgenabschaatzung zum Thema Nachwachsende Rohstoffe" (Technical Process Assessment of Renewable Energy Raw Materials) by D. Wintzer, B. Furniss, S. Klein-Vielhauer, L. Leible, E. Nieke, Ch. Rosch and H. Tangen, Landswirtschaftsverlag GmbH, Münster, Germany, 1993.		
SPECIFICATIONS OF RME:	Density (kg/l) = 0.880	
	Energy Content (MJ/kg) = 37.20	
CULTIVATION[a]**:** Hohe intensität (high intensity) winter oilseed rape		
N Fertiliser:	Input (kg N/ha.a) = 180	
	Yield (kg RME/ha.a) = 1190	
	Energy Requirement (MJ/kg N) = ?	
	Carbon Requirement (kg CO_2/kg N) = ?	
Totals[b]:	Energy Input (MJ/ha.a)	Carbon Output (kg CO_2/ha.a)
	14,930	?
Reference System[c]:	Fallow set-aside maintenance	
	Energy Credit (MJ/ha.a)	Carbon Credit (kg CO_2/ha.a)
	5,520	?
PROCESSING[d]**:**		
Methanol:	Input (kg methanol/kg RME) = ?	
	Energy Requirement (MJ/kg methanol) = ?	
	Carbon Requirement (kg CO_2/kg methanol) = ?	
	Energy Input (MJ/kg RME)	Carbon Output (kg CO_2/kg RME)
Drying:	0.80	?
Extracting:	3.43	?
Refining:		?
Totals[e]:	16.78	?
ALLOCATION[f]**:** There are no clear details on the allocation procedures used, if any.		
FINAL RESULTS[g]**:**		
Per Energy	Energy (MJ/MJ)	Carbon (kg CO_2/MJ)
unadjusted:	?	?
adjusted:	0.47	0.036
Per Weight:	Energy (MJ/kg RME)	Carbon (kg CO_2/kg RME)
unadjusted:	?	?
adjusted:	17.48	1.34
REFERENCE FUEL[h]**:**	Density (kg/l) = 0.840	
	Energy Content (MJ/kg) = 42.70	
	Gross Energy Requirement (MJ/MJ) = ?	
	Gross Energy Requirement (MJ/kg) = ?	
	Carbon Requirement (kg CO_2/MJ) = 0.079	
	Carbon Requirement (kg CO_2/kg) = 3.36	
ESTIMATED SAVINGS[i]**:**		
Per Energy	Energy (MJ/MJ)	Carbon (kg CO_2/MJ)
unadjusted:	?	?
adjusted:	0.53	0.043
Per Weight	Energy (MJ/kg RME)	Carbon (kg CO_2/kg RME)
unadjusted:	?	?
adjusted:	19.72	1.59

SUMMARY SHEET FOR LIFE CYCLE ASSESSMENT OF BIODIESEL PRODUCTION		
SOURCE: "Technikfolgenabschaatzung zum Thema Nachwachsende Rohstoffe" (Technical Process Assessment of Renewable Energy Raw Materials) by D. Wintzer, B. Furniss, S. Klein-Vielhauer, L. Leible, E. Nieke, Ch. Rosch and H. Tangen, Landswirtschaftsverlag GmbH, Münster, Germany, 1993.		
SPECIFICATIONS OF RME:	Density (kg/l) = 0.880	
	Energy Content (MJ/kg) = 37.20	
CULTIVATION[a]**:** N-Angabe (nitrogen-conserving) winter oilseed rape		
N Fertiliser:	Input (kg N/ha.a) = 134	
	Yield (kg RME/ha.a) = 1130	
	Energy Requirement (MJ/kg N) = ?	
	Carbon Requirement (kg CO_2/kg N) = ?	
Totals[b]:	Energy Input (MJ/ha.a)	Carbon Output (kg CO_2/ha.a)
	12,620	?
Reference System[c]:	Fallow set-aside maintenance	
	Energy Credit (MJ/ha.a)	Carbon Credit (kg CO_2/ha.a)
	7,074	?
PROCESSING[d]**:**		
Methanol:	Input (kg methanol/kg RME) = ?	
	Energy Requirement (MJ/kg methanol) = ?	
	Carbon Requirement (kg CO_2/kg methanol) = ?	
	Energy Input (MJ/kg RME)	Carbon Output (kg CO_2/kg RME)
Drying:	0.76	?
Extracting:	?	?
Refining:		?
Totals[e]:	?	?
ALLOCATION[f]**:** There are no clear details on the allocation procedures used, if any.		
FINAL RESULTS[g]**:**		
Per Energy	Energy (MJ/MJ)	Carbon (kg CO_2/MJ)
unadjusted:	?	?
adjusted:	?	?
Per Weight:	Energy (MJ/kg RME)	Carbon (kg CO_2/kg RME)
unadjusted:	?	?
adjusted:	?	?
REFERENCE FUEL[h]**:**	Density (kg/l) = 0.840	
	Energy Content (MJ/kg) = 42.70	
	Gross Energy Requirement (MJ/MJ) = ?	
	Gross Energy Requirement (MJ/kg) = ?	
	Carbon Requirement (kg CO_2/MJ) = 0.079	
	Carbon Requirement (kg CO_2/kg) = 3.36	
ESTIMATED SAVINGS[i]**:**		
Per Energy	Energy (MJ/MJ)	Carbon (kg CO_2/MJ)
unadjusted:	?	?
adjusted:	?	?
Per Weight	Energy (MJ/kg RME)	Carbon (kg CO_2/kg RME)
unadjusted:	?	?
adjusted:	?	?

SUMMARY SHEET FOR LIFE CYCLE ASSESSMENT OF BIODIESEL PRODUCTION		
SOURCE: "Technikfolgenabschaatzung zum Thema Nachwachsende Rohstoffe" (Technical Process Assessment of Renewable Energy Raw Materials) by D. Wintzer, B. Furniss, S. Klein-Vielhauer, L. Leible, E. Nieke, Ch. Rosch and H. Tangen, Landswirtschaftsverlag GmbH, Münster, Germany, 1993.		
SPECIFICATIONS OF RME:	Density (kg/l) = 0.880	
	Energy Content (MJ/kg) = 37.20	
CULTIVATION[a]: WSG (mainly organic) winter oilseed rape		
N Fertiliser:	Input (kg N/ha.a) = 83	
	Yield (kg RME/ha.a) =	
	Energy Requirement (MJ/kg N) = ?	
	Carbon Requirement (kg CO_2/kg N) = ?	
Totals[b]:	Energy Input (MJ/ha.a)	Carbon Output (kg CO_2/ha.a)
		?
Reference System[c]:	Fallow set-aside maintenance	
	Energy Credit (MJ/ha.a)	Carbon Credit (kg CO_2/ha.a)
		?
PROCESSING[d]:		
Methanol:	Input (kg methanol/kg RME) = ?	
	Energy Requirement (MJ/kg methanol) = ?	
	Carbon Requirement (kg CO_2/kg methanol) = ?	
	Energy Input (MJ/kg RME)	Carbon Output (kg CO_2/kg RME)
Drying:		?
Extracting:		?
Refining:		?
Totals[e]:		?
ALLOCATION[f]: There are no clear details on the allocation procedures used, if any.		
FINAL RESULTS[g]:		
Per Energy	Energy (MJ/MJ)	Carbon (kg CO_2/MJ)
unadjusted:	?	?
adjusted:	?	?
Per Weight:	Energy (MJ/kg RME)	Carbon (kg CO_2/kg RME)
unadjusted:	?	?
adjusted:	?	?
REFERENCE FUEL[h]:	Density (kg/l) = 0.840	
	Energy Content (MJ/kg) = 42.70	
	Gross Energy Requirement (MJ/MJ) = ?	
	Gross Energy Requirement (MJ/kg) = ?	
	Carbon Requirement (kg CO_2/MJ) = 0.079	
	Carbon Requirement (kg CO_2/kg) = 3.36	
ESTIMATED SAVINGS[i]:		
Per Energy	Energy (MJ/MJ)	Carbon (kg CO_2/MJ)
unadjusted:	?	?
adjusted:	?	?
Per Weight	Energy (MJ/kg RME)	Carbon (kg CO_2/kg RME)
unadjusted:	?	?
adjusted:	?	?

SUMMARY SHEET FOR LIFE CYCLE ASSESSMENT OF BIODIESEL PRODUCTION		
SOURCE: "Alternative Road Transport Fuels – A Preliminary Life-Cycle Study for the UK" by M. P. Gover, S. A. Collings, G. S. Hitchcock, D. P. Moon and G. T. Williams, Report R92, Volume 2, Energy Technology Support Unit, Harwell, United Kingdom, March 1996.		
SPECIFICATIONS OF RME:	Density (kg/l) = 0.880	
	Energy Content (MJ/kg) = 37.10 (net)	
CULTIVATION[a]: Winter oilseed rape with a yield of 3200 kg/ha.a		
N Fertiliser:	Input (kg N/ha.a) = 185	
	Yield (kg RME/ha.a) = 1184	
	Energy Requirement (MJ/kg N) = 65.30	
	Carbon Requirement (kg CO_2/kg N) = 2.26	
Totals[b]:	Energy Input (MJ/ha.a)	Carbon Output (kg CO_2/ha.a)
	18,131	521
Reference System[c]:	None	
	Energy Credit (MJ/ha.a)	Carbon Credit (kg CO_2/ha.a)
	0	0
PROCESSING[d]:		
Methanol:	Input (kg methanol/kg RME) = 0.100	
	Energy Requirement (MJ/kg methanol) = 33.00	
	Carbon Requirement (kg CO_2/kg methanol) = ?	
	Energy Input (MJ/kg RME)	Carbon Output (kg CO_2/kg RME)
Drying:	?	?
Extracting:	8.52	0.48
Refining:	11.00	0.44
Totals[e]:	20.92	0.97
ALLOCATION[f]: Energy and carbon dioxide credits are determined for use of straw as a fuel but these are not taken into account in the recommended results. Energy and carbon dioxide credits are included for rapemeal on the basis of substitution by soyameal. There is no allocation for glycerine.		
FINAL RESULTS[g]:		
Per Energy	Energy (MJ/MJ)	Carbon (kg CO_2/MJ)
unadjusted:	0.98	0.037
adjusted:	0.89	0.032
Per Weight:	Energy (MJ/kg RME)	Carbon (kg CO_2/kg RME)
unadjusted:	36.36	1.36
adjusted:	33.02	1.19
REFERENCE FUEL[h]:	Density (kg/l) = 0.830 to 0.850	
	Energy Content (MJ/kg) = 42.99 (net)	
	Gross Energy Requirement (MJ/MJ) = 1.22	
	Gross Energy Requirement (MJ/kg) = 52.45	
	Carbon Requirement (kg CO_2/MJ) = ?	
	Carbon Requirement (kg CO_2/kg) = ?	
ESTIMATED SAVINGS[i]:		
Per Energy	Energy (MJ/MJ)	Carbon (kg CO_2/MJ)
unadjusted:	0.24	?
adjusted:	0.33	?
Per Weight	Energy (MJ/kg RME)	Carbon (kg CO_2/kg RME)
unadjusted:	10.32	?
adjusted:	14.19	?

SUMMARY SHEET FOR LIFE CYCLE ASSESSMENT OF BIODIESEL PRODUCTION		
SOURCE: "Alternative Road Transport Fuels – A Preliminary Life-Cycle Study for the UK" by M. P. Gover, S. A. Collings, G. S. Hitchcock, D. P. Moon and G. T. Williams, Report R92, Volume 2, Energy Technology Support Unit, Harwell, United Kingdom, March 1996.		
SPECIFICATIONS OF RME:	Density (kg/l) = 0.880	
	Energy Content (MJ/kg) = 37.10 (net)	
CULTIVATION[a]: Spring oilseed rape with a yield of 3200 kg/ha.a		
N Fertiliser:	Input (kg N/ha.a) = 120	
	Yield (kg RME/ha.a) = 814	
	Energy Requirement (MJ/kg N) = 65.30	
	Carbon Requirement (kg CO_2/kg N) = 2.26	
Totals[b]:	Energy Input (MJ/ha.a)	Carbon Output (kg CO_2/ha.a)
	12,162	314
Reference System[c]:	None	
	Energy Credit (MJ/ha.a)	Carbon Credit (kg CO_2/ha.a)
	0	0
PROCESSING[d]:		
Methanol:	Input (kg methanol/kg RME) = 0.100	
	Energy Requirement (MJ/kg methanol) = 33.00	
	Carbon Requirement (kg CO_2/kg methanol) = ?	
	Energy Input (MJ/kg RME)	Carbon Output (kg CO_2/kg RME)
Drying:	?	?
Extracting:	8.52	0.48
Refining:	11.00	0.44
Totals[e]:	20.92	0.97
ALLOCATION[f]: Energy and carbon dioxide credits are determined for use of straw as a fuel but these are not taken into account in the recommended results. Energy and carbon dioxide credits are included for rapemeal on the basis of substitution by soyameal. There is no allocation for glycerine.		
FINAL RESULTS[g]:		
Per Energy	Energy (MJ/MJ)	Carbon (kg CO_2/MJ)
unadjusted:	0.97	0.036
adjusted:	0.88	0.032
Per Weight:	Energy (MJ/kg RME)	Carbon (kg CO_2/kg RME)
unadjusted:	35.95	1.35
adjusted:	32.65	1.19
REFERENCE FUEL[h]:	Density (kg/l) = 0.830 to 0.850	
	Energy Content (MJ/kg) = 42.99 (net)	
	Gross Energy Requirement (MJ/MJ) = 1.22	
	Gross Energy Requirement (MJ/kg) = 52.45	
	Carbon Requirement (kg CO_2/MJ) = ?	
	Carbon Requirement (kg CO_2/kg) = ?	
ESTIMATED SAVINGS[i]:		
Per Energy	Energy (MJ/MJ)	Carbon (kg CO_2/MJ)
unadjusted:	0.25	?
adjusted:	0.34	?
Per Weight	Energy (MJ/kg RME)	Carbon (kg CO_2/kg RME)
unadjusted:	10.79	?
adjusted:	14.62	?

SUMMARY SHEET FOR LIFE CYCLE ASSESSMENT OF BIODIESEL PRODUCTION		
SOURCE: "Comparative Life-Cycle Assessment of Diesel and Biodiesel" by C. Spirinckx and D. Ceuterick, VITO (Flemish Institute for Technological Research), Mol, Belgium, 1996.		
SPECIFICATIONS OF RME:	Density (kg/l) = ?	
	Energy Content (MJ/kg) = 37.20	
CULTIVATION[(a)]: Winter oilseed rape with a yield of 3200 kg/ha/a (15% moisture)		
N Fertiliser:	Input (kg N/ha.a) = ?	
	Yield (kg RME/ha.a) ?=	
	Energy Requirement (MJ/kg N) = 45.00	
	Carbon Requirement (kg CO_2/kg N) = ?	
Totals[(b)]:	Energy Input (MJ/ha.a)	Carbon Output (kg CO_2/ha.a)
	?	?
Reference System[(c)]:	?	
	Energy Credit (MJ/ha.a)	Carbon Credit (kg CO_2/ha.a)
	?	?
PROCESSING[(d)]:		
Methanol:	Input (kg methanol/kg RME) = 0.109	
	Energy Requirement (MJ/kg methanol) = ?	
	Carbon Requirement (kg CO_2/kg methanol) = ?	
	Energy Input (MJ/kg RME)	Carbon Output (kg CO_2/kg RME)
Drying:	0.50	?
Extracting:	?	?
Refining:	?	?
Totals[(e)]:	?	?
ALLOCATION[(f)]: Energy and carbon dioxide associated with cultivation are allocated by the mass of oilseed and straw produced. Energy and carbon dioxide associated with processing are allocated between rapeseed oil, rape meal, glycerine and biodiesel on the basis of their market prices.		
FINAL RESULTS[(g)]:		
Per Energy	Energy (MJ/MJ)	Carbon (kg CO_2/MJ)
unadjusted:	?	?
adjusted:	0.55	?
Per Weight:	Energy (MJ/kg RME)	Carbon (kg CO_2/kg RME)
unadjusted:	?	?
adjusted:	20.53	?
REFERENCE FUEL[(h)]:	Density (kg/l) = ?	
	Energy Content (MJ/kg) = 42.90	
	Gross Energy Requirement (MJ/MJ) = 1.14	
	Gross Energy Requirement (MJ/kg) = 49.06	
	Carbon Requirement (kg CO_2/MJ) = ?	
	Carbon Requirement (kg CO_2/kg) = ?	
ESTIMATED SAVINGS[(i)]:		
Per Energy	Energy (MJ/MJ)	Carbon (kg CO_2/MJ)
unadjusted:	?	?
adjusted:	0.59	?
Per Weight	Energy (MJ/kg RME)	Carbon (kg CO_2/kg RME)
unadjusted:	?	?
adjusted:	25.38	?

SUMMARY SHEET FOR LIFE CYCLE ASSESSMENT OF BIODIESEL PRODUCTION		
SOURCE: "Nachwachsende Energieträger – Grundlagen, Verfaben, Ökologische Bilanzierung" (Renewable Energy Sources, Basis, Processes and Ecological Balance) by M. Kaltschmitt and G. A. Reinhardt (eds), Vieweg, Braunschweig/Weisbaden, Germany,1997		
SPECIFICATIONS OF RME:	Density (kg/l) = 0.875 to 0.900	
	Energy Content (MJ/kg) = 37.20	
CULTIVATION[(a)]: Winter oilseed rape		
N Fertiliser:	Input (kg N/ha.a) = 146	
	Yield (kg RME/ha.a) = 1143	
	Energy Requirement (MJ/kg N) = 47.10	
	Carbon Requirement (kg CO_2/kg N) = 2.47	
Totals[(b)]:	Energy Input (MJ/ha.a)	Carbon Output (kg CO_2/ha.a)
	10,015	?
Reference System[(c)]:		
	Energy Credit (MJ/ha.a)	Carbon Credit (kg CO_2/ha.a)
	1,024	?
PROCESSING[(d)]:		
Methanol:	Input (kg methanol/kg RME) = 0.109	
	Energy Requirement (MJ/kg methanol) = 38.09	
	Carbon Requirement (kg CO_2/kg methanol) = 2.72	
	Energy Input (MJ/kg RME)	Carbon Output (kg CO_2/kg RME)
Drying:	1.56	?
Extracting:	2.78	?
Refining:	7.09	?
Totals[(e)]:	11.43	?
ALLOCATION[(f)]: Various allocation procedures are examined, involving energy content, mass, price, mass and energy content, price and energy content. Additionally, the effects of burning rape meal in energy plants, and allocating all inputs and outputs to biodiesel alone are considered. Here, allocation by energy content is illustrated.		
FINAL RESULTS[(g)]:		
Per Energy	Energy (MJ/MJ)	Carbon (kg CO_2/MJ)
unadjusted:	0.58	?
adjusted:	0.39	?
Per Weight:	Energy (MJ/kg RME)	Carbon (kg CO_2/kg RME)
unadjusted:	21.09	?
adjusted:	14.36	?
REFERENCE FUEL[(h)]:	Density (kg/l) = 0.815 to 0.855	
	Energy Content (MJ/kg) = 42.70	
	Gross Energy Requirement (MJ/MJ) = 1.11	
	Gross Energy Requirement (MJ/kg) = 47.4	
	Carbon Requirement (kg CO_2/MJ) = 0.074	
	Carbon Requirement (kg CO_2/kg) = 3.18	
ESTIMATED SAVINGS[(i)]:		
Per Energy	Energy (MJ/MJ)	Carbon (kg CO_2/MJ)
unadjusted:	0.54	?
adjusted:	0.72	?
Per Weight	Energy (MJ/kg RME)	Carbon (kg CO_2/kg RME)
unadjusted:	20.12	?
adjusted:	26.85	?

SUMMARY SHEET FOR LIFE CYCLE ASSESSMENT OF BIODIESEL PRODUCTION		
SOURCE: "Financial and Environmental Impact of Biodiesel as an Alternative to Fossil Diesel in the UK" ECOTEC Research and Consulting Ltd., Birmingham, United Kingdom, November 1999.		
SPECIFICATIONS OF RME:	Density (kg/l) = 0.846	
	Energy Content (MJ/kg) = 37.10	
CULTIVATION[a]: Winter oilseed rape		
N Fertiliser:	Input (kg N/ha.a) = ?	
	Yield (kg RME/ha.a) = 1184	
	Energy Requirement (MJ/kg N) = ?	
	Carbon Requirement (kg CO_2/kg N) = ?	
Totals[b]:	Energy Input (MJ/ha.a)	Carbon Output (kg CO_2/ha.a)
	4,600	421
Reference System[c]:	Fallow set-aside maintenance	
	Energy Credit (MJ/ha.a)	Carbon Credit (kg CO_2/ha.a)
	?	?
PROCESSING[d]:		
Methanol:	Input (kg methanol/kg RME) = ?	
	Energy Requirement (MJ/kg methanol) = ?	
	Carbon Requirement (kg CO_2/kg methanol) = ?	
	Energy Input (MJ/kg RME)	Carbon Output (kg CO_2/kg RME)
Drying:	?	?
Extracting:	?	0.03 to 0.50
Refining:	?	0.14 to 0.44
Totals[e]:	?	?
ALLOCATION[f]: There is no discussion of an allocation procedure. Hence, it is assumed that all inputs and outputs are allocated to biodiesel.		
FINAL RESULTS[g]:		
Per Energy	Energy (MJ/MJ)	Carbon (kg CO_2/MJ)
unadjusted:	?	?
adjusted:	?	?
Per Weight:	Energy (MJ/kg RME)	Carbon (kg CO_2/kg RME)
unadjusted:	?	?
adjusted:	?	?
REFERENCE FUEL[h]:	Density (kg/l) = ?	
	Energy Content (MJ/kg) = ?	
	Gross Energy Requirement (MJ/MJ) = ?	
	Gross Energy Requirement (MJ/kg) = ?	
	Carbon Requirement (kg CO_2/MJ) = ?	
	Carbon Requirement (kg CO_2/kg) = ?	
ESTIMATED SAVINGS[i]:		
Per Energy	Energy (MJ/MJ)	Carbon (kg CO_2/MJ)
unadjusted:	?	?
adjusted:	?	?
Per Weight	Energy (MJ/kg RME)	Carbon (kg CO_2/kg RME)
unadjusted:	?	?
adjusted:	?	?

SUMMARY SHEET FOR LIFE CYCLE ASSESSMENT OF BIODIESEL PRODUCTION		
SOURCE: "Energy Balances in the Growth of Oilseed Rape and of Wheat for Bioethanol" by I. R. Richards, Levington Agriculture Ltd., Ipswich, United Kingdom, June 2000		
SPECIFICATIONS OF RME:	Density (kg/l) = ?	
	Energy Content (MJ/kg) = 36.00	
CULTIVATION[(a)]: Winter oilseed rape with straw ploughed in		
N Fertiliser:	Input (kg N/ha.a) = 180	
	Yield (kg RME/ha.a) = 1510	
	Energy Requirement (MJ/kg N) = 38.00	
	Carbon Requirement (kg CO_2/kg N) = 0.45 to 2.08 (average = 1.14)	
Totals[(b)]:	Energy Input (MJ/ha.a)	Carbon Output (kg CO_2/ha.a)
	13,254	626
Reference System[(c)]:	None	
	Energy Credit (MJ/ha.a)	Carbon Credit (kg CO_2/ha.a)
	0	0
PROCESSING[(d)]:		
Methanol:	Input (kg methanol/kg RME) = ?	
	Energy Requirement (MJ/kg methanol) = ?	
	Carbon Requirement (kg CO_2/kg methanol) = ?	
	Energy Input (MJ/kg RME)	Carbon Output (kg CO_2/kg RME)
Drying:	?	?
Extracting:	0.43	?
Refining:	11.00	?
Totals[(e)]:	11.43	?
ALLOCATION[(f)]: No explicit allocation procedure but suggests that allocation by energy content is appropriate.		
FINAL RESULTS[(g)]:		
Per Energy	Energy (MJ/MJ)	Carbon (kg CO_2/MJ)
unadjusted:	0.56	0.012
adjusted:	?	?
Per Weight:	Energy (MJ/kg RME)	Carbon (kg CO_2/kg RME)
unadjusted:	20.20	0.42
adjusted:	?	?
REFERENCE FUEL[(h)]:	Density (kg/l) = ?	
	Energy Content (MJ/kg) = ?	
	Gross Energy Requirement (MJ/MJ) = ?	
	Gross Energy Requirement (MJ/kg) = ?	
	Carbon Requirement (kg CO_2/MJ) = ?	
	Carbon Requirement (kg CO_2/kg) = ?	
ESTIMATED SAVINGS[(i)]:		
Per Energy	Energy (MJ/MJ)	Carbon (kg CO_2/MJ)
unadjusted:	?	?
adjusted:	?	?
Per Weight	Energy (MJ/kg RME)	Carbon (kg CO_2/kg RME)
unadjusted:	?	?
adjusted:	?	?

SUMMARY SHEET FOR LIFE CYCLE ASSESSMENT OF BIODIESEL PRODUCTION		
SOURCE: "Energy Balances in the Growth of Oilseed Rape and of Wheat for Bioethanol" by I. R. Richards, Levington Agriculture Ltd., Ipswich, United Kingdom, June 2000		
SPECIFICATIONS OF RME:	Density (kg/l) = ?	
	Energy Content (MJ/kg) = 36.00	
CULTIVATION[(a)]: Winter oilseed rape with straw used as a fuel		
N Fertiliser:	Input (kg N/ha.a) = 180	
	Yield (kg RME/ha.a) = 1510	
	Energy Requirement (MJ/kg N) = 38.00	
	Carbon Requirement (kg CO_2/kg N) = 0.45 to 2.08 (average = 1.14)	
Totals[(b)]:	Energy Input (MJ/ha.a)	Carbon Output (kg CO_2/ha.a)
	13,911	751
Reference System[(c)]:	None	
	Energy Credit (MJ/ha.a)	Carbon Credit (kg CO_2/ha.a)
	0	0
PROCESSING[(d)]:		
Methanol:	Input (kg methanol/kg RME) = ?	
	Energy Requirement (MJ/kg methanol) = ?	
	Carbon Requirement (kg CO_2/kg methanol) = ?	
	Energy Input (MJ/kg RME)	Carbon Output (kg CO_2/kg RME)
Drying:	?	?
Extracting:	0.43	?
Refining:	11.00	?
Totals[(e)]:	11.43	?
ALLOCATION[(f)]: No explicit allocation procedure but suggests that allocation by energy content is appropriate with energy credits for straw and rape meal.		
FINAL RESULTS[(g)]:		
Per Energy	Energy (MJ/MJ)	Carbon (kg CO_2/MJ)
unadjusted:	0.57	0.014
adjusted:	?	?
Per Weight:	Energy (MJ/kg RME)	Carbon (kg CO_2/kg RME)
unadjusted:	20.63	0.50
adjusted:	?	?
REFERENCE FUEL[(h)]:	Density (kg/l) = ?	
	Energy Content (MJ/kg) = ?	
	Gross Energy Requirement (MJ/MJ) = ?	
	Gross Energy Requirement (MJ/kg) = ?	
	Carbon Requirement (kg CO_2/MJ) = ?	
	Carbon Requirement (kg CO_2/kg) = ?	
ESTIMATED SAVINGS[(i)]:		
Per Energy	Energy (MJ/MJ)	Carbon (kg CO_2/MJ)
unadjusted:	?	?
adjusted:	?	?
Per Weight	Energy (MJ/kg RME)	Carbon (kg CO_2/kg RME)
unadjusted:	?	?
adjusted:	?	?

SUMMARY SHEET FOR LIFE CYCLE ASSESSMENT OF BIODIESEL PRODUCTION		
SOURCE: "Comparison of Transport Fuels: Life-Cycle Emissions Analysis of Alternative Fuels for Heavy Vehicles" by. T. Beer, T. Grant, G. Morgan, J. Lapszewicz, P. Anyon, J. Edwards, P. Nelson, H. Watson and D. Williams, CSIRO, Aspendale, Australia, 2002.		
SPECIFICATIONS OF RME:	Density (kg/l) = 0.880	
	Energy Content (MJ/kg) = 33.3 (gross)	
CULTIVATION[(a)]:		
N Fertiliser:	Input (kg N/ha.a) = 20	
	Yield (kg RME/ha.a) =?	
	Energy Requirement (MJ/kg N) = ?	
	Carbon Requirement (kg CO_2/kg N) = ?	
Totals[(b)]:	Energy Input (MJ/ha.a)	Carbon Output (kg CO_2/ha.a)
	?	?
Reference System[(c)]:	Unknown	
	Energy Credit (MJ/ha.a)	Carbon Credit (kg CO_2/ha.a)
	?	?
PROCESSING[(d)]:		
Methanol:	Input (kg methanol/kg RME) = ?	
	Energy Requirement (MJ/kg methanol) = ?	
	Carbon Requirement (kg CO_2/kg methanol) = ?	
	Energy Input (MJ/kg RME)	Carbon Output (kg CO_2/kg RME)
Drying:	?	?
Extracting:	?	?
Refining:	?	?
Totals[(e)]:	?	?
ALLOCATION[(f)]: Possible allocation is on the basis of the calorific values of oilseed, straw, rape meal, glycerine and biodiesel.		
FINAL RESULTS[(g)]:		
Per Energy	Energy (MJ/MJ)	Carbon (kg CO_2/MJ)
unadjusted:	?	?
adjusted:	0.43	?
Per Weight:	Energy (MJ/kg RME)	Carbon (kg CO_2/kg RME)
unadjusted:	?	?
adjusted:	14.32	?
REFERENCE FUEL[(h)]:	Density (kg/l) = 0.835	
	Energy Content (MJ/kg) = 45.90 (gross)	
	Gross Energy Requirement (MJ/MJ) = 1.18	
	Gross Energy Requirement (MJ/kg) = 54.16	
	Carbon Requirement (kg CO_2/MJ) = ?	
	Carbon Requirement (kg CO_2/kg) = ?	
ESTIMATED SAVINGS[(i)]:		
Per Energy	Energy (MJ/MJ)	Carbon (kg CO_2/MJ)
unadjusted:	?	?
adjusted:	0.76	?
Per Weight	Energy (MJ/kg RME)	Carbon (kg CO_2/kg RME)
unadjusted:	?	?
adjusted:	34.88	?

APPENDIX C: Ammonium Nitrate Fertiliser Production

Table C1. Energy Requirement of Ammonium Nitrate Fertiliser

Functional Unit:	Bagged ammonium nitrate fertiliser produced via ammonia and nitric acid from natural gas and delivered to the point of use									
Final Unit of Measurement:	kg N									
Relevant Location:	United Kingdom									
Relevant Period:	1996									
Allocation Procedures:	Based on average market prices, assuming 0.43 kg of ammonia per kg ammonium nitrate at £8.44/kg NH_3 (Ref. C1) and 1.394 kg of recovered carbon dioxide per kg ammonium nitrate at £0.21/kg CO_2 (Ref. C1), giving an allocation of 93% to ammonia and 7% to recovered carbon dioxide in the ammonia plant.									
Contribution	Per Unit	Primary Energy Input (MJ)								
		Direct		Indirect		Feedstock		Total		Notes
		Value	Range	Value	Range	Value	Range	Value	Range	
Ammonia Production:										
- *Natural Gas Feedstock*	kg N	-	-	2.899	±0.510	26.346	±1.060	29.245	±1.061	(a)
- Natural Gas Fuel	kg N	9.170	±3.199	1.010	±0.351	-	-	10.180	±3.218	(b)
- Steam Export	kg N	-4.671	±3.933	-0.515	±1.895	-	-	-5.186	±4.366	(c)
- Electricity	kg N	0.725	±0.345	1.515	±1.010	-	-	2.240	±1.067	(d)
- Capital Plant	kg N	-	-	2.083	±0.521	-		2.083	±0.521	(e)
Sub-Totals	kg N	5.224	±5.081	6.992	±2.295	26.346	±1.060	38.562	±5.675	(f)
Nitric Acid Production:										
- Steam Export	kg N	-4.026	-	-0.443	-	-	-	-4.469	-	(g)
- Capital Plant	kg N	-	-	0.566	±0.229	-	-	0.566	±0.229	(h)
Sub-Totals	kg N	-4.026	-	0.123	±0.229	-	-	-3.903	±0.229	(i)
Ammonium Nitrate Production:										
- Natural Gas Fuel	kg N	2.000	-	0.220	-	-	-	2.220	-	(j)
- Capital Plant	kg N	-	-	1.134	±0.454	-	-	1.134	±0.454	(k)
Sub-Totals	kg N	2.000	-	1.354	±0.454	-	-	3.354	±0.454	
Packaging	kg N	-	-	0.766	-	0.249	-	1.015	-	(l)
Transport	kg N	1.171	±0.046	0.409	±0.051	-	-	1.580	±0.069	(m)
Totals	**Kg N**	**4.369**	**±5.081**	**9.644**	**±2.351**	**26.595**	**±1.060**	**40.608**	**±5.699**	

Notes

(a) Average natural gas feedstock requirement of 23.059 ±0.929 MJ/kg NH_3 for ammonia production in the EU in 1998 (Ref. C2) and a primary energy efficiency of 0.9009 for natural gas production in the UK in 1996 (Ref. C3).

(b) Natural gas fuel consumption of 8.025 ± 2.800 MJ/kg NH_3 (Ref. C4) and a primary energy efficiency of 0.9009 for natural gas production in the UK in 1996 (Ref. C3).

(c) Assuming steam export of 3.475 ± 2.925 MJ/kg NH_3 (Ref. C4) which displaces steam raised from a natural gas-fired boiler with an efficiency of 85%, and a primary energy efficiency of 0.9009 for natural gas production in the UK in 1996 (Ref. C3).

(d) Electricity consumption of 0.636 ± 0.303 MJ/kg NH_3 (Ref. C4) and a primary energy efficiency of 0.324 for electricity generation in the UK in 1996 (Ref. C3).

(e) Based on a primary energy input to ammonia plant construction of 1.822 ± 0.455 MJ/kg NH_3 derived from an energy intensity for "Industrial Plant and Steelwork" of 39 ± 10 MJ/£ (Ref. C5).

(f) Based on a total ammonia requirement of 0.43 kg/kg of ammonium nitrate fertiliser (Ref. C2).

(g) Assuming steam export of 1.556 MJ/kg HNO_3 (Ref. C2) which displaces steam raised from a natural gas-fired boiler with an efficiency of 85%, and a primary energy efficiency of 0.9009 for natural gas production in the UK in 1996 (Ref. C3).

(h) Based on a primary energy input to nitric acid plant construction of 0.257 ± 0.104 MJ/kg HNO_3 derived from an energy intensity for "Industrial Plant and Steelwork" of 39 ± 10 MJ/£ (Ref. C5).

(i) Based on a nitric acid requirement of 0.77 kg/kg ammonium nitrate fertiliser (Ref. C6).

(j) Natural gas fuel consumption of 0.700 MJ/kg NH_4NO_3 (Ref. C4) and a primary energy efficiency of 0.9009 for natural gas production in the UK in 1996 (Ref. C3).

(k) Based on a primary energy input to ammonium nitrate plant construction of 1.134 ± 0.454 MJ/kg NH_4NO_3 derived from an energy intensity for "Industrial Plant and Steelwork" of 39 ± 10 MJ/£ (Ref. C5).

(l) Assuming 0.004 kg polyethylene bags/kg NH_4NO_3 derived and an energy requirement of polyethylene of 88.55 MJ/kg (Ref. C7).

(m) Assuming an round trip distance of 500 kilometres, and based on a direct energy requirement of 0.8196 ± 0.031 MJ/t-km and an indirect energy requirement of 0.2857 ± 0.0352 MJ/t-km for road bulk carrier transport (Ref. C4).

References

C1. Airgas Price List, www.cehs.siu.edu/gas/price_list.htm, accessed 5 April 2002.

C2. "Energy Consumption and Greenhouse Gas Emissions in Fertiliser Production" by G. Kongshaug, Proceedings of the IFA Technical Conference in Marrakesh, Morocco, International Fertiliser Industry Association, Paris, France, 1998.

C3. "Methodology for Environmental Profiles of Construction Materials, Components and Buildings" Centre for Sustainable Construction at the Building Research Establishment Ltd., CRC Ltd., London, United Kingdom, 2000.

C4. "Carbon and Energy Modelling of Biomass Systems: Conversion Plant and Data Updates" by N. D. Mortimer and M. A. Elsayed, ETSU Report B/U1/00644/00/00REP, Energy Technology Support Unit, Harwell, United Kingdom, August 2001.

C5. "An Input-Output Analysis of Carbon Dioxide Emissions for the UK" by R. Hetherington, Energy Conversion Management, Vol. 37, Nos. 6 – 8, pp. 979 – 984, 1996.

C6. "Ammonium Nitrate" in 'Kirk-Othmer Encyclopedia of Chemical Technology' 4th Edition, Vol. 2, John Wiley and Sons Inc., New York, United States of America, 1992, pp. 698 – 705.

C7. "Eco-Profiles of the European Plastics Industry, Report 3: Polyethylene and Polypropylene" by I. Boustead, European Centre for Plastics in the Environment, Brussels, Belgium, 1993.

Table C2. Carbon Requirement of Ammonium Nitrate Fertiliser

Functional Unit:	Bagged ammonium nitrate fertiliser produced via ammonia and nitric acid from natural gas and delivered to the point of use
Final Unit of Measurement:	kg N
Relevant Location:	United Kingdom
Relevant Period:	1996
Allocation Procedures:	Based on average market prices, assuming 0.43 kg of ammonia per kg ammonium nitrate at £8.44/kg NH_3 (Ref. C1) and 1.394 kg of recovered carbon dioxide per kg ammonium nitrate at £0.21/kg CO_2 (Ref. C1), giving an allocation of 93% to ammonia and 7% to recovered carbon dioxide in the ammonia plant.

Contribution	Per Unit	Carbon Dioxide Output (kg CO_2)						
		Direct		Indirect		Total		Notes
		Value	Range	Value	Range	Value	Range	
Ammonia Production:								
- Natural Gas Feedstock	kg N	-	-	1.379	±0.055	1.379	±0.055	(a)
- Natural Gas Fuel	kg N	0.478	±0.167	0.016	±0.005	0.494	±0.167	(b)
- Steam Export	kg N	-0.244	±0.205	-0.008	±0.007	-0.252	±0.205	(c)
- Electricity	kg N	-	-	0.109	±0.052	0.109	±0.052	(d)
- Capital Plant	kg N	-	-	0.101	-	0.101	-	(e)
Sub-Totals	kg N	0.234	±0.264	1.597	±0.076	1.831	±0.275	(f)
Nitric Acid Production:								
- Steam Export	kg N	-0.210	-	-0.007	-	-0.217	-	(g)
- Capital Plant	kg N	-	-	0.029	-	0.029	-	(h)
Sub-Totals	kg N	-0.210	-	0.022	-	-0.188	-	(i)
Ammonium Nitrate Production:								
- Natural Gas Fuel	kg N	0.104	-	-	-	0.104	-	(j)
- Capital Plant	kg N	-	-	0.054	-	0.054	-	(k)
Sub-Totals	kg N	0.104	-	0.054	-	0.158	-	
Packaging	kg N	-	-	0.014	-	0.014	-	(l)
Transport	kg N	0.080	±0.003	0.009	-	0.089	±0.003	(m)
Totals	**kg N**	**0.208**	**±0.264**	**1.696**	**±0.076**	**1.904**	**±0.275**	

Notes

(a) Average natural gas feedstock requirement of 23.059 ±0.929 MJ/kg NH_3 for ammonia production in the EU in 1998 (Ref. C2), with a direct carbon requirement of 0.0522 kg CO_2/MJ and an indirect carbon requirement of 0.0017 kg CO_2/MJ for natural gas in the UK in 1996 (Ref. C3), and allocation of 93% of the recovered carbon dioxide emissions to the ammonia.

(b) Natural gas fuel consumption of 8.025 ± 2.800 MJ/kg NH_3 (Ref. C4), with a direct carbon requirement of 0.0522 kg CO_2/MJ and an indirect carbon requirement of 0.0017 kg CO_2/MJ for natural gas in the UK in 1996 (Ref. C3).

(c) Assuming steam export of 3.475 ± 2.925 MJ/kg NH_3 (Ref. C4) which displaces steam raised from a natural gas-fired boiler with an efficiency of 85%, with a direct carbon requirement of 0.0522 kg CO_2/MJ and an indirect carbon requirement of 0.0017 kg CO_2/MJ for natural gas in the UK in 1996 (Ref. C3).

(d) Electricity consumption of 0.636 ± 0.303 MJ/kg NH_3 (Ref. C4) and an indirect carbon requirement of 0.1504 kg CO_2/MJ for electricity generation in the UK in 1996 (Ref. C3).

(e) Based on a carbon dioxide output for ammonia plant construction of 0.089 ± 0.022 kg CO_2/kg NH_3 derived from a carbon intensity for "Industrial Plant and Steelwork" of 1.9 ± 0.5 kg CO_2/£ (Ref. C5).

(f) Based on a total ammonia requirement of 0.43 kg/kg of ammonium nitrate fertiliser (Ref. C2).

(g) Assuming steam export of 1.556 MJ/kg HNO_3 (Ref. C2) which displaces steam raised from a natural gas-fired boiler with an efficiency of 85%, with a direct carbon requirement of 0.0522 kg CO_2/MJ and an indirect carbon requirement of 0.0017 kg CO_2/MJ for natural gas in the UK in 1996 (Ref. C3).

(h) Based on a carbon dioxide output for nitric acid plant construction of 0.013 ± 0.005 kg CO_2/kg NH_3 derived from a carbon intensity for "Industrial Plant and Steelwork" of 1.9 ± 0.5 kg CO_2/£ (Ref. C5).

(i) Based on a nitric acid requirement of 0.77 kg/kg ammonium nitrate fertiliser (Ref. C6).

(j) Natural gas fuel consumption of 0.700 MJ/kg NH_4NO_3 (Ref. C4) with a direct carbon requirement of 0.0522 kg CO_2/MJ and an indirect carbon requirement of 0.0017 kg CO_2/MJ for natural gas in the UK in 1996 (Ref. C3).

(k) Based on a carbon dioxide output for ammonium nitrate plant construction of 0.054 kg CO_2/kg NH_4NO_3 derived from a carbon intensity for "Industrial Plant and Steelwork" of 1.9 ± 0.5 kg CO_2/£ (Ref. C5).

(l) Assuming 0.004 kg polyethylene bags/kg NH_4NO_3 derived and a carbon requirement of polyethylene of 1.25 kg CO_2/kg (Ref. C7).

(m) Assuming an round trip distance of 500 kilometres, and based on a direct carbon requirement of 0.0562 ± 0.0021 kg CO_2/t-km and an indirect carbon requirement of 0.0161 ± 0.0017 kg CO_2/t-km for road bulk carrier transport (Ref. C4).

References

C1. Airgas Price List, www.cehs.siu.edu/gas/price_list.htm, accessed 5 April 2002.

C2. "Energy Consumption and Greenhouse Gas Emissions in Fertiliser Production" by G. Kongshaug, Proceedings of the IFA Technical Conference in Marrakesh, Morocco, International Fertiliser Industry Association, Paris, France, 1998.

C3. "Methodology for Environmental Profiles of Construction Materials, Components and Buildings" Centre for Sustainable Construction at the Building Research Establishment Ltd., CRC Ltd., London, United Kingdom, 2000.

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C5. "An Input-Output Analysis of Carbon Dioxide Emissions for the UK" by R. Hetherington, Energy Conversion Management, Vol. 37, Nos. 6 – 8, pp. 979 – 984, 1996.

C6. "Ammonium Nitrate" in 'Kirk-Othmer Encyclopedia of Chemical Technology' 4th Edition, Vol. 2, John Wiley and Sons Inc., New York, United States of America, 1992, pp. 698 – 705.

C7. "Eco-Profiles of the European Plastics Industry, Report 3: Polyethylene and Polypropylene" by I. Boustead, European Centre for Plastics in the Environment, Brussels, Belgium, 1993.

Table C3. Methane Requirement of Ammonium Nitrate Fertiliser

Functional Unit:	Bagged ammonium nitrate fertiliser produced via ammonia and nitric acid from natural gas and delivered to the point of use							
Final Unit of Measurement:	kg N							
Relevant Location:	United Kingdom							
Relevant Period:	1996							
Allocation Procedures:	Based on average market prices, assuming 0.43 kg of ammonia per kg ammonium nitrate at £8.44/kg NH_3 (Ref. C1) and 1.394 kg of recovered carbon dioxide per kg ammonium nitrate at £0.21/kg CO_2 (Ref. C1), giving an allocation of 93% to ammonia and 7% to recovered carbon dioxide in the ammonia plant.							

Contribution	Per Unit	Methane Output (kg CH_4)						
		Direct		Indirect		Total		Notes
		Value	Range	Value	Range	Value	Range	
Ammonia Production:								
- Natural Gas Feedstock	kg N	-	-	0.0030	±0.0001	0.0030	±0.0001	(a)
- Natural Gas Fuel	kg N	-	-	0.0010	±0.0003	0.0010	±0.0003	(b)
- Steam Export	kg N	-	-	-0.0005	±0.0004	-0.0005	±0.0004	(c)
- Electricity	kg N	-	-	0.0003	±0.0001	0.0003	±0.0001	(d)
- Capital Plant	kg N	-	-	-	-	-	-	(e)
Sub-Totals	kg N	-	-	0.0038	±0.0005	0.0038	±0.0005	(f)
Nitric Acid Production:								
- Steam Export	kg N	-	-	-0.0004	-	-0.0004	-	(g)
- Capital Plant	kg N	-	-	-	-	-	-	(h)
Sub-Totals	kg N	-	-	-0.0004	-	-0.0004	-	(i)
Ammonium Nitrate Production:								
- Natural Gas Fuel	kg N	-	-	0.0002	-	0.0002	-	(j)
- Capital Plant	kg N	-	-	-	-	-	-	(k)
Sub-Totals	kg N	-	-	0.0002	-	0.0002	-	
Packaging	kg N	-	-	-	-	-	-	(l)
Transport	kg N	-	-	0.0001	-	0.0001	-	(m)
Totals	**kg N**	**-**	**-**	**0.0037**	**±0.0005**	**0.0037**	**±0.0005**	

Notes

(a) Average natural gas feedstock requirement of 23.059 ±0.929 MJ/kg NH_3 for ammonia production in the EU in 1998 (Ref. C2), with a direct methane requirement of 3.70 x 10^{-6} kg CH_4/MJ and an indirect methane requirement of 1.083 x 10^{-4} kg CH_4/MJ for natural gas in the UK in 1996 (Ref. C3).

(b) Natural gas fuel consumption of 8.025 ± 2.800 MJ/kg NH_3 (Ref. C4), with a direct methane requirement of 3.70 x 10^{-6} kg CH_4/MJ and an indirect methane requirement of 1.083 x 10^{-4} kg CH_4/MJ for natural gas in the UK in 1996 (Ref. C3).

(c) Assuming steam export of 3.475 ± 2.925 MJ/kg NH_3 (Ref. C4) which displaces steam raised from a natural gas-fired boiler with an efficiency of 85%, with a direct methane requirement of 3.70 x 10^{-6} kg CH_4/MJ and an indirect methane requirement of 1.083 x 10^{-4} kg CH_4/MJ for natural gas in the UK in 1996 (Ref. C3).

(d) Electricity consumption of 0.636 ± 0.303 MJ/kg NH_3 (Ref. C4) and an indirect methane requirement of 4.043 x 10^{-4} kg CH_4/MJ for electricity generation in the UK in 1996 (Ref. C3).

(e) Based on a primary energy input to ammonia plant construction of 1.822 ± 0.455 MJ/kg NH_3 and an estimated total methane requirement of 1.192 x 10^{-7} kg CH_4/MJ primary energy for construction (Ref. C5).

(f) Based on a total ammonia requirement of 0.43 kg/kg of ammonium nitrate fertiliser (Ref. C2).

(g) Assuming steam export of 1.556 MJ/kg HNO_3 (Ref. C2) which displaces steam raised from a natural gas-fired boiler with an efficiency of 85%, with a direct methane requirement of 3.70 x 10^{-6} kg CH_4/MJ and an indirect methane requirement of 1.083 x 10^{-4} kg CH_4/MJ for natural gas in the UK in 1996 (Ref. C3).

(h) Based on a primary energy input to nitric acid plant construction of 0.257 ± 0.104 MJ/kg HNO_3 and an estimated total methane requirement of 1.192 x 10^{-7} kg CH_4/MJ primary energy for construction (Ref. C5).

(i) Based on a nitric acid requirement of 0.77 kg/kg ammonium nitrate fertiliser (Ref. C6).

(j) Natural gas fuel consumption of 0.700 MJ/kg NH_4NO_3 (Ref. C4) with a direct methane requirement of 3.70 x 10^{-6} kg CH_4/MJ and an indirect methane requirement of 1.083 x 10^{-4} kg CH_4/MJ for natural gas in the UK in 1996 (Ref. C3).

(k) Based on a primary energy input to ammonium nitrate plant construction of 1.134 ± 0.454 MJ/kg NH_4NO_3 and an estimated total methane requirement of 1.192 x 10^{-7} kg CH_4/MJ primary energy for construction (Ref. C5).

(l) Assuming 0.004 kg polyethylene bags/kg NH_4NO_3 derived and a methane requirement of polyethylene of 1.05 x 10^{-5} kg CH_4/kg (Refs. C6 and C7).

(m) Assuming an round trip distance of 500 kilometres, and based on a direct carbon requirement of 0.0562 ± 0.0021 kg CO_2/t-km and an indirect carbon requirement of 0.0161 ± 0.0017 kg CO_2/t-km for road bulk carrier transport (Ref. C4).

References

C1. Airgas Price List, www.cehs.siu.edu/gas/price_list.htm, accessed 5 April 2002.

C2. "Energy Consumption and Greenhouse Gas Emissions in Fertiliser Production" by G. Kongshaug, Proceedings of the IFA Technical Conference in Marrakesh, Morocco, International Fertiliser Industry Association, Paris, France, 1998.

C3. "Methodology for Environmental Profiles of Construction Materials, Components and Buildings" Centre for Sustainable Construction at the Building Research Establishment Ltd., CRC Ltd., London, United Kingdom, 2000.

C4. "Carbon and Energy Modelling of Biomass Systems: Conversion Plant and Data Updates" by N. D. Mortimer and M. A. Elsayed, ETSU Report B/U1/00644/00/00REP, Energy Technology Support Unit, Harwell, United Kingdom, August 2001.

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C6. "Ammonium Nitrate" in 'Kirk-Othmer Encyclopedia of Chemical Technology' 4th Edition, Vol. 2, John Wiley and Sons Inc., New York, United States of America, 1992, pp. 698 – 705.

C7. "Eco-Profiles of the European Plastics Industry, Report 3: Polyethylene and Polypropylene" by I. Boustead, European Centre for Plastics in the Environment, Brussels, Belgium, 1993.

Table C4. Nitrous Oxide Requirement of Ammonium Nitrate Fertiliser

Functional Unit:	Bagged ammonium nitrate fertiliser produced via ammonia and nitric acid from natural gas and delivered to the point of use
Final Unit of Measurement:	kg N
Relevant Location:	United Kingdom
Relevant Period:	1996
Allocation Procedures:	Based on average market prices, assuming 0.43 kg of ammonia per kg ammonium nitrate at £8.44/kg NH_3 (Ref. C1) and 1.394 kg of recovered carbon dioxide per kg ammonium nitrate at £0.21/kg CO_2 (Ref. C1), giving an allocation of 93% to ammonia and 7% to recovered carbon dioxide in the ammonia plant.

Contribution	Per Unit	Nitrous Oxide Output (kg N_2O)						
		Direct		Indirect		Total		Notes
		Value	Range	Value	Range	Value	Range	
Ammonia Production:								
- Natural Gas Feedstock	kg N	-	-	-	-	-	-	(a)
- Natural Gas Fuel	kg N	-	-	-	-	-	-	(b)
- Steam Export	kg N	-	-	-	-	-	-	(c)
- Electricity	kg N	-	-	-	-	-	-	(d)
- Capital Plant	kg N	-	-	-	-	-	-	(e)
Sub-Totals	kg N	-	-	-	-	-	-	(f)
Nitric Acid Production:								
- Direct Emissions	kg N	0.01467	-	-	-	0.01467	-	(g)
- Steam Export	kg N	-	-	-	-	-	-	(h)
- Capital Plant	kg N	-	-	-	-	-	-	(i)
Sub-Totals	kg N	0.01467	-	-	-	0.01467	-	(j)
Ammonium Nitrate Production:								
- Natural Gas Fuel	kg N	-	-	-	-	-	-	(k)
- Capital Plant	kg N	-	-	-	-	-	-	(l)
Sub-Totals	kg N	-	-	-	-	-	-	
Packaging	kg N	-	-	-	-	-	-	(m)
Transport	kg N	-	-	-	-	-	-	(n)
Totals	**kg N**	**0.01467**	**-**	**-**	**-**	**0.01467**	**-**	

Notes

(a) Average natural gas feedstock requirement of 23.059 ±0.929 MJ/kg NH_3 for ammonia production in the EU in 1998 (Ref. C2), with a direct nitrous oxide requirement of 0.05228.9 x 10^{-8} kg N_2O/MJ and an indirect carbon requirement of 1.1 x 10^{-8} kg N_2O/MJ for natural gas in the UK in 1996 (Ref. C3).

(b) Natural gas fuel consumption of 8.025 ± 2.800 MJ/kg NH_3 (Ref. C4), with a direct nitrous oxide requirement of 0.05228.9 x 10^{-8} kg N_2O/MJ and an indirect carbon requirement of 1.1 x 10^{-8} kg N_2O/MJ for natural gas in the UK in 1996 (Ref. C3).

(c) Assuming steam export of 3.475 ± 2.925 MJ/kg NH_3 (Ref. C4) which displaces steam raised from a natural gas-fired boiler with an efficiency of 85%, with a direct nitrous oxide requirement of 0.05228.9 x 10^{-8} kg N_2O/MJ and an indirect carbon requirement of 1.1 x 10^{-8} kg N_2O/MJ for natural gas in the UK in 1996 (Ref. C3).

(d) Electricity consumption of 0.636 ± 0.303 MJ/kg NH_3 (Ref. C4) and an indirect nitrous oxide requirement of 5.577 x 10^{-6} kg N_2O/MJ for electricity generation in the UK in 1996 (Ref. C3).

(e) Based on a primary energy input to ammonia plant construction of 1.822 ± 0.455 MJ/kg NH_3 and an estimated total nitrous oxide requirement of 1.866 x 10^{-9} kg N_2O/MJ primary energy for construction (Ref. C5).

(f) Based on a total ammonia requirement of 0.43 kg/kg of ammonium nitrate fertiliser (Ref. C2).

(g) Average nitrous oxide emissions for nitric acid plants in the EU in 1998 (Ref. C2).

(h) Assuming steam export of 1.556 MJ/kg HNO_3 (Ref. C2) which displaces steam raised from a natural gas-fired boiler with an efficiency of 85%, with a direct carbon requirement of 0.0522 kg CO_2/MJ and an indirect carbon requirement of 0.0017 kg CO_2/MJ for natural gas in the UK in 1996 (Ref. C3).

(i) Based on a carbon dioxide output for nitric acid plant construction of 0.013 ± 0.005 kg CO_2/kg NH_3 derived from a carbon intensity for "Industrial Plant and Steelwork" of 1.9 ± 0.5 kg CO_2/£ (Ref. C5).

(j) Based on a nitric acid requirement of 0.77 kg/kg ammonium nitrate fertiliser (Ref. C6).

(k) Natural gas fuel consumption of 0.700 MJ/kg NH_4NO_3 (Ref. C4) with a direct nitrous oxide requirement of 0.05228.9 x 10^{-8} kg N_2O/MJ and an indirect carbon requirement of 1.1 x 10^{-8} kg N_2O/MJ for natural gas in the UK in 1996 (Ref. C3).

(l) Based on a primary energy input to ammonium nitrate plant construction of 1.134 ± 0.454 MJ/kg NH_4NO_3 and an estimated total nitrous oxide requirement of 1.866 x 10^{-9} kg N_2O/MJ primary energy for construction (Ref. C5).

(m) Assuming 0.004 kg polyethylene bags/kg NH_4NO_3 derived and a nitrous oxide requirement of polyethylene of 1.65 x 10^{-7} kg N_2O/kg (Ref. C7).

(n) Assuming an round trip distance of 500 kilometres, and based on a direct nitrous oxide requirement of 4.6 x 10^{-7} ± 1.7 x 10^{-8} kg N_2O/t-km and an indirect carbon requirement of 2.1 x 10^{-8} ± 8.0 x 10^{-10} kg N_2O/t-km for road bulk carrier transport (Ref. C4).

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Table C2. Total Greenhouse Gas Requirement of Ammonium Nitrate Fertiliser

Functional Unit:	Bagged ammonium nitrate fertiliser produced via ammonia and nitric acid from natural gas and delivered to the point of use							
Final Unit of Measurement:	kg N							
Relevant Location:	United Kingdom							
Relevant Period:	1996							
Allocation Procedures:	Based on average market prices, assuming 0.43 kg of ammonia per kg ammonium nitrate at £8.44/kg NH_3 (Ref. C1) and 1.394 kg of recovered carbon dioxide per kg ammonium nitrate at £0.21/kg CO_2 (Ref. C1), giving an allocation of 93% to ammonia and 7% to recovered carbon dioxide in the ammonia plant.							
Contribution	Per Unit	Greenhouse Gas Output (kg eq CO_2)						
		Direct		Indirect		Total		Notes
		Value	Range	Value	Range	Value	Range	
Ammonia Production:								
- Natural Gas Feedstock	kg N	-	-	1.453	±0.054	1.453	±0.054	(a)
- Natural Gas Fuel	kg N	0.478	±0.167	0.042	±0.010	0.520	±0.167	(a)
- Steam Export	kg N	-0.244	±0.206	-0.021	±0.012	-0.265	±0.206	(a)
- Electricity	kg N	-	-	0.117	±0.052	0.117	±0.052	(a)
- Capital Plant	kg N	-	-	0.101	-	0.101	-	(a)
Sub-Totals	kg N	0.234	±0.265	1.692	±0.077	1.926	±0.276	(b)
Nitric Acid Production:								
- Direct Emissions	kg N	4.694	-			4.694	-	(a)
- Steam Export	kg N	-0.210	-	-0.016	-	-0.226	-	(a)
- Capital Plant	kg N	-	-	0.029	-	0.029	-	(a)
Sub-Totals	kg N	4.484	-	0.013	-	4.497	-	(c)
Ammonium Nitrate Production:								
- Natural Gas Fuel	kg N	0.106	-	0.005	-	0.111	-	(a)
- Capital Plant	kg N	-	-	0.054	-	0.054	-	(a)
Sub-Totals	kg N	0.106	-	0.059	-	0.165	-	
Packaging	kg N	-	-	0.014	-	0.014	-	(a)
Transport	kg N	0.080	±0.006	0.011	-	0.091	±0.006	(a)
Totals	**kg N**	**4.904**	**±0.265**	**1.789**	**±0.077**	**6.693**	**±0.276**	

Notes

(a) Summation of results from previous spreadsheets with conversion using a global warming potential for methane of 24.5 kg eq CO_2/kg CH_4 and a global warming potential for nitrous oxide of 320 kg eq CO_2/kg N_2O.

(b) Based on a total ammonia requirement of 0.43 kg/kg of ammonium nitrate fertiliser (Ref. C2).

(c) Based on a nitric acid requirement of 0.77 kg/kg ammonium nitrate fertiliser (Ref. C6).

APPENDIX D: Conventional Production of Biodiesel from Oilseed Rape

Table D1. Energy Requirement for Conventional Production of Biodiesel from Oilseed Rape by Solvent Extraction

Functional Unit:	Biodiesel at point of distribution derived from oilseed rape using solvent extraction
Final Unit of Measurement:	1 tonne of biodiesel
Relevant Location:	United Kingdom
Relevant Period:	1996
Allocation Procedures:	Based on average market prices, assuming 2.782 tonnes of rape straw at £25/t (UK 1992; Ref. D1) and 2.839 tonnes of raw oilseed at £152/t (UK 1997 - 2000 average; Ref. D2), giving a 86% allocation to biodiesel, 1.575 tonnes of rape meal at £84/t (UK 1997 - 2000 average; Ref. D2) and 1.079 tonnes of crude rapeseed oil at £323 per tonne (UK 1997 - 2000 average; Ref. D2), giving a 72% allocation to biodiesel, and 0.100 tonnes of glycerine at £388/t (UK 1997 - 2000 average; Ref. D2) and 1.000 tonnes of biodiesel at £268/t (UK 1997 - 2000 average; Ref. D2), giving a 87% allocation to biodiesel.

Contribution	Per Unit	Primary Energy Input (MJ)								
		Direct		Indirect		Feedstock		Total		Notes
		Value	Range	Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:										
- N Fertiliser	t bd	-	-	1,367	±546	2,595	±104	3,962	±556	(a)
- Other Fertiliser	t bd	-	-	635	±95	-	-	635	±95	(b)
- Pesticides	t bd	-	-	382	±57	-	-	382	±57	(c)
- Seeds	t bd	-	-	19	±3	-	-	19	±3	(d)
- Diesel Fuel	t bd	1,187	±188	131	±62	-	-	1,318	±198	(e)
Reference System:										
- Diesel Fuel	t bd	- 459	±72	- 50	±24	-	-	-509	±76	(f)
Sub-Totals	t bd	728	±201	2,484	±561	2,595	±104	5,807	±605	(g)
Transport:										
- Diesel Fuel	t bd	379	±14	132	±16	-	-	511	±22	(h, i)
Drying:										
- Fuel Oil	t bd	510	±81	56	±29	-	-	566	±85	(j, k)
Storage:										
- Electricity	t bd	70	±11	144	±14	-	-	214	±18	(k, l)
Solvent Extraction:										
- Natural Gas	t bd	1,512	±227	166	±75	-	-	1,678	±239	(m)
- Electricity	t bd	204	±30	425	±10	-	-	629	±32	(n)
- Hexane	t bd	-	-	87	±13	-	-	87	±13	(o)
Sub-Totals	t bd	1,716	±229	678	±77	-	-	2,394	±242	(p)
Refining:										
- Electricity	t bd	10	±2	21	±5	-	-	31	±5	(q)
- Natural Gas	t bd	163	±25	18	±7	-	-	181	±26	(r)
- Heavy Fuel Oil	t bd	18	±3	3	-	-	-	21	±3	(s)
- Light Fuel Oil	t bd	139	±21	15	6	-	-	154	±22	(t)
- Phosph. Acid	t bd	-	-	10	±2	-	-	10	±2	(u)
- Smectite	t bd	-	-	14	±2	-	-	14	±2	(v)
Sub-Totals	t bd	330	±33	81	±11	-	-	411	±34	(w)
Esterification:										
- Electricity	t bd	72	±10	150	±66	-	-	222	±18	(x)
- Natural Gas	t bd	1,220	±183	134	±60	-	-	1,354	±193	(y)
- Heavy Fuel Oil	t bd	140	±21	16	±7	-	-	156	±22	(z)
- Light Fuel Oil	t bd	140	±21	16	±7	-	-	156	±22	(aa)
- Caustic Soda	t bd	-	-	207	±31	-	-	207	±31	(bb)
- Methanol	t bd	-	-	3,611	±542	-	-	3,611	±542	(cc)
Sub-Totals	t bd	1,572	±185	4,134	±579	-	-	5,706	±607	(dd)
Plant Construct.	t bd	3	-	97	±18	-	-	100	±18	(ee)
Plant Maintain.	t bd	-	-	62	±11	-	-	62	±11	(ff)
Distribution:										
- Diesel Fuel	t bd	369	±14	129	±16	-	-	498	±21	(gg)
Totals	**t bd**	**5,677**	**±368**	**7,997**	**±811**	**2,595**	**±104**	**16,269**	**±896**	

Abbreviations

ha.a = hectare year
t bd = tonne of biodiesel

Notes

(a) Ammonium nitrate fertiliser application rate of 196 kg/ha.a based on a 4 year average for the UK between 1997 and 2000 (Ref. D3) and a direct and indirect energy requirement of 14.013 ± 5.599 MJ/kg N and a feedstock energy requirement of 26.595 ± 1.060 MJ/kg N for ammonium nitrate (Appendix C).

(b) Other fertiliser application rates for phosphate of 50 kg P_2O_5/ ha.a and for potash of 48 kg K_2O/ha.a (Ref. D5), and for lime of 18.9 kg CaO (Ref. D5), with total energy requirements for phosphate fertiliser of 15.8 MJ/kg P_2O_5 , for potash fertiliser of 9.3 MJ/ kg K_2O, and for lime of 2.1 MJ/kg CaO (Ref. D5).

(c) Application rate for a mixture of pesticides, herbicides and fungicides of 2.8 kg/ha.a (Ref. D6) and a total energy requirement for general pesticides, herbicides and fungicides of 274.1 MJ/kg (Ref. D5).

(d) Sowing rate of 5 kg/ha.a (Ref. D7) and a total energy requirement of 7.8 MJ/kg of seed (Ref. D5).

(e) Diesel fuel consumption of 2,385 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides and fungicides, and harvesting (Ref. D5) and a gross energy requirement of 1.110 MJ/MJ for diesel fuel in the UK in 1996 (Ref. D8).

(f) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. D5) and a gross energy requirement of 1.110 MJ/MJ for diesel fuel in the UK in 1996 (Ref. D8).

(g) Land requirement of 0.924 ha.a/t of biodiesel and allocation of 86% x 72% x 87% = 53.87% to biodiesel.

(h) Average round trip distance of 260 km (Ref. D9) by bulk road carrier transport with a direct energy requirement of 0.8196 ± 0.0310 MJ/t-km, an indirect energy requirement of 0.2857 ± 0.0352 MJ/t-km and a total energy requirement of 1.1053 ± 0.0469 MJ/t-km (Ref. D10).

(i) Raw oilseed requirement of 2.839 t/t of biodiesel and allocation of 72% x 87% = 62.64% to biodiesel.

(j) Fuel oil consumption of 305 MJ/t of dried oilseed for drying (Ref. D5) and a gross energy requirement of 1.110 MJ/MJ for fuel oil in the UK in 1996 (Ref. D8).

(k) Dried oilseed requirement of 2.664t/t of biodiesel and allocation of 72% x 87% = 62.64% to biodiesel.

(l) Electricity consumption of 11.6 kWh/t of dried oilseed for cooling (Ref. D5) and a gross energy requirement of 3.083 MJ/MJ for electricity in the UK in 1996 (Ref. D8).

(m) Steam consumption of 716 kg/t of crude rapeseed oil (Ref. D5), with assumed boiler efficiency of 80% giving natural gas consumption of 2.5 MJ/kg steam, and a gross energy requirement of 1.110 MJ/MJ for natural gas in the UK in 1996 (Ref. D8).

(n) Electricity consumption of 84 kWh/t of crude rapeseed oil (Ref. D5) and a gross energy requirement of 3.083 MJ/MJ for electricity in the UK in 1996 (Ref. D8).

(o) Hexane consumption of 2.5 kg/t of crude rapeseed oil and a total energy requirement of 52.05 MJ/kg of hexane (Ref. D5).

(p) Crude rapeseed oil requirement of 1.079 t/t of biodiesel and allocation of 72% x 87% = 62.64% to biodiesel.

(q) Electricity consumption of 3.1 kWh/t refined rapeseed oil (Ref. D5) and a gross energy requirement of 3.083 MJ/MJ for electricity in the UK in 1996 (Ref. D8).

(r) Natural gas consumption of 178 MJ/t of refined rapeseed oil (Ref. D5) and a gross energy requirement of 1.110 MJ/MJ for natural gas in the UK in 1996 (Ref. D8).

(s) Heavy fuel oil consumption of 20 MJ/t of refined rapeseed oil (Ref. D5) and a gross energy requirement of 1.110 MJ/MJ for heavy fuel oil in the UK in 1996 (Ref. D8).

(t) Light fuel oil consumption of 152 MJ/t of refined rapeseed oil (Ref. D5) and a gross energy requirement of 1.110 MJ/MJ for light fuel oil in the UK in 1996 (Ref. D8).

(u) Phosphoric acid consumption of 1 kg/t of refined rapeseed oil and a total energy requirement of 11.4 MJ/kg for phosphoric acid (Ref. D5).

(v) Smectite consumption of 6 kg/t of refined rapeseed oil and a total energy requirement of 2.55 MJ/kg for smectite (Ref. D5).

(w) Refined rapeseed oil requirement of 1.052 t/t of biodiesel and allocation of 87% to biodiesel.

(x) Electricity consumption of 23 kWh/t of biodiesel (Ref. D5) and a gross energy requirement of 3.083 MJ/MJ for electricity in the UK in 1996 (Ref. D8).

(y) Natural gas consumption of 1,402 MJ/t of biodiesel (Ref. D5) and a gross energy requirement of 1.110 MJ/MJ for natural gas in the UK in 1996 (Ref. D8).

(z) Heavy fuel oil consumption of 161 MJ/t of biodiesel (Ref. D5) and a gross energy requirement of 1.110 MJ/MJ for heavy fuel oil in the UK in 1996 (Ref. D8).

(aa) Light fuel oil consumption of 161 MJ/t of biodiesel (Ref. D5) and a gross energy requirement of 1.110 MJ/MJ for light fuel oil in the UK in 1996 (Ref. D8).

(bb) Caustic soda (50% concentration) consumption of 12 kg/t of biodiesel and a total energy requirement of 19.87 MJ/kg of caustic soda (Ref. D5).

(cc) Methanol consumption of 109 kg/t of biodiesel and a total energy requirement of 38.08 MJ/kg of methanol (Ref. D5).

(dd) Allocation of 87% to biodiesel.

(ee) Primary energy input of 131,004 ± 23,909 GJ for construction of a biodiesel plant (Ref. D10) with a capacity of a 40,000 t/a and a 25 year life, assuming oil mill (assumed similar to solvent extraction plant) accounting for 72% of the primary energy input by weight and 72% contribution to biodiesel by price of co-products, and assuming refining and esterification plants accounting for 28% of the primary energy input by weight and 87% contribution to biodiesel by price of co-products.

(ff) Primary energy input of annual plant maintenance assumed to be 2.5% of primary energy input to plant construction (Ref. D10).

(gg) Average round trip distance of 450 km (Ref. D9) by bulk road carrier transport with a direct energy requirement of 0.8196 ± 0.0310 MJ/t-km, an indirect energy requirement of 0.2857 ± 0.0352 MJ/t-km and a total energy requirement of 1.1053 ± 0.0469 MJ/t-km (Ref. D10).

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Table D2. Carbon Requirement for Conventional Production of Biodiesel from Oilseed Rape by Solvent Extraction

Functional Unit: :	Biodiesel at point of distribution derived from oilseed rape using solvent extraction							
Final Unit of Measurement:	1 tonne of biodiesel							
Relevant Location:	United Kingdom							
Relevant Period:	1996							
Allocation Procedures:	Based on average market prices, assuming 2.782 tonnes of rape straw at £25/t (UK 1992; Ref. D1) and 2.839 tonnes of raw oilseed at £152/t (UK 1997 - 2000 average; Ref. D2), giving a 86% allocation to biodiesel, 1.575 tonnes of rape meal at £84/t (UK 1997 - 2000 average; Ref. D2) and 1.079 tonnes of crude rapeseed oil at £323 per tonne (UK 1997 - 2000 average; Ref. D2), giving a 72% allocation to biodiesel, and 0.100 tonnes of glycerine at £388/t (UK 1997 - 2000 average; Ref. D2) and 1.000 tonnes of biodiesel at £268/t (UK 1997 - 2000 average; Ref. D2), giving a 87% allocation to biodiesel.							
Contribution	Per Unit	Carbon Dioxide Output (kg CO_2)						
		Direct		Indirect		Total		Notes
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	t bd	-	-	186	±27	186	±27	(a)
- Other Fertiliser	t bd	-	-	30	±4	30	±4	(b)
- Pesticides	t bd	-	-	7	±1	7	±1	(c)
- Seeds	t bd	-	-	-	-	-	-	(d)
- Diesel Fuel	t bd	82	±12	9	±1	91	±12	(e)
Reference System:								
- Diesel Fuel	t bd	- 32	±4	- 3	-	- 35	±4	(f)
Sub-Totals	t bd	50	±13	229	±27	279	±30	(g)
Transport:								
- Diesel Fuel	t bd	26	±1	7	±1	33	±1	(h, i)
Drying:								
- Fuel Oil	t bd	37	±6	4	±1	41	±6	(j, k)
Storage:								
- Electricity	t bd	-	-	17	±2	17	±2	(k, l)
Solvent Extraction:								
- Natural Gas	t bd	79	±12	3	-	82	±12	(m)
- Electricity	t bd	-	-	30	±5	30	±5	(n)
- Hexane	t bd	-	-	1	-	1	-	(o)
Sub-Totals	t bd	79	±12	34	±5	113	±13	(p)
Refining:								
- Electricity	t bd	-	-	2	-	2	-	(q)
- Natural Gas	t bd	8	±1	1	-	9	±1	(r)
- Heavy Fuel Oil	t bd	2	-	-	-	2	-	(s)
- Light Fuel Oil	t bd	10	±2	1	-	11	±2	(t)
- Phosph. Acid	t bd	-	-	1	-	1	-	(u)
- Smectite	t bd	-	-	1	-	1	-	(v)
Sub-Totals	t bd	20	±2	6	-	26	±2	(w)
Esterification:								
- Electricity	t bd	-	-	10	±2	10	±2	(x)
- Natural Gas	t bd	63	±10	2	-	65	±10	(y)
- Heavy Fuel Oil	t bd	10	±2	1	-	11	±2	(z)
- Light Fuel Oil	t bd	10	±2	1	-	11	±2	(aa)
- Caustic Soda	t bd	-	-	11	±2	11	±2	(bb)
- Methanol	t bd	-	-	258	±39	258	±39	(cc)
Sub-Totals	t bd	84	±10	284	±39	368	±40	(dd)
Plant Construction	t bd	-	-	5	±1	5	±1	(ee)
Plant Maintenance	t bd	-	-	2	-	2	-	(ff)
Distribution:								
- Diesel Fuel	t bd	25	±1	7	±1	32	±1	(gg)
Totals	**t bd**	**321**	**±21**	**595**	**±48**	**916**	**±52**	

Abbreviations

ha.a = hectare year
t bd = tonne of biodiesel

Notes

(a) Ammonium nitrate fertiliser application rate of 196 kg/ha.a based on a 4 year average for the UK between 1997 and 2000 (Ref. D3) and a total carbon requirement for ammonium nitrate of 1.904 ± 0.275 kg CO_2/kg N (Appendix C).

(b) Other fertiliser application rates for phosphate of 50 kg P_2O_5/ ha.a and for potash of 48 kg K_2O/ha.a (Ref. D4), and for lime of 18.9 kg CaO (Ref. D5), with total carbon requirements for phosphate fertiliser of 0.700 kg CO_2/kg P_2O_5 , for potash fertiliser of 0.453 kg CO_2/ kg K_2O, and for lime of 0.179 kg CO_2/kg CaO (Ref. D5).

(c) Application rate for a mixture of pesticides, herbicides and fungicides of 2.8 kg/ha.a (Ref. D6) and a total carbon requirement for general pesticides, herbicides and fungicides of 4.921 kg CO_2/kg (Ref. D5).

(d) Sowing rate of 5 kg/ha.a (Ref. D7) and a total carbon requirement of 0.316 kg CO_2/kg of seed (Ref. D5).

(e) Diesel fuel consumption of 2,385 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides and fungicides, and harvesting (Ref. D5), and a direct carbon requirement of 0.0686 kg CO_2/MJ, an indirect carbon requirement of 0.0081 kg CO_2/MJ and a total carbon requirement of 0.0767 kg CO_2/MJ for diesel fuel in the UK in 1996 (Ref. D8).

(f) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. D5), and a direct carbon requirement of 0.0686 kg CO_2/MJ, an indirect carbon requirement of 0.0081 kg CO_2/MJ and a total carbon requirement of 0.0767 kg CO_2/MJ for diesel fuel in the UK in 1996 (Ref. D8).

(g) Land requirement of 0.924 ha.a/t of biodiesel and allocation of 86% x 72% x 87% = 53.87% to biodiesel.

(h) Average round trip distance of 260 km (Ref. D9) by bulk road carrier transport with a direct carbon requirement of 0.0562 ± 0.0021 kg CO_2/t-km, an indirect carbon requirement of 0.0161 ± 0.0017 kg CO_2/t-km and a total carbon requirement of 0.0723 ± 0.0027 kg CO_2/t-km (Ref. D10).

(i) Raw oilseed requirement of 2.839 t/t of biodiesel and allocation of 72% x 87% = 62.64% to biodiesel.

(j) Fuel oil consumption of 305 MJ/t of dried oilseed for drying (Ref. D5), and a direct carbon requirement of 0.0730 kg CO_2/MJ, an indirect carbon requirement of 0.0081 kg CO_2/MJ and a total carbon requirement of 0.0811 kg CO_2/MJ for fuel oil in the UK in 1996 (Ref. D8).

(k) Dried oilseed requirement of 2.664t/t of biodiesel and allocation of 72% x 87% = 62.64% to biodiesel.

(l) Electricity consumption of 11.6 kWh/t of dried oilseed for cooling (Ref. D5), and an indirect carbon requirement of 0.1504 kg CO_2/MJ for electricity in the UK in 1996 (Ref. D8).

(m) Steam consumption of 716 kg/t of crude rapeseed oil (Ref. D5), with assumed boiler efficiency of 80% giving natural gas consumption of 2.5 MJ/kg steam, and a direct carbon requirement of 0.0522 kg CO_2/MJ, an indirect carbon requirement of 0.0017 kg CO_2/MJ and a total carbon requirement of 0.0539 kg CO_2/MJ for natural gas in the UK in 1996 (Ref. D8).

(n) Electricity consumption of 84 kWh/t of crude rapeseed oil (Ref. D5) and an indirect carbon requirement of 0.1504 kg CO_2/MJ for electricity in the UK in 1996 (Ref. D8).

(o) Hexane consumption of 2.5 kg/t of crude rapeseed oil and a total carbon requirement of 0.543 kg CO_2/kg of hexane (Ref. D5).

(p) Crude rapeseed oil requirement of 1.079 t/t of biodiesel and allocation of 72% x 87% = 62.64% to biodiesel.

(q) Electricity consumption of 3.1 kWh/t refined rapeseed oil (Ref. D%) and an indirect carbon requirement of 0.1504 kg CO_2/MJ for electricity in the UK in 1996 (Ref. D8).

(r) Natural gas consumption of 178 MJ/t of refined rapeseed oil (Ref. D5) and a direct carbon requirement of 0.0522 kg CO_2/MJ, an indirect carbon requirement of 0.0017 kg CO_2/MJ and a total carbon requirement of 0.0539 kg CO_2/MJ for natural gas in the UK in 1996 (Ref. D8).

(s) Heavy fuel oil consumption of 20 MJ/t of refined rapeseed oil (Ref. D5) and a direct carbon requirement of 0.0730 kg CO_2/MJ, an indirect carbon requirement of 0.0081 kg CO_2/MJ and a total carbon requirement of 0.0811 kg CO_2/MJ for heavy fuel oil in the UK in 1996 (Ref. D8).

(t) Light fuel oil consumption of 152 MJ/t of refined rapeseed oil (Ref. D5) and a direct carbon requirement of 0.0730 kg CO_2/MJ, an indirect carbon requirement of 0.0081 kg CO_2/MJ and a total carbon requirement of 0.0811 kg CO_2/MJ for light fuel oil in the UK in 1996 (Ref. D8).

(u) Phosphoric acid consumption of 1 kg/t of refined rapeseed oil and a total carbon requirement of 0.768 kg CO_2 /kg for phosphoric acid (Ref. D5).

(v) Smectite consumption of 6 kg/t of refined rapeseed oil and a total carbon requirement of 0.197 kg CO_2 /kg for smectite (Ref. D5).

(w) Refined rapeseed oil requirement of 1.052 t/t of biodiesel and allocation of 87% to biodiesel.

(x) Electricity consumption of 23 kWh/t of biodiesel (Ref. D5) and an indirect carbon requirement of 0.1504 kg CO_2/MJ for electricity in the UK in 1996 (Ref. D8).

(y) Natural gas consumption of 1,402 MJ/t of biodiesel (Ref. D5) and a direct carbon requirement of 0.0522 kg CO_2/MJ, an indirect carbon requirement of 0.0017 kg CO_2/MJ and a total carbon requirement of 0.0539 kg CO_2/MJ for natural gas in the UK in 1996 (Ref. D8).

(z) Heavy fuel oil consumption of 161 MJ/t of biodiesel (Ref. D5) and a direct carbon requirement of 0.0730 kg CO_2/MJ, an indirect carbon requirement of 0.0081 kg CO_2/MJ and a total carbon requirement of 0.0811 kg CO_2/MJ for heavy fuel oil in the UK in 1996 (Ref. D8).

(aa) Light fuel oil consumption of 161 MJ/t of biodiesel (Ref. D5) and a direct carbon requirement of 0.0730 kg CO_2/MJ, an indirect carbon requirement of 0.0081 kg CO_2/MJ and a total carbon requirement of 0.0811 kg CO_2/MJ for light fuel oil in the UK in 1996 (Ref. D8).

(bb) Caustic soda (50% concentration) consumption of 12 kg/t of biodiesel and a total carbon requirement of 1.120 kg CO_2/kg of caustic soda (Ref. D5).

(cc) Methanol consumption of 109 kg/t of biodiesel and a total carbon requirement of 2.722 kg CO_2/kg of methanol (Ref. D5).

(dd) Allocation of 87% to biodiesel.

(ee) Carbon dioxide output of 6,287 ± 1,116 tonnes CO_2 from construction of a biodiesel plant (Ref. D10) with a capacity of a 40,000 t/a and a 25 year life, assuming oil mill (assumed similar to solvent extraction plant) accounting for 72% of the carbon dioxide output by weight and 72% contribution to biodiesel by price of co-products, and assuming refining and esterification plants accounting for 28% of the carbon dioxide output by weight and 87% contribution to biodiesel by price of co-products.

(ff) Carbon dioxide output for annual plant maintenance assumed to be 2.5% of carbon dioxide output from plant construction (Ref. D10).

(gg) Average round trip distance of 450 km (Ref. D9) by bulk road carrier transport with a direct carbon requirement of 0.0562 ± 0.0021 MJ/t-km, an indirect carbon requirement of 0.0161 ± 0.0017 MJ/t-km and a total carbon requirement of 0.0723 ± 0.0027 MJ/t-km (Ref. D10).

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D10. "Carbon and Energy Modelling of Biomass Systems: Conversion Plant and Data Updates" by N. D. Mortimer and M. A. Elsayed, ETSU Report B/U1/00644/00/00REP, Energy Technology Support Unit, Harwell, United Kingdom, August 2001.

Table D3. Methane Requirement for Conventional Production of Biodiesel from Oilseed Rape by Solvent Extraction

Functional Unit: :	Biodiesel at point of distribution derived from oilseed rape using solvent extraction
Final Unit of Measurement:	1 tonne of biodiesel
Relevant Location:	United Kingdom
Relevant Period:	1996
Allocation Procedures:	Based on average market prices, assuming 2.782 tonnes of rape straw at £25/t (UK 1992; Ref. D1) and 2.839 tonnes of raw oilseed at £152/t (UK 1997 - 2000 average; Ref. D2), giving a 86% allocation to biodiesel, 1.575 tonnes of rape meal at £84/t (UK 1997 - 2000 average; Ref. D2) and 1.079 tonnes of crude rapeseed oil at £323 per tonne (UK 1997 - 2000 average; Ref. D2), giving a 72% allocation to biodiesel, and 0.100 tonnes of glycerine at £388/t (UK 1997 - 2000 average; Ref. D2) and 1.000 tonnes of biodiesel at £268/t (UK 1997 - 2000 average; Ref. D2), giving a 87% allocation to biodiesel.

Contribution	Per Unit	Methane Output (kg CH_4)						
		Direct		Indirect		Total		Notes
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	t bd	-	-	0.351	±0.059	0.351	±0.059	(a)
- Other Fertiliser	t bd	-	-	0.001	-	0.001	-	(b)
- Pesticides	t bd	-	-	0.001	-	0.001	-	(c)
- Seeds	t bd	-	-	-	-	-	-	(d)
- Diesel Fuel	t bd	-	-	0.024	±0.003	0.024	±0.003	(e)
Reference System:								
- Diesel Fuel	t bd	-	-	-0.009	±0.001	-0.009	±0.001	(f)
Sub-Totals	t bd	-	-	0.368	±0.059	0.368	±0.059	(g)
Transport:								
- Diesel Fuel	t bd	-	-	0.008	±0.001	0.008	±0.001	(h, i)
Drying:								
- Fuel Oil	t bd	0.001	-	0.010	±0.002	0.011	±0.002	(j, k)
Storage:								
- Electricity	t bd	-	-	0.028	±0.004	0.028	±0.004	(k, l)
Solvent Extraction:								
- Natural Gas	t bd	0.005	±0.001	0.164	±0.024	0.169	±0.024	(m)
- Electricity	t bd	-	-	0.082	±0.012	0.082	±0.012	(n)
- Hexane	t bd	-	-	0.001	-	0.001	-	(o)
Sub-Totals	t bd	0.005	±0.001	0.247	±0.027	0.252	±0.027	(p)
Refining:								
- Electricity	t bd	-	-	0.005	±0.001	0.005	±0.001	(q)
- Natural Gas	t bd	0.001	-	0.017	±0.003	0.018	±0.003	(r)
- Heavy Fuel Oil	t bd	-	-	-	-	-	-	(s)
- Light Fuel Oil	t bd	-	-	0.003	±0.001	0.003	±0.001	(t)
- Phosph. Acid	t bd	-	-	0.001	-	0.001	-	(u)
- Smectite	t bd	-	-	-	-	-	-	(v)
Sub-Totals	t bd	0.001	-	0.026	±0.003	0.027	±0.003	(w)
Esterification:								
- Electricity	t bd	-	-	0.029	±0.004	0.029	±0.004	(x)
- Natural Gas	t bd	0.004	±0.001	0.132	±0.020	0.136	±0.020	(y)
- Heavy Fuel Oil	t bd	0.001	-	0.003	±0.001	0.003	±0.001	(z)
- Light Fuel Oil	t bd	0.001	-	0.003	±0.001	0.003	±0.001	(aa)
- Caustic Soda	t bd	-	-	0.034	±0.005	0.034	±0.005	(bb)
- Methanol	t bd	-	-	0.123	±0.018	0.123	±0.018	(cc)
Sub-Totals	t bd	0.006	±0.001	0.324	±0.028	0.330	±0.028	(dd)
Plant Construction	t bd	**-**	**-**	**-**	**-**	**-**	**-**	(ee)
Plant Maintenance	t bd	**-**	**-**	**-**	**-**	**-**	**-**	(ff)
Distribution:								
- Diesel Fuel	t bd	-	-	0.008	-	0.008	-	(gg)
Totals	**t bd**	**0.013**	**±0.001**	**1.019**	**±0.071**	**1.032**	**±0.071**	

Abbreviations

ha.a = hectare year
t bd = tonne of biodiesel

Notes

(a) Ammonium nitrate fertiliser application rate of 196 kg/ha.a based on a 4 year average for the UK between 1997 and 2000 (Ref. D3) and a total methane requirement for ammonium nitrate of $3.6 \times 10^{-3} \pm 0.6 \times 10^{-3}$ kg CH_4/kg N (Appendix C).

(b) Other fertiliser application rates for phosphate of 50 kg P_2O_5/ ha.a and for potash of 48 kg K_2O/ha.a (Ref. D4), and for lime of 18.9 kg CaO (Ref. D5), with total carbon requirements for phosphate fertiliser of 2.3×10^{-5} kg CH_4/kg P_2O_5 , for potash fertiliser of 2.1×10^{-5} kg CH_4/ kg K_2O, and for lime of 3.9×10^{-6} kg CH_4/kg CaO (Ref. D5).

(c) Application rate for a mixture of pesticides, herbicides and fungicides of 2.8 kg/ha.a (Ref. D6) and a total methane requirement for general pesticides, herbicides and fungicides of 1.8×10^{-4} kg CH_4/kg (Ref. D5).

(d) Sowing rate of 5 kg/ha.a (Ref. D7) and a total methane requirement of 0 kg CH_4/kg of seed (Ref. D5).

(e) Diesel fuel consumption of 2,385 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides and fungicides, and harvesting (Ref. D5), and a direct methane requirement of 6.0×10^{-7} kg CH_4/MJ, an indirect methane requirement of 2.04×10^{-5} kg CH_4/MJ and a total methane requirement of 2.1×10^{-5} kg CH_4/MJ for diesel fuel in the UK in 1996 (Ref. D8).

(f) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. D5), and a direct methane requirement of 6.0×10^{-7} kg CH_4/MJ, an indirect methane requirement of 2.04×10^{-5} kg CH_4/MJ and a total methane requirement of 2.1×10^{-5} kg CH_4/MJ for diesel fuel in the UK in 1996 (Ref. D8).

(g) Land requirement of 0.924 ha.a/t of biodiesel and allocation of 86% x 72% x 87% = 53.87% to biodiesel.

(h) Average round trip distance of 260 km (Ref. D9) by bulk road carrier transport with a direct methane requirement of $4.900 \times 10^{-7} \pm 2.000 \times 10^{-8}$ kg CH_4/t-km, an indirect methane requirement of $1.672 \times 10^{-5} \pm 6.3 \times 10^{-7}$ kg CH_4/t-km and a total methane requirement of $1.721 \times 10^{-5} \pm 6.5 \times 10^{-7}$ kg CH_4/t-km (Ref. D10).

(i) Raw oilseed requirement of 2.839 t/t of biodiesel and allocation of 72% x 87% = 62.64% to biodiesel.

(j) Fuel oil consumption of 305 MJ/t of dried oilseed for drying (Ref. D5), and a direct methane requirement of 2.6×10^{-6} kg CH_4/MJ, an indirect methane requirement of 2.04×10^{-5} kg CH_4/MJ and a total methane requirement of 2.3×10^{-5} kg CH_4/MJ for fuel oil in the UK in 1996 (Ref. D8).

(k) Dried oilseed requirement of 2.664t/t of biodiesel and allocation of 72% x 87% = 62.64% to biodiesel.

(l) Electricity consumption of 11.6 kWh/t of dried oilseed for cooling (Ref. D5), and an indirect methane requirement of 4.043×10^{-4} kg CH_4/MJ for electricity in the UK in 1996 (Ref. D8).

(m) Steam consumption of 716 kg/t of crude rapeseed oil (Ref. D5), with assumed boiler efficiency of 80% giving natural gas consumption of 2.5 MJ/kg steam, and a direct methane requirement of 3.70×10^{-6} kg CH_4/MJ, an indirect methane requirement of 1.083×10^{-4} kg CH_4/MJ and a total methane requirement of 1.12×10^{-4} kg CH_4/MJ for natural gas in the UK in 1996 (Ref. D8).

(n) Electricity consumption of 84 kWh/t of crude rapeseed oil (Ref. D5) and an indirect methane requirement of 4.043×10^{-4} kg CH_4/MJ for electricity in the UK in 1996 (Ref. D8).

(o) Hexane consumption of 2.5 kg/t of crude rapeseed oil and a total carbon requirement of 6.73×10^{-4} kg CH_4/kg of hexane (Ref. D5).

(p) Crude rapeseed oil requirement of 1.079 t/t of biodiesel and allocation of 72% x 87% = 62.64% to biodiesel.

(q) Electricity consumption of 3.1 kWh/t refined rapeseed oil (Ref. D5) and an indirect methane requirement of 4.043×10^{-4} kg CH_4/MJ for electricity in the UK in 1996 (Ref. D8).

(r) Natural gas consumption of 178 MJ/t of refined rapeseed oil (Ref. D5) and a direct methane requirement of 3.70×10^{-6} kg CH_4/MJ, an indirect methane requirement of 1.083×10^{-4} kg CH_4/MJ and a total methane requirement of 1.12×10^{-4} kg CH_4/MJ for natural gas in the UK in 1996 (Ref. D8).

(s) Heavy fuel oil consumption of 20 MJ/t of refined rapeseed oil (Ref. D5) and a direct methane requirement of 2.6×10^{-6} kg CH_4/MJ, an indirect methane requirement of 2.04×10^{-5} kg CH_4/MJ and a total methane requirement of 2.3×10^{-5} kg CH_4/MJ for heavy fuel oil in the UK in 1996 (Ref. D8).

(t) Light fuel oil consumption of 152 MJ/t of refined rapeseed oil (Ref. D5) and a direct methane requirement of 2.6×10^{-6} kg CH_4/MJ, an indirect methane requirement of 2.04×10^{-5} kg CH_4/MJ and a total methane requirement of 2.3×10^{-5} kg CH_4/MJ for light fuel oil in the UK in 1996 (Ref. D8).

(u) Phosphoric acid consumption of 1 kg/t of refined rapeseed oil and a total methane requirement of 1.23×10^{-3} kg CH_4 /kg for phosphoric acid (Ref. D5).

(v) Smectite consumption of 6 kg/t of refined rapeseed oil and a total methane requirement of 3.7×10^{-5} kg CH_4 /kg for smectite (Ref. D5).

(w) Refined rapeseed oil requirement of 1.052 t/t of biodiesel and allocation of 87% to biodiesel.

(x) Electricity consumption of 23 kWh/t of biodiesel (Ref. D5) and an indirect methane requirement of 4.043×10^{-4} kg CH_4/MJ for electricity in the UK in 1996 (Ref. D8).

(y) Natural gas consumption of 1,402 MJ/t of biodiesel (Ref. D5) and a direct methane requirement of 3.70×10^{-6} kg CH_4/MJ, an indirect methane requirement of 1.083×10^{-4} kg CH_4/MJ and a total methane requirement of 1.12×10^{-4} kg CH_4/MJ for natural gas in the UK in 1996 (Ref. D8).

(z) Heavy fuel oil consumption of 161 MJ/t of biodiesel (Ref. D5) and a direct methane requirement of 2.6×10^{-6} kg CH_4/MJ, an indirect methane requirement of 2.04×10^{-5} kg CH_4/MJ and a total methane requirement of 2.3×10^{-5} kg CH_4/MJ for heavy fuel oil in the UK in 1996 (Ref. D8).

(aa) Light fuel oil consumption of 161 MJ/t of biodiesel (Ref. D5) and a direct methane requirement of 2.6×10^{-6} kg CH_4/MJ, an indirect methane requirement of 2.04×10^{-5} kg CH_4/MJ and a total methane requirement of 2.3×10^{-5} kg CH_4/MJ for light fuel oil in the UK in 1996 (Ref. D8).

(bb) Caustic soda (50% concentration) consumption of 12 kg/t of biodiesel and a total methane requirement of 3.25×10^{-3} kg CH_4/kg of caustic soda (Ref. D5).

(cc) Methanol consumption of 109 kg/t of biodiesel and a total methane requirement of 1.3×10^{-3} kg CH_4/kg of methanol (Ref. D5).

(dd) Allocation of 87% to biodiesel.

(ee) Primary energy input of 131,004 ± 23,909 GJ for construction of a biodiesel plant (Ref. D10) with a capacity of a 40,000 t/a and a 25 year life, and an estimated total methane requirement of 1.192×10^{-7} kg CH_4/MJ primary energy input to construction (Ref. D11), assuming oil mill (assumed similar to solvent extraction plant) accounting for 72% of the primary energy input by weight and 72% contribution to biodiesel by price of co-products, and assuming refining and esterification plants accounting for 28% of the primary energy input by weight and 87% contribution to biodiesel by price of co-products.

(ff) Methane output of annual plant maintenance assumed to be 2.5% of methane output from plant construction (Ref. D10).

(gg) Average round trip distance of 450 km (Ref. D9) by bulk road carrier transport with a direct carbon requirement of $4.900 \times 10^{-7} \pm 2.000 \times 10^{-8}$ kg CH_4/t-km, an indirect methane requirement of $1.672 \times 10^{-5} \pm 6.3 \times 10^{-7}$ kg CH_4/t-km and a total methane requirement of $1.721 \times 10^{-5} \pm 6.5 \times 10^{-7}$ kg CH_4/t-km (Ref. D10).

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Table D4. Nitrous Oxide Requirement for Conventional Production of Biodiesel from Oilseed Rape by Solvent Extraction

Functional Unit: :	Biodiesel at point of distribution derived from oilseed rape using solvent extraction
Final Unit of Measurement:	1 tonne of biodiesel
Relevant Location:	United Kingdom
Relevant Period:	1996
Allocation Procedures:	Based on average market prices, assuming 2.782 tonnes of rape straw at £25/t (UK 1992; Ref. D1) and 2.839 tonnes of raw oilseed at £152/t (UK 1997 - 2000 average; Ref. D2), giving a 86% allocation to biodiesel, 1.575 tonnes of rape meal at £84/t (UK 1997 - 2000 average; Ref. D2) and 1.079 tonnes of crude rapeseed oil at £323 per tonne (UK 1997 - 2000 average; Ref. D2), giving a 72% allocation to biodiesel, and 0.100 tonnes of glycerine at £388/t (UK 1997 - 2000 average; Ref. D2) and 1.000 tonnes of biodiesel at £268/t (UK 1997 - 2000 average; Ref. D2), giving a 87% allocation to biodiesel.

Contribution	Per Unit	Nitrous Oxide Output (kg N_2O)						
		Direct		Indirect		Total		Notes
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	t bd	0.351	±0.053	1.434	±0.215	1.785	±0.222	(a)
- Other Fertiliser	t bd	-	-	0.001	-	0.001	-	(b)
- Pesticides	t bd	-	-	0.002	-	0.002	-	(c)
- Seeds	t bd	-	-	0.003	-	0.003	-	(d)
- Diesel Fuel	t bd	-	-	-	-	-	-	(e)
Reference System:								
- Diesel Fuel	t bd	-	-	-	-	-	-	(f)
Sub-Totals	t bd	0.351	±0.053	1.440	±0.215	1.791	±0.222	(g)
Transport:								
- Diesel Fuel	t bd	-	-	-	-	-	-	(h, i)
Drying:								
- Fuel Oil	t bd	-	-	-	-	-	-	(j, k)
Storage:								
- Electricity	t bd	-	-	-	-	-	-	(k, l)
Solvent Extraction:								
- Natural Gas	t bd	-	-	-	-	-	-	(m)
- Electricity	t bd	-	-	0.002	-	0.002	-	(n)
- Hexane	t bd	-	-	-	-	-	-	(o)
Sub-Totals	t bd	-	-	0.002	-	0.002	-	(p)
Refining:								
- Electricity	t bd	-	-	-	-	-	-	(q)
- Natural Gas	t bd	-	-	-	-	-	-	(r)
- Heavy Fuel Oil	t bd	-	-	-	-	-	-	(s)
- Light Fuel Oil	t bd	-	-	-	-	-	-	(t)
- Phosph. Acid	t bd	-	-	-	-	-	-	(u)
- Smectite	t bd	-	-	-	-	-	-	(v)
Sub-Totals	t bd	-	-	-	-	-	-	(w)
Esterification:								
- Electricity	t bd	-	-	-	-	-	-	(x)
- Natural Gas	t bd	-	-	-	-	-	-	(y)
- Heavy Fuel Oil	t bd	-	-	-	-	-	-	(z)
- Light Fuel Oil	t bd	-	-	-	-	-	-	(aa)
- Caustic Soda	t bd	-	-	-	-	-	-	(bb)
- Methanol	t bd	-	-	0.001	-	0.001	-	(cc)
Sub-Totals	t bd	-	-	0.001	-	0.001	-	(dd)
Plant Construction	t bd	**-**	**-**	**-**	**-**	**-**	**-**	(ee)
Plant Maintenance	t bd	**-**	**-**	**-**	**-**	**-**	**-**	(ff)
Distribution:								(gg)
- Diesel Fuel	t bd	**-**	**-**	**-**	**-**	**-**	**-**	
Totals	**t bd**	**0.351**	**±0.053**	**1.443**	**±0.215**	**1.794**	**±0.222**	

Abbreviations

ha.a = hectare year
t bd = tonne of biodiesel

Notes

(a) Ammonium nitrate fertiliser application rate of 196 kg/ha.a based on a 4 year average for the UK between 1997 and 2000 (Ref. D3) and a direct nitrous oxide requirement of 0.0036 kg N_2O/kg N (Appendix C), an indirect nitrous oxide requirement of 0.0147 kg N_2O/kg N (Ref. D5) and a total nitrous oxide requirement for ammonium nitrate of 0.0183 kg N_2O/kg N (Appendix C).

(b) Other fertiliser application rates for phosphate of 50 kg P_2O_5/ ha.a and for potash of 48 kg K_2O/ha.a (Ref. D5), and for lime of 18.9 kg CaO (Ref. D4), with total nitrous oxide requirements for phosphate fertiliser of 4.2 x 10^{-5} kg N_2O/kg P_2O_5 , for potash fertiliser of 9.4 x 10^{-6} kg N_2O/ kg K_2O, and for lime of 1.6 x 10^{-5} kg N_2O/kg CaO (Ref. D4).

(c) Application rate for a mixture of pesticides, herbicides and fungicides of 2.8 kg/ha.a (Ref. D6) and a total nitrous oxide requirement for general pesticides, herbicides and fungicides of 1.51 x 10^{-3} kg N_2O/kg (Ref. D4).

(d) Sowing rate of 5 kg/ha.a (Ref. D7) and a total nitrous oxide requirement of 0.001 kg N_2O/kg of seed (Ref. D4).

(e) Diesel fuel consumption of 2,385 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides and fungicides, and harvesting (Ref. D4), and a direct nitrous oxide requirement of 5.64 x 10^{-7} kg N_2O/MJ, an indirect nitrous oxide requirement of 2.60 x 10^{-8} kg N_2/MJ and a total nitrous oxide requirement of 5.90 x 10^{-7} kg N_2O/MJ for diesel fuel in the UK in 1996 (Ref. D8).

(f) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. D4), and a direct nitrous oxide requirement of 5.64 x 10^{-7} kg N_2O/MJ, an indirect nitrous oxide requirement of 2.60 x 10^{-8} kg N_2/MJ and a total nitrous oxide requirement of 5.90 x 10^{-7} kg N_2O/MJ for diesel fuel in the UK in 1996 (Ref. D8).

(g) Land requirement of 0.924 ha.a/t of biodiesel and allocation of 86% x 72% x 87% = 53.87% to biodiesel.

(h) Average round trip distance of 260 km (Ref. D9) by bulk road carrier transport with a direct nitrous oxide requirement of 4.6 x 10^{-7} ± 1.7 x 10^{-8} kg N_2O/t-km, an indirect nitrous oxide requirement of 2.1 x 10^{-8} ± 8 x 10^{-10} kg N_2O/t-km and a total nitrous oxide requirement of 4.8 x 10^{-7} ± 1.8 x 10^{-8} kg N_2O/t-km (Ref. D10).

(i) Raw oilseed requirement of 2.839 t/t of biodiesel and allocation of 72% x 87% = 62.64% to biodiesel.

(j) Fuel oil consumption of 305 MJ/t of dried oilseed for drying (Ref. D4), and a direct nitrous oxide requirement of 5.74 x 10^{-7} kg N_2O/MJ, an indirect nitrous oxide requirement of 2.6 x 10^{-8} kg N_2O/MJ and a total nitrous oxide requirement of 6 x 10^{-7} kg N_2O/MJ for fuel oil in the UK in 1996 (Ref. D8).

(k) Dried oilseed requirement of 2.664t/t of biodiesel and allocation of 72% x 87% = 62.64% to biodiesel.

(l) Electricity consumption of 11.6 kWh/t of dried oilseed for cooling (Ref. D4), and an indirect nitrous oxide requirement of 5.577 x 10^{-6} kg N_2O/MJ for electricity in the UK in 1996 (Ref. D8).

(m) Steam consumption of 716 kg/t of crude rapeseed oil (Ref. D4), with assumed boiler efficiency of 80% giving natural gas consumption of 2.5 MJ/kg steam, and a direct nitrous requirement of 8.9 x 10^{-8} kg N_2O/MJ, an indirect nitrous oxide requirement of 1.1 x 10^{-8} kg N_2O/MJ and a total nitrous oxide requirement of 1.0 x 10^{-7} kg N_2O/MJ for natural gas in the UK in 1996 (Ref. D8).

(n) Electricity consumption of 84 kWh/t of crude rapeseed oil (Ref. D4) and an indirect nitrous oxide requirement of 5.577 x 10^{-6} kg N_2O/MJ for electricity in the UK in 1996 (Ref. D8).

(o) Hexane consumption of 2.5 kg/t of crude rapeseed oil and a total nitrous oxide requirement of 1.35 x 10^{-5} kg N_2O/kg of hexane (Ref. D4).

(p) Crude rapeseed oil requirement of 1.079 t/t of biodiesel and allocation of 72% x 87% = 62.64% to biodiesel.

(q) Electricity consumption of 3.1 kWh/t refined rapeseed oil (Ref. D4) and an indirect nitrous oxide requirement of 5.577 x 10^{-6} kg N_2O/MJ for electricity in the UK in 1996 (Ref. D8).

(r) Natural gas consumption of 178 MJ/t of refined rapeseed oil (Ref. D4) and a direct nitrous requirement of 8.9 x 10^{-8} kg N_2O/MJ, an indirect nitrous oxide requirement of 1.1 x 10^{-8} kg N_2O/MJ and a total nitrous oxide requirement of 1.0 x 10^{-7} kg N_2O/MJ for natural gas in the UK in 1996 (Ref. D8).

(s) Heavy fuel oil consumption of 20 MJ/t of refined rapeseed oil (Ref. D4) and a direct nitrous oxide requirement of 5.74 x 10^{-7} kg N_2O/MJ, an indirect nitrous oxide requirement of 2.6 x 10^{-8} kg N_2O/MJ and a total nitrous oxide requirement of 6 x 10^{-7} kg N_2O/MJ for heavy fuel oil in the UK in 1996 (Ref. D8).

(t) Light fuel oil consumption of 152 MJ/t of refined rapeseed oil (Ref. D4) and a direct nitrous oxide requirement of 5.74 x 10^{-7} kg N_2O/MJ, an indirect nitrous oxide requirement of 2.6 x 10^{-8} kg N_2O/MJ and a total nitrous oxide requirement of 6 x 10^{-7} kg N_2O/MJ for light fuel oil in the UK in 1996 (Ref. D8).

(u) Phosphoric acid consumption of 1 kg/t of refined rapeseed oil and a total nitrous oxide requirement of 2 x 10^{-5} kg N_2O /kg for phosphoric acid (Ref. D4).

(v) Smectite consumption of 6 kg/t of refined rapeseed oil and a total carbon requirement of 6.5 x 10^{-6} kg N_2O /kg for smectite (Ref. D4).

(w) Refined rapeseed oil requirement of 1.052 t/t of biodiesel and allocation of 87% to biodiesel.

(x) Electricity consumption of 23 kWh/t of biodiesel (Ref. D4) and an indirect nitrous oxide requirement of 5.577 x 10^{-6} kg N_2O/MJ for electricity in the UK in 1996 (Ref. D8).

(y) Natural gas consumption of 1,402 MJ/t of biodiesel (Ref. D4) and a direct nitrous requirement of 8.9 x 10^{-8} kg N_2O/MJ, an indirect nitrous oxide requirement of 1.1 x 10^{-8} kg N_2O/MJ and a total nitrous oxide requirement of 1.0 x 10^{-7} kg N_2O/MJ for natural gas in the UK in 1996 (Ref. D8).

(z) Heavy fuel oil consumption of 161 MJ/t of biodiesel (Ref. D4) and a direct nitrous oxide requirement of 5.74 x 10^{-7} kg N_2O/MJ, an indirect nitrous oxide requirement of 2.6 x 10^{-8} kg N_2O/MJ and a total nitrous oxide requirement of 6 x 10^{-7} kg N_2O/MJ for heavy fuel oil in the UK in 1996 (Ref. D8).

(aa) Light fuel oil consumption of 161 MJ/t of biodiesel (Ref. D4) and a direct nitrous oxide requirement of 5.74 x 10^{-7} kg N_2O/MJ, an indirect nitrous oxide requirement of 2.6 x 10^{-8} kg N_2O/MJ and a total nitrous oxide requirement of 6 x 10^{-7} kg N_2O/MJ for light fuel oil in the UK in 1996 (Ref. D8).

(bb) Caustic soda (50% concentration) consumption of 12 kg/t of biodiesel and a total nitrous oxide requirement of 0 kg N_2O/kg of caustic soda (Ref. D4).

(cc) Methanol consumption of 109 kg/t of biodiesel and a total methane requirement of 1.5 x 10^{-5} kg N_2O/kg of methanol (Ref. D4).

(dd) Allocation of 87% to biodiesel.

(ee) Primary energy input of 131,004 ± 23,909 GJ for construction of a biodiesel plant (Ref. D10) with a capacity of a 40,000 t/a and a 25 year life, and an estimated total nitrous oxide requirement of 1.866 x 10^{-9} kg N_2O/MJ primary energy input to construction (Ref. D11), assuming oil mill (assumed similar to solvent extraction plant) accounting for 72% of the primary energy input by weight and 72% contribution to biodiesel by price of co-products, and assuming refining and esterification plants accounting for 28% of the primary energy input by weight and 87% contribution to biodiesel by price of co-products.

(ff) Nitrous oxide output of annual plant maintenance assumed to be 2.5% of methane output from plant construction (Ref. D10).

(gg) Average round trip distance of 450 km (Ref. D9) by bulk road carrier transport with a direct nitrous oxide requirement of 4.6 x 10^{-7} ± 1.7 x 10^{-8} kg N_2O/t-km, an indirect nitrous oxide requirement of 2.1 x 10^{-8} ± 8 x 10^{-10} kg N_2O/t-km and a total nitrous oxide requirement of 4.8 x 10^{-7} ± 1.8 x 10^{-8} kg N_2O/t-km (Ref. D10).

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Table D5 Greenhouse Gas Requirement for Conventional Production of Biodiesel from Oilseed Rape by Solvent Extraction

Functional Unit: :	Biodiesel at point of distribution derived from oilseed rape using solvent extraction
Final Unit of Measurement:	1 tonne of biodiesel
Relevant Location:	United Kingdom
Relevant Period:	1996
Allocation Procedures:	Based on average market prices, assuming 2.782 tonnes of rape straw at £25/t (UK 1992; Ref. D1) and 2.839 tonnes of raw oilseed at £152/t (UK 1997 - 2000 average; Ref. D2), giving a 86% allocation to biodiesel, 1.575 tonnes of rape meal at £84/t (UK 1997 - 2000 average; Ref. D2) and 1.079 tonnes of crude rapeseed oil at £323 per tonne (UK 1997 - 2000 average; Ref. 2), giving a 72% allocation to biodiesel, and 0.100 tonnes of glycerine at £388/t (UK 1997 - 2000 average; Ref. D2) and 1.000 tonnes of biodiesel at £268/t (UK 1997 - 2000 average; Ref. D2), giving a 87% allocation to biodiesel.

Contribution	Per Unit	Greenhouse Gas Output (kg eq CO_2)						
		Direct		Indirect		Total		Notes
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	t bd	112	±17	654	±74	766	±76	(a)
- Other Fertiliser	t bd	-	-	30	±4	30	±4	(a)
- Pesticides	t bd	-	-	7	±1	7	±1	(a)
- Seeds	t bd	-	-	2	-	2	-	(a)
- Diesel Fuel	t bd	82	±12	10	±1	92	±12	(a)
Reference System:								
- Diesel Fuel	t bd	-32	±4	-3	-	-35	±4	(a)
Sub-Totals	t bd	162	±21	700	±74	862	±77	(b)
Transport:								
- Diesel Fuel	t bd	26	±1	7	±1	33	±1	(a, c)
Drying:								
- Fuel Oil	t bd	37	±6	4	±1	41	±6	(a, d)
Storage:								
- Electricity	t bd	-	-	18	±2	18	±2	(a, d)
Solvent Extraction:								
- Natural Gas	t bd	79	±12	7	±1	86	±12	(a)
- Electricity	t bd	-	-	33	±5	33	±5	(a)
- Hexane	t bd	-	-	1	-	1	-	(a)
Sub-Totals	t bd	79	±12	41	±5	120	±13	(e)
Refining:								
- Electricity	t bd	-	-	2	-	2	-	(a)
- Natural Gas	t bd	8	±1	1	-	9	±1	(a)
- Heavy Fuel Oil	t bd	2	-	-	-	2	-	(a)
- Light Fuel Oil	t bd	10	±2	2	-	12	±2	(a)
- Phosph. Acid	t bd	-	-	1	-	1	-	(a)
- Smectite	t bd	-	-	1	-	1	-	(a)
Sub-Totals	t bd	20	±2	7	-	27	±2	(f)
Esterification:								
- Electricity	t bd	-	-	11	±2	11	±2	(a)
- Natural Gas	t bd	64	±10	5	±1	69	±10	(a)
- Heavy Fuel Oil	t bd	10	±2	1	-	11	±2	(a)
- Light Fuel Oil	t bd	10	±2	1	-	11	±2	(a)
- Caustic Soda	t bd	-	-	12	±2	12	±2	(a)
- Methanol	t bd	-	-	262	±39	262	±39	(a)
Sub-Totals	t bd	84	±10	292	±39	376	±40	(g)
Plant Construction	t bd	-	-	5	±1	5	±1	(a)
Plant Maintenance	t bd	-	-	2	-	2	-	(a)
Distribution:								
- Diesel Fuel	t bd	25	±1	7	±1	32	±1	(a)
Totals	**t bd**	**433**	**±27**	**1,083**	**±84**	**1,516**	**±88**	

Abbreviations

ha.a = hectare year
t bd = tonne of biodiesel

Notes

(a) Summation of results from previous spreadsheets with conversion using a global warming potential for methane of 24.5 kg eq CO_2/kg CH_4 and a global warming potential for nitrous oxide of 320 kg eq CO_2/kg N_2O.

(b) Land requirement of 0.924 ha.a/t of biodiesel and allocation of 86% x 72% x 87% = 53.87% to biodiesel.

(c) Dried oilseed requirement of 2.664t/t of biodiesel and allocation of 72% x 87% = 62.64% to biodiesel.

(d) Raw oilseed requirement of 2.839 t/t of biodiesel and allocation of 72% x 87% = 62.64% to biodiesel.

(e) Crude rapeseed oil requirement of 1.079 t/t of biodiesel and allocation of 72% x 87% = 62.64% to biodiesel.

(f) Refined rapeseed oil requirement of 1.052 t/t of biodiesel and allocation of 87% to biodiesel.

(g) Allocation of 87% to biodiesel.

References

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APPENDIX E: Modified Production of Biodiesel from Oilseed Rape

Table E1. Energy Requirement for Modified Production of Biodiesel from Oilseed Rape with Low-Nitrogen Cultivation, Straw Replacing Heating Fuel and Biodiesel Replacing Diesel Fuel

Functional Unit:	Biodiesel at point of distribution derived from oilseed rape using solvent extraction
Final Unit of Measurement:	1 tonne of biodiesel
Relevant Location:	United Kingdom
Relevant Period:	1996
Allocation Procedures:	Based on average market prices, assuming 4.054 tonnes of surplus rape straw sold at £25/t (UK 1992; Ref. D1) and 3.005 tonnes of raw oilseed at £152/t (UK 1997 - 2000 average; Ref. D2), giving a 82% allocation to biodiesel, 1.666 tonnes of rape meal at £84/t (UK 1997 - 2000 average; Ref. D2) and 1.142 tonnes of crude rapeseed oil at £323 per tonne (UK 1997 - 2000 average; Ref. D2), giving a 72% allocation to biodiesel, and 0.106 tonnes of glycerine at £388/t (UK 1997 - 2000 average; Ref. D2) and 1.058 tonnes of biodiesel at £268/t (UK 1997 - 2000 average; Ref. D2), giving a 87% allocation to biodiesel.

Contribution	Per Unit	Primary Energy Input (MJ)								
		Direct		Indirect		Feedstock		Total		Notes
		Value	Range	Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:										
- N Fertiliser	t bd	-	-	600	±240	1,139	±45	1,739	±244	(a)
- Other Fertiliser	t bd	-	-	385	±58	-	-	385	±58	(b)
- Pesticides	t bd	-	-	377	±57	-	-	377	±57	(c)
- Seeds	t bd	-	-	21	±3	-	-	21	±3	(d)
Reference System:	t bd									
- Diesel Fuel	t bd	- 487	±73	- 53	±35	-	-	-540	±81	(e)
Sub-Totals	t bd	- 487	±73	1,330	±256	1,139	±45	1,982	±270	(f)
Transport:										
- Indirect	t bd	-	-	140	±17	-	-	140	±17	(g, h)
Storage:										
- Electricity	t bd	74	±11	153	±15	-	-	227	±19	(i, j)
Solvent Extraction:										
- Electricity	t bd	216	±32	451	±46	-	-	667	±56	(k)
- Hexane	t bd	-	-	93	±14	-	-	93	±14	(l)
Sub-Totals	t bd	216	±32	544	±48	-	-	760	±58	(m)
Refining:										
- Electricity	t bd	11	±2	22	±5	-	-	33	±5	(n)
- Phosph. Acid	t bd	-	-	11	±2	-	-	11	±2	(o)
- Smectite	t bd	-	-	15	±2	-	-	15	±2	(p)
Sub-Totals	t bd	11	±2	48	±6	-	-	59	±6	(q)
Esterification:										
- Electricity	t bd	76	±11	158	±17	-	-	234	±20	(r)
- Caustic Soda	t bd	-	-	219	±33	-	-	219	±33	(s)
- Methanol	t bd	-	-	3,821	±573	-	-	3,821	±573	(t)
Sub-Totals	t bd	76	±11	4,198	±574	-	-	4,274	±574	(u)
Plant Construct.	t bd	3	-	103	±19	-	-	106	±19	(v)
Plant Maintain.	t bd	-	-	66	±12	-	-	66	±12	(w)
Distribution:										
- Indirect	t bd			136	±17	-	-	136	±17	(x)
Totals	**t bd**	**- 107**	**±81**	**6,718**	**±631**	**1,139**	**±45**	**7,750**	**±638**	

Abbreviations

ha.a = hectare year
t bd = tonne of biodiesel

Notes

(a) Ammonium nitrate fertiliser application rate of 81 kg/ha.a based on low-nitrogen cultivation (Ref. D3) and a direct and indirect energy requirement of 14.013 ± 5.599 MJ/kg N and a feedstock energy requirement of 26.595 ± 1.060 MJ/kg N for ammonium nitrate (Appendix C).

(b) Other fertiliser application rates for phosphate of 28.5 kg P_2O_5/ ha.a and for potash of 27.4 kg K_2O/ha.a, and for lime of 10.8 kg CaO based on low-nitrogen cultivation (Ref. D3), with total energy requirements for phosphate fertiliser of 15.8 MJ/kg P_2O_5 , for potash fertiliser of 9.3 MJ/ kg K_2O, and for lime of 2.1 MJ/kg CaO (Ref. D4).

(c) Application rate for a mixture of pesticides, herbicides and fungicides of 2.6 kg/ha.a (Ref. D3) and a total energy requirement for general pesticides, herbicides and fungicides of 274.1 MJ/kg (Ref. D4).

(d) Sowing rate of 5 kg/ha.a (Ref. D5) and a total energy requirement of 7.8 MJ/kg of seed (Ref. D4).

(e) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. D4) and a gross energy requirement of 1.110 MJ/MJ for diesel fuel in the UK in 1996 (Ref. D6).

(f) Land requirement of 1.029 ha.a/t of biodiesel and allocation of 82% x 72% x 87% = 51.36% to biodiesel.

(g) Average round trip distance of 260 km (Ref. D7) by biodiesel-fuelled bulk road carrier transport with an indirect energy requirement of 0.2857 ± 0.0352 MJ/t-km (Ref. D8).

(h) Raw oilseed requirement of 3.005 t/t of biodiesel and allocation of 72% x 87% = 62.64% to biodiesel.

(i) Electricity consumption of 11.6 kWh/t of dried oilseed for cooling (Ref. D4) and a gross energy requirement of 3.083 MJ/MJ for electricity in the UK in 1996 (Ref. D6).

(j) Dried oilseed requirement of 2.820 t/t of biodiesel and allocation of 72% x 87% = 62.64% to biodiesel.

(k) Electricity consumption of 84 kWh/t of crude rapeseed oil (Ref. D4) and a gross energy requirement of 3.083 MJ/MJ for electricity in the UK in 1996 (Ref. D6).

(l) Hexane consumption of 2.5 kg/t of crude rapeseed oil and a total energy requirement of 52.05 MJ/kg of hexane (Ref. D4).

(m) Crude rapeseed oil requirement of 1.142 t/t of biodiesel and allocation of 72% x 87% = 62.64% to biodiesel.

(n) Electricity consumption of 3.1 kWh/t refined rapeseed oil (Ref. D4) and a gross energy requirement of 3.083 MJ/MJ for electricity in the UK in 1996 (Ref. D6).

(o) Phosphoric acid consumption of 1 kg/t of refined rapeseed oil and a total energy requirement of 11.4 MJ/kg for phosphoric acid (Ref. D4).

(p) Smectite consumption of 6 kg/t of refined rapeseed oil and a total energy requirement of 2.55 MJ/kg for smectite (Ref. D4).

(q) Refined rapeseed oil requirement of 1.114 t/t of biodiesel and allocation of 87% to biodiesel.

(r) Electricity consumption of 23 kWh/t of biodiesel (Ref. D4) and a gross energy requirement of 3.083 MJ/MJ for electricity in the UK in 1996 (Ref. D6).

(s) Caustic soda (50% concentration) consumption of 12 kg/t of biodiesel and a total energy requirement of 19.87 MJ/kg of caustic soda (Ref. D4).

(t) Methanol consumption of 109 kg/t of biodiesel and a total energy requirement of 38.08 MJ/kg of methanol (Ref. D4).

(u) Total output of 1.058 t of biodiesel and allocation of 87% to biodiesel.

(v) Primary energy input of 131,004 ± 23,909 GJ for construction of a biodiesel plant (Ref. D8) with a capacity of a 40,000 t/a and a 25 year life, assuming oil mill (assumed similar to solvent extraction plant) accounting for 72% of the primary energy input by weight and 72% contribution to biodiesel by price of co-products, and assuming refining and esterification plants accounting for 28% of the primary energy input by weight and 87% contribution to biodiesel by price of co-products.

(w) Primary energy input of annual plant maintenance assumed to be 2.5% of primary energy input to plant construction (Ref. D8).

(x) Average round trip distance of 450 km (Ref. D7) by biodiesel-fuelled bulk road carrier transport with an indirect energy requirement of 0.2857 ± 0.0352 MJ/t-km (Ref. D8).

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Table E2. Carbon Requirement for Modified Production of Biodiesel from Oilseed Rape with Low-Nitrogen Cultivation, Straw Replacing Heating Fuel and Biodiesel Replacing Diesel Fuel

Functional Unit: :	Biodiesel at point of distribution derived from oilseed rape using solvent extraction
Final Unit of Measurement:	1 tonne of biodiesel
Relevant Location:	United Kingdom
Relevant Period:	1996
Allocation Procedures:	Based on average market prices, assuming 4.054 tonnes of surplus rape straw sold at £25/t (UK 1992; Ref. D1) and 3.005 tonnes of raw oilseed at £152/t (UK 1997 - 2000 average; Ref. D2), giving a 82% allocation to biodiesel, 1.666 tonnes of rape meal at £84/t (UK 1997 - 2000 average; Ref. D2) and 1.142 tonnes of crude rapeseed oil at £323 per tonne (UK 1997 - 2000 average; Ref. D2), giving a 72% allocation to biodiesel, and 0.106 tonnes of glycerine at £388/t (UK 1997 - 2000 average; Ref. D2) and 1.058 tonnes of biodiesel at £268/t (UK 1997 - 2000 average; Ref. D2), giving a 87% allocation to biodiesel.

Contribution	Per Unit	Carbon Dioxide Output (kg CO_2)						
		Direct		Indirect		Total		Notes
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	t bd	-	-	82	±12	82	±12	(a)
- Other Fertiliser	t bd	-	-	18	±3	18	±3	(b)
- Pesticides	t bd	-	-	6	±1	6	±1	(c)
- Seeds	t bd	-	-	-	-	-	-	(d)
Reference System:								
- Diesel Fuel	t bd	- 33	±5	- 4	-	- 37	±5	(e)
Sub-Totals	t bd	- 33	±5	102	±12	69	±13	(f)
Transport:								
- Indirect	t bd	-	-	8	±1	8	±1	(g, h)
Storage:								
- Electricity	t bd	-	-	11	±2	11	±2	(i, j)
Solvent Extraction:								
- Electricity	t bd	-	-	33	±5	33	±5	(k)
- Hexane	t bd	-	-	1	-	1	-	(l)
Sub-Totals	t bd			34	±5	34	±5	(m)
Refining:								
- Electricity	t bd	-	-	2	-	2	-	(n)
- Phosph. Acid	t bd	-	-	1	-	1	-	(o)
- Smectite	t bd	-	-	1	-	1	-	(p)
Sub-Totals	t bd	-	-	4	-	4	-	(q)
Esterification:								
- Electricity	t bd	-	-	11	±2	11	±2	(r)
- Caustic Soda	t bd	-	-	12	±2	12	±2	(s)
- Methanol	t bd	-	-	273	±40	273	±30	(t)
Sub-Totals	t bd	-	-	296	±40	296	±40	(u)
Plant Construction	t bd	-	-	5	±1	5	±1	(v)
Plant Maintenance	t bd	-	-	2	-	2	-	(w)
Distribution:								
- Diesel Fuel	t bd	-	-	8	±1	8	±1	(x)
Totals	**t bd**	**- 33**	**±5**	**470**	**±42**	**437**	**±42**	

Abbreviations

ha.a = hectare year
t bd = tonne of biodiesel

Notes

(a) Ammonium nitrate fertiliser application rate of 81 kg/ha.a based on low-nitrogen cultivation (Ref. D3) and a total carbon requirement for ammonium nitrate of 1.904 ± 0.275 kg CO_2/kg N (Appendix C).

(b) Other fertiliser application rates for phosphate of 28.5 kg P_2O_5/ ha.a and for potash of 27.4 kg K_2O/ha.a, and for lime of 10.8 kg CaO based on low-nitrogen cultivation (Ref. D3), with total carbon requirements for phosphate fertiliser of 0.700 kg CO_2/kg P_2O_5 , for potash fertiliser of 0.453 kg CO_2/ kg K_2O, and for lime of 0.179 kg CO_2/kg CaO (Ref. D4).

(c) Application rate for a mixture of pesticides, herbicides and fungicides of 2.3 kg/ha.a based on low-nitrogen cultivation (Ref. D3) and a total carbon requirement for general pesticides, herbicides and fungicides of 4.921 kg CO_2/kg (Ref. D4).

(d) Sowing rate of 5 kg/ha.a (Ref. D5) and a total carbon requirement of 0.316 kg CO_2/kg of seed (Ref. D4).

(e) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. D4), and a direct carbon requirement of 0.0686 kg CO_2/MJ, an indirect carbon requirement of 0.0081 kg CO_2/MJ and a total carbon requirement of 0.0767 kg CO_2/MJ for diesel fuel in the UK in 1996 (Ref. D6).

(f) Land requirement of 1.029 ha.a/t of biodiesel and allocation of 82% x 72% x 87% = 51.36% to biodiesel.

(g) Average round trip distance of 260 km (Ref. D7) by biodiesel-fuelled bulk road carrier transport with an indirect carbon requirement of 0.0161 ± 0.0017 kg CO_2/t-km (Ref. D6).

(h) Raw oilseed requirement of 3.005 t/t of biodiesel and allocation of 72% x 87% = 62.64% to biodiesel.

(i) Electricity consumption of 11.6 kWh/t of dried oilseed for cooling (Ref. D4), and an indirect carbon requirement of 0.1504 kg CO_2/MJ for electricity in the UK in 1996 (Ref. D6).

(j) Dried oilseed requirement of 2.820 t/t of biodiesel and allocation of 72% x 87% = 62.64% to biodiesel.

(k) Electricity consumption of 84 kWh/t of crude rapeseed oil (Ref. D4) and an indirect carbon requirement of 0.1504 kg CO_2/MJ for electricity in the UK in 1996 (Ref. D6).

(l) Hexane consumption of 2.5 kg/t of crude rapeseed oil and a total carbon requirement of 0.543 kg CO_2/kg of hexane (Ref. D4).

(m) Crude rapeseed oil requirement of 1.142 t/t of biodiesel and allocation of 72% x 87% = 62.64% to biodiesel.

(n) Electricity consumption of 3.1 kWh/t refined rapeseed oil (Ref. D%) and an indirect carbon requirement of 0.1504 kg CO_2/MJ for electricity in the UK in 1996 (Ref. D6).

(o) Phosphoric acid consumption of 1 kg/t of refined rapeseed oil and a total carbon requirement of 0.768 kg CO_2 /kg for phosphoric acid (Ref. D4).

(p) Smectite consumption of 6 kg/t of refined rapeseed oil and a total carbon requirement of 0.197 kg CO_2 /kg for smectite (Ref. D4).

(q) Refined rapeseed oil requirement of 1.114 t/t of biodiesel and allocation of 87% to biodiesel.

(r) Electricity consumption of 23 kWh/t of biodiesel (Ref. D4) and an indirect carbon requirement of 0.1504 kg CO_2/MJ for electricity in the UK in 1996 (Ref. D6).

(s) Caustic soda (50% concentration) consumption of 12 kg/t of biodiesel and a total carbon requirement of 1.120 kg CO_2/kg of caustic soda (Ref. D4).

(t) Methanol consumption of 109 kg/t of biodiesel and a total carbon requirement of 2.722 kg CO_2/kg of methanol (Ref. D4).

(u) Total output of 1.058 t biodiesel and allocation of 87% to biodiesel.

(v) Carbon dioxide output of 6,287 ± 1,116 tonnes CO_2 from construction of a biodiesel plant (Ref. D8) with a capacity of a 40,000 t/a and a 25 year life, assuming oil mill (assumed similar to solvent extraction plant) accounting for 72% of the carbon dioxide output by weight and 72% contribution to biodiesel by price of co-products, and assuming refining and esterification plants accounting for 28% of the carbon dioxide output by weight and 87% contribution to biodiesel by price of co-products.

(w) Carbon dioxide output for annual plant maintenance assumed to be 2.5% of carbon dioxide output from plant construction (Ref. D8).

(x) Average round trip distance of 450 km (Ref. D7) by biodiesel-fuelled bulk road carrier transport with an indirect carbon requirement of 0.0161 ± 0.0017 MJ/t-km (Ref. D8).

<u>References</u>

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D8. "Carbon and Energy Modelling of Biomass Systems: Conversion Plant and Data Updates" by N. D. Mortimer and M. A. Elsayed, ETSU Report B/U1/00644/00/00REP, Energy Technology Support Unit, Harwell, United Kingdom, August 2001.

Table E3. Methane Requirement for Modified Production of Biodiesel from Oilseed Rape with Low-Nitrogen Cultivation, Straw Replacing Heating Fuel and Biodiesel Replacing Diesel Fuel

Functional Unit: :	Biodiesel at point of distribution derived from oilseed rape using solvent extraction
Final Unit of Measurement:	1 tonne of biodiesel
Relevant Location:	United Kingdom
Relevant Period:	1996
Allocation Procedures:	Based on average market prices, assuming 4.054 tonnes of surplus rape straw sold at £25/t (UK 1992; Ref. D1) and 3.005 tonnes of raw oilseed at £152/t (UK 1997 - 2000 average; Ref. D2), giving a 82% allocation to biodiesel, 1.666 tonnes of rape meal at £84/t (UK 1997 - 2000 average; Ref. D2) and 1.142 tonnes of crude rapeseed oil at £323 per tonne (UK 1997 - 2000 average; Ref. D2), giving a 72% allocation to biodiesel, and 0.106 tonnes of glycerine at £388/t (UK 1997 - 2000 average; Ref. D2) and 1.058 tonnes of biodiesel at £268/t (UK 1997 - 2000 average; Ref. D2), giving a 87% allocation to biodiesel.

Contribution	Per Unit	Methane Output (kg CH_4)						Notes
		Direct		Indirect		Total		
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	t bd	-	-	0.154	±0.026	0.154	±0.026	(a)
- Other Fertiliser	t bd	-	-	0.001	-	0.001	-	(b)
- Pesticides	t bd	-	-	-	-	-	-	(c)
- Seeds	t bd	-	-	-	-	-	-	(d)
Reference System:			-					
- Diesel Fuel	t bd	-		-0.010	±0.001	-0.010	±0.001	(e)
			-					
Sub-Totals	t bd	-	-	0.145	±0.026	0.145	±0.026	(f)
Transport:								
- Indirect	t bd	-	-	0.008	±0.001	0.008	±0.001	(g, h)
Storage:								
- Electricity	t bd	-	-	0.030	±0.004	0.030	±0.004	(i, j)
Solvent Extraction:								
- Electricity	t bd	-	-	0.087	±0.013	0.087	±0.013	(k)
- Hexane	t bd	-	-	0.001	-	0.001	-	(l)
Sub-Totals	t bd	-	-	0.088	±0.013	0.088	±0.013	(m)
Refining:								
- Electricity	t bd	-	-	0.004	±0.001	0.004	±0.001	(n)
- Phosph. Acid	t bd	-	-	0.001	-	0.001	-	(o)
- Smectite	t bd	-	-	-	-	-	-	(p)
Sub-Totals	t bd	-	-	0.005	±0.001	0.005	±0.001	(q)
Esterification:								
- Electricity	t bd	-	-	0.031	±0.005	0.031	±0.005	(r)
- Caustic Soda	t bd	-	-	0.036	±0.005	0.036	±0.005	(s)
- Methanol	t bd	-	-	0.130	±0.020	0.130	±0.020	(t)
Sub-Totals	t bd	-	-	0.197	±0.021	0.197	±0.021	(u)
Plant Construction	t bd	-	-	-	-	-	-	(v)
Plant Maintenance	t bd	-	-	-	-	-	-	(w)
Distribution:								
- Diesel Fuel	t bd	-	-	0.008	-	0.008	-	(x)
Totals	**t bd**	**-**	**-**	**0.481**	**±0.036**	**0.481**	**±0.036**	

Abbreviations

ha.a = hectare year
t bd = tonne of biodiesel

Notes

(a) Ammonium nitrate fertiliser application rate of 81 kg/ha.a based on low-nitrogen cultivation (Ref. D3) and a total methane requirement for ammonium nitrate of $3.6 \times 10^{-3} \pm 0.6 \times 10^{-3}$ kg CH_4/kg N (Appendix C).

(b) Other fertiliser application rates for phosphate of 28.5 kg P_2O_5/ ha.a and for potash of 27.4 kg K_2O/ha.a, and for lime of 10.8 kg CaO based on low-nitrogen cultivation (Ref. D3), with total carbon requirements for phosphate fertiliser of 2.3×10^{-5} kg CH_4/kg P_2O_5 , for potash fertiliser of 2.1×10^{-5} kg CH_4/ kg K_2O, and for lime of 3.9×10^{-6} kg CH_4/kg CaO (Ref. D4).

(c) Application rate for a mixture of pesticides, herbicides and fungicides of 2.6 kg/ha.a based on low-nitrogen cultivation (Ref. D3) and a total methane requirement for general pesticides, herbicides and fungicides of 1.8×10^{-4} kg CH_4/kg (Ref. D4).

(d) Sowing rate of 5 kg/ha.a (Ref. D5) and a total methane requirement of 0 kg CH_4/kg of seed (Ref. D4).

(e) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. D5), and a direct methane requirement of 6.0×10^{-7} kg CH_4/MJ, an indirect methane requirement of 2.04×10^{-5} kg CH_4/MJ and a total methane requirement of 2.1×10^{-5} kg CH_4/MJ for diesel fuel in the UK in 1996 (Ref. D8).

(f) Land requirement of 1.029 ha.a/t of biodiesel and allocation of 82% x 72% x 87% = 51.36% to biodiesel.

(g) Average round trip distance of 260 km (Ref. D7) by biodiesel-fuelled bulk road carrier transport with an indirect methane requirement of $1.672 \times 10^{-5} \pm 6.3 \times 10^{-7}$ kg CH_4/t-km (Ref. D8).

(h) Raw oilseed requirement of 3.005 t/t of biodiesel and allocation of 72% x 87% = 62.64% to biodiesel.

(i) Electricity consumption of 11.6 kWh/t of dried oilseed for cooling (Ref. D4), and an indirect methane requirement of 4.043×10^{-4} kg CH_4/MJ for electricity in the UK in 1996 (Ref. D6).

(j) Dried oilseed requirement of 2.820 t/t of biodiesel and allocation of 72% x 87% = 62.64% to biodiesel.

(k) Electricity consumption of 84 kWh/t of crude rapeseed oil (Ref. D4) and an indirect methane requirement of 4.043 x 10^{-4} kg CH_4/MJ for electricity in the UK in 1996 (Ref. D6).

(l) Hexane consumption of 2.5 kg/t of crude rapeseed oil and a total carbon requirement of 6.73×10^{-4} kg CH_4/kg of hexane (Ref. D4).

(m) Crude rapeseed oil requirement of 1.142 t/t of biodiesel and allocation of 72% x 87% = 62.64% to biodiesel.

(n) Electricity consumption of 3.1 kWh/t refined rapeseed oil (Ref. D4) and an indirect methane requirement of 4.043 x 10^{-4} kg CH_4/MJ for electricity in the UK in 1996 (Ref. D6).

(o) Phosphoric acid consumption of 1 kg/t of refined rapeseed oil and a total methane requirement of 1.23×10^{-3} kg CH_4 /kg for phosphoric acid (Ref. D4).

(p) Smectite consumption of 6 kg/t of refined rapeseed oil and a total methane requirement of 3.7×10^{-5} kg CH_4 /kg for smectite (Ref. D4).

(q) Refined rapeseed oil requirement of 1.114 t/t of biodiesel and allocation of 87% to biodiesel.

(r) Electricity consumption of 23 kWh/t of biodiesel (Ref. D4) and an indirect methane requirement of 4.043×10^{-4} kg CH_4/MJ for electricity in the UK in 1996 (Ref. D6).

(s) Caustic soda (50% concentration) consumption of 12 kg/t of biodiesel and a total methane requirement of 3.25 x 10^{-3} kg CH_4/kg of caustic soda (Ref. D4).

(t) Methanol consumption of 109 kg/t of biodiesel and a total methane requirement of 1.3×10^{-3} kg CH_4/kg of methanol (Ref. D4).

(u) Total output of 1.058 t biodiesel and allocation of 87% to biodiesel.

(v) Primary energy input of 131,004 ± 23,909 GJ for construction of a biodiesel plant (Ref. D8) with a capacity of a 40,000 t/a and a 25 year life, and an estimated total methane requirement of 1.192×10^{-7} kg CH_4/MJ primary energy input to construction (Ref. D9), assuming oil mill (assumed similar to solvent extraction plant) accounting for 72% of the primary energy input by weight and 72% contribution to biodiesel by price of co-products, and assuming refining and esterification plants accounting for 28% of the primary energy input by weight and 87% contribution to biodiesel by price of co-products.

(w) Methane output of annual plant maintenance assumed to be 2.5% of methane output from plant construction (Ref. D8).

(x) Average round trip distance of 450 km (Ref. D7) by bulk road carrier transport with an indirect methane requirement of $1.672 \times 10^{-5} \pm 6.3 \times 10^{-7}$ kg CH_4/t-km (Ref. D8).

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Table E4. Nitrous Oxide Requirement for Modified Production of Biodiesel from Oilseed Rape with Low-Nitrogen Cultivation, Straw Replacing Heating Fuel and Biodiesel Replacing Diesel Fuel

Functional Unit: :	Biodiesel at point of distribution derived from oilseed rape using solvent extraction
Final Unit of Measurement:	1 tonne of biodiesel
Relevant Location:	United Kingdom
Relevant Period:	1996
Allocation Procedures:	Based on average market prices, assuming 4.054 tonnes of surplus rape straw sold at £25/t (UK 1992; Ref. D1) and 3.005 tonnes of raw oilseed at £152/t (UK 1997 - 2000 average; Ref. D2), giving a 82% allocation to biodiesel, 1.666 tonnes of rape meal at £84/t (UK 1997 - 2000 average; Ref. D2) and 1.142 tonnes of crude rapeseed oil at £323 per tonne (UK 1997 - 2000 average; Ref. D2), giving a 72% allocation to biodiesel, and 0.106 tonnes of glycerine at £388/t (UK 1997 - 2000 average; Ref. D2) and 1.058 tonnes of biodiesel at £268/t (UK 1997 - 2000 average; Ref. D2), giving a 87% allocation to biodiesel.

Contribution	Per Unit	Nitrous Oxide Output (kg N_2O)						Notes
		Direct		Indirect		Total		
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	t bd	0.154	±0.023	0.629	±0.094	0.783	±0.097	(a)
- Other Fertiliser	t bd	-	-	0.001	-	0.001	-	(b)
- Pesticides	t bd	-	-	0.002	-	0.002	-	(c)
- Seeds	t bd	-	-	0.003	-	0.003	-	(d)
Reference System:								
- Diesel Fuel	t bd	-	-	-	-	-	-	(e)
Sub-Totals	t bd	0.154	±0.023	0.635	±0.094	0.789	±0.097	(f)
Transport:								
- Indirect	t bd	-	-	-	-	-	-	(g, h)
Storage:								
- Electricity	t bd	-	-	-	-	-	-	(i, j)
Solvent Extraction:								
- Electricity	t bd	-	-	0.001	-	0.001	-	(k)
- Hexane	t bd	-	-	-	-	-	-	(l)
Sub-Totals	t bd	-	-	0.001	-	0.001	-	(m)
Refining:								
- Electricity	t bd	-	-	-	-	-	-	(n)
- Phosph. Acid	t bd	-	-	-	-	-	-	(o)
- Smectite	t bd	-	-	-	-	-	-	(p)
Sub-Totals	tbd	-	-	-	-	-	-	(q)
Esterification:								
- Electricity	t bd	-	-	-	-	-	-	(r)
- Caustic Soda	t bd	-	-	-	-	-	-	(s)
- Methanol	t bd	-	-	0.002	-	0.002	-	(t)
Sub-Totals	t bd	-	-	0.002	-	0.002	-	(u)
Plant Construction	t bd	-	-	-	-	-	-	(v)
Plant Maintenance	t bd	-	-	-	-	-	-	(w)
Distribution:								
- Diesel Fuel	t bd	-	-	-	-	-	-	(x)
Totals	**t bd**	**0.154**	**±0.023**	**0.638**	**±0.094**	**0.792**	**±0.097**	

Abbreviations

ha.a = hectare year
t bd = tonne of biodiesel

Notes

(a) Ammonium nitrate fertiliser application rate of 81 kg/ha.a based on low-nitrogen cultivation (Ref. D3) and a direct nitrous oxide requirement of 0.0036 kg N_2O/kg N (Appendix C), an indirect nitrous oxide requirement of 0.0147 kg N_2O/kg N (Ref. D4) and a total nitrous oxide requirement for ammonium nitrate of 0.0183 kg N_2O/kg N (Appendix C).

(b) Other fertiliser application rates for phosphate of 28.5 kg P_2O_5/ ha.a and for potash of 27.4 kg K_2O/ha.a, and for lime of 10.8 kg CaO based on low-nitrogen cultivation (Ref. D3), with total nitrous oxide requirements for phosphate fertiliser of 4.2 x 10^{-5} kg N_2O/kg P_2O_5 , for potash fertiliser of 9.4 x 10^{-6} kg N_2O/ kg K_2O, and for lime of 1.6 x 10^{-5} kg N_2O/kg CaO (Ref. D4).

(c) Application rate for a mixture of pesticides, herbicides and fungicides of 2.6 kg/ha.a based on low-nitrogen cultivation (Ref. D3) and a total nitrous oxide requirement for general pesticides, herbicides and fungicides of 1.51 x 10^{-3} kg N_2O/kg (Ref. D4).

(d) Sowing rate of 5 kg/ha.a (Ref. D5) and a total nitrous oxide requirement of 0.001 kg N_2O/kg of seed (Ref. D4).

(e) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. D4), and a direct nitrous oxide requirement of 5.64 x 10^{-7} kg N_2O/MJ, an indirect nitrous oxide requirement of 2.60 x 10^{-8} kg N_2/MJ and a total nitrous oxide requirement of 5.90 x 10^{-7} kg N_2O/MJ for diesel fuel in the UK in 1996 (Ref. D7).

(f) Land requirement of 1.029 ha.a/t of biodiesel and allocation of 82% x 72% x 87% = 51.36% to biodiesel.

(g) Average round trip distance of 260 km (Ref. D8) by biodiesel-fuelled bulk road carrier transport with an indirect nitrous oxide requirement of 2.1 x 10^{-8} ± 8 x 10^{-10} kg N_2O/t-km (Ref. D9).

(h) Raw oilseed requirement of 3.005 t/t of biodiesel and allocation of 72% x 87% = 62.64% to biodiesel.

(i) Electricity consumption of 11.6 kWh/t of dried oilseed for cooling (Ref. D4), and an indirect nitrous oxide requirement of 5.577 x 10^{-6} kg N_2O/MJ for electricity in the UK in 1996 (Ref. D7).

(j) Dried oilseed requirement of 2.820 t/t of biodiesel and allocation of 72% x 87% = 62.64% to biodiesel.

(k) Electricity consumption of 84 kWh/t of crude rapeseed oil (Ref. D4) and an indirect nitrous oxide requirement of 5.577 x 10^{-6} kg N_2O/MJ for electricity in the UK in 1996 (Ref. D7).

(l) Hexane consumption of 2.5 kg/t of crude rapeseed oil and a total nitrous oxide requirement of 1.35 x 10^{-5} kg N_2O/kg of hexane (Ref. D4).

(m) Crude rapeseed oil requirement of 1.142 t/t of biodiesel and allocation of 72% x 87% = 62.64% to biodiesel.

(n) Electricity consumption of 3.1 kWh/t refined rapeseed oil (Ref. D4) and an indirect nitrous oxide requirement of 5.577 x 10^{-6} kg N_2O/MJ for electricity in the UK in 1996 (Ref. D7).

(o) Phosphoric acid consumption of 1 kg/t of refined rapeseed oil and a total nitrous oxide requirement of 2 x 10^{-5} kg N_2O /kg for phosphoric acid (Ref. D4).

(p) Smectite consumption of 6 kg/t of refined rapeseed oil and a total carbon requirement of 6.5 x 10^{-6} kg N_2O /kg for smectite (Ref. D4).

(q) Refined rapeseed oil requirement of 1.114 t/t of biodiesel and allocation of 87% to biodiesel.

(r) Electricity consumption of 23 kWh/t of biodiesel (Ref. D4) and an indirect nitrous oxide requirement of 5.577 x 10^{-6} kg N_2O/MJ for electricity in the UK in 1996 (Ref. D7).

(s) Caustic soda (50% concentration) consumption of 12 kg/t of biodiesel and a total nitrous oxide requirement of 0 kg N_2O/kg of caustic soda (Ref. D4).

(t) Methanol consumption of 109 kg/t of biodiesel and a total methane requirement of 1.5 x 10^{-5} kg N_2O/kg of methanol (Ref. D4).

(u) Total output of 1.058 t biodiesel and allocation of 87% to biodiesel.

(v) Primary energy input of 131,004 ± 23,909 GJ for construction of a biodiesel plant (Ref. D9) with a capacity of a 40,000 t/a and a 25 year life, and an estimated total nitrous oxide requirement of 1.866 x 10^{-9} kg N_2O/MJ primary energy input to construction (Ref. D10), assuming oil mill (assumed similar to solvent extraction plant) accounting for 72% of the primary energy input by weight and 72% contribution to biodiesel by price of co-products, and assuming refining and esterification plants accounting for 28% of the primary energy input by weight and 87% contribution to biodiesel by price of co-products.

(w) Nitrous oxide output of annual plant maintenance assumed to be 2.5% of methane output from plant construction (Ref. D9).

(x) Average round trip distance of 450 km (Ref. D8) by biodiesel-fuelled bulk road carrier transport with an indirect nitrous oxide requirement of $2.1 \times 10^{-8} \pm 8 \times 10^{-10}$ kg N_2O/t-km (Ref. D9).

References

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Table E5. <u>Greenhouse Gas Requirement for Modified Production of Biodiesel from Oilseed Rape with Low-Nitrogen Cultivation, Straw Replacing Heating Fuel and Biodiesel Replacing Diesel Fuel</u>

Functional Unit: :	Biodiesel at point of distribution derived from oilseed rape using solvent extraction
Final Unit of Measurement:	1 tonne of biodiesel
Relevant Location:	United Kingdom
Relevant Period:	1996
Allocation Procedures:	Based on average market prices, assuming 4.054 tonnes of surplus rape straw sold at £25/t (UK 1992; Ref. D1) and 3.005 tonnes of raw oilseed at £152/t (UK 1997 - 2000 average; Ref. D2), giving a 82% allocation to biodiesel, 1.666 tonnes of rape meal at £84/t (UK 1997 - 2000 average; Ref. D2) and 1.142 tonnes of crude rapeseed oil at £323 per tonne (UK 1997 - 2000 average; Ref. D2), giving a 72% allocation to biodiesel, and 0.106 tonnes of glycerine at £388/t (UK 1997 - 2000 average; Ref. D2) and 1.058 tonnes of biodiesel at £268/t (UK 1997 - 2000 average; Ref. D2), giving a 87% allocation to biodiesel.

Contribution	Per Unit	Greenhouse Gas Output (kg eq CO_2)						Notes
		Direct		Indirect		Total		
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	t bd	49	±7	287	±32	336	±33	(a)
- Other Fertiliser	t bd	-	-	18	±3	18	±3	(a)
- Pesticides	t bd	-	-	7	±1	7	±1	(a)
- Seeds	t bd	-	-	1	-	1	-	(a)
Reference System:								
- Diesel Fuel	t bd	-33	±5	-4	-	-37	±5	(a)
Sub-Totals	t bd	16	±9	309	±32	325	±34	(b)
Transport:								
- Indirect	t bd	-	-	8	±1	8	±1	(a, c)
Storage:								
- Electricity	t bd	-	-	12	±2	12	±2	(a, d)
Solvent Extraction:								
- Electricity	t bd	-	-	35	±5	35	±5	(a)
- Hexane	t bd	-	-	1	-	1	-	(a)
Sub-Totals	t bd	-	-	36	±5	36	±5	(e)
Refining:								
- Electricity	t bd	-	-	2	-	2	-	(a)
- Phosph. Acid	t bd	-	-	1	-	1	-	(a)
- Smectite	t bd	-	-	1	-	1	-	(a)
Sub-Totals	t bd	-	-	4	-	4	-	(f)
Esterification:								
- Electricity	t bd	-	-	12	±2	12	±2	(a)
- Caustic Soda	t bd	-	-	13	±2	13	±2	(a)
- Methanol	t bd	-	-	277	±40	277	±40	(a)
Sub-Totals	t bd	-	-	302	±40	302	±40	(g)
Plant Construction	t bd	-	-	5	±1	5	±1	(a)
Plant Maintenance	t bd	-	-	2	-	2	-	(a)
Distribution:								
- Diesel Fuel	t bd	-	-	8	±1	8	±1	(a)
Totals	**t bd**	**16**	**±9**	**686**	**±52**	**702**	**±53**	

Abbreviations

ha.a = hectare year
t bd = tonne of biodiesel

Notes

(a) Summation of results from previous spreadsheets with conversion using a global warming potential for methane of 24.5 kg eq CO_2/kg CH_4 and a global warming potential for nitrous oxide of 320 kg eq CO_2/kg N_2O.

(b) Land requirement of 1.029 ha.a/t of biodiesel and allocation of 82% x 72% x 87% = 51.36% to biodiesel.

(c) Dried oilseed requirement of 2.820 t/t of biodiesel and allocation of 72% x 87% = 62.64% to biodiesel.

(d) Raw oilseed requirement of 3.005 t/t of biodiesel and allocation of 72% x 87% = 62.64% to biodiesel.

(e) Crude rapeseed oil requirement of 1.142 t/t of biodiesel and allocation of 72% x 87% = 62.64% to biodiesel.

(f) Refined rapeseed oil requirement of 1.114 t/t of biodiesel and allocation of 87% to biodiesel.

(g) Total output of 1.058 t of biodiesel and allocation of 87% to biodiesel.

References

D1. "A Review of the Potential of Biodiesel as a Transport Fuel" by F. Culshaw and C. Butler, ETSU-R-71, Energy Technology Support Unit, Harwell, United Kingdom, September 1992.

D2. "The Cost of Production of Rape Methyl Ester (RME) Biodiesel" by P. Smith, Cargill plc, United Kingdom, January 2001.