Energy and Greenhouse Gas Emissions for Bioethanol Production from Wheat Grain and Sugar Beet

Article · January 2004

3 authors:

Nigel D Mortimer
North Energy Associates Ltd

Malek Elsayed

Ralph E. Horne
RMIT University

RESOURCES RESEARCH UNIT

SCHOOL OF ENVIRONMENT AND DEVELOPMENT

SHEFFIELD HALLAM UNIVERSITY

ENERGY AND GREENHOUSE GAS EMISSIONS FOR BIOETHANOL PRODUCTION FROM WHEAT GRAIN AND SUGAR BEET

by N. D. Mortimer, M. A. Elsayed and R. E. Horne

Final Report

for British Sugar plc

Report No. 23/1

January 2004

EXECUTIVE SUMMARY

1. This Final Report records the findings of a study for British Sugar plc to evaluate the energy and greenhouse gas emissions (carbon dioxide, methane and nitrous oxide) associated with the production of bioethanol from wheat grain and sugar beet under current conditions in the United Kingdom. The background to this study is set in the context of concerns over fuel security and global climate change posed by the demands of a growing road transport sector. The need to reduce the energy resource depletion and greenhouse gas emissions of this important sector is expressed in potential encouragement for fuels derived from biomass as alternatives to conventional fossil fuels.

2. The main aims of the study are established as estimating the amount of energy and greenhouse gas emissions associated with possible means of producing bioethanol from wheat and sugar beet in the United Kingdom using current technology, and to compare subsequent estimates with the amount of energy and greenhouse gas emissions associated with the production and use of unleaded petrol derived from crude oil.

3. Eight different Models of bioethanol production are examined. These include bioethanol production from wheat grain and sugar beet with a natural gas-fired boiler and "imported" grid electricity (Models 1 and 2, respectively); bioethanol production from wheat grain and sugar beet using natural gas-fired combined heat and power plant, with a steam or gas turbine (Models 3, 3a, 4a and 4b, respectively), and bioethanol production from wheat grain and sugar beet incorporating a straw-fired combined heat and power plant with a steam turbine (Models 7 and 8, respectively).

4. The structure of the Final Report is described. The key features of life cycle assessment, as the basis for evaluation, are summarised, essential definitions are introduced and allocation procedures for partitioning primary energy and greenhouse gas emissions between joint products are explained. Baseline results for unleaded petrol produced from crude oil are established. Using an earlier study, baseline flow charts and results for the production of bioethanol from wheat grain and sugar beet are presented.

5. The agreed flow charts and important aspects of the calculation of the primary energy and greenhouse gas emissions associated with the production of bioethanol by the technologies represented by Models 1 to 8 are explained briefly. Detailed results, basic data, essential assumptions and sources of information are provided for Models 1 to 8 in Appendices A to H.

6. Results from this study are compared with baseline results. This comparison shows that estimated primary energy and greenhouse gas emissions for the production of bioethanol from wheat grain and sugar beet using a natural-fired boiler and "imported" grid electricity (Models 1 and 2) are higher that equivalent baseline results. This is due to the use of more detailed, more complete and, probably, more reliable descriptions of the entire process chain, in general, and the bioethanol production plants, in particular.

7. Key conclusions are drawn. In particular, it is determined that significant reductions in primary energy and greenhouse gas emissions can be achieved in comparison with the baseline results by using natural gas-fired combined heat and power plants, with either steam or gas turbines, in the bioethanol plant (Models 3, 3a, 4a and 4b). The greatest reductions in primary energy and

greenhouse gas emissions can be accomplished by utilising a straw-fired combined heat and power plant with a steam turbine in the bioethanol plant (Models 7 and 8). Bioethanol produced from wheat grain and sugar beet in all the Models considered in this study generate net savings in primary energy, and carbon dioxide and total greenhouse gas emissions when replacing unleaded petrol produced from crude oil. Bioethanol produced from wheat grain incorporating a straw-fired combined heat and power plant with a steam turbine (Model 7) more than totally avoids energy resource depletion, is "carbon neutral" in terms of in total carbon dioxide emissions and reaches a very low level of total greenhouse gas emissions. Bioethanol produced from sugar beet incorporating a straw-fired combined heat and power plant with a steam turbine (Model 8) more than totally avoids energy resource depletion and is more than "carbon neutral" in terms of total carbon dioxide emissions and total greenhouse gas emissions.

CONTENTS

Page Number

1. INTRODUCTION

1.1 Background

In the United Kingdom (UK) and rest of the European Union (EU), the road transport sector is a major consumer of depletable energy resources, mainly in the form of fossil fuels, and a significant source of greenhouse gas (GHG) emissions, chiefly as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Combined with expectations of continued growth in this sector, this presents serious problems for energy resource depletion, fuel security, global climate change and sustainable development. It is clear that realistic and effective national policies are needed to address these problems. A range of diverse strategies are now beginning to emerge. Amongst these strategies is potential encouragement for the production of transport fuels for biomass (Ref. 1). In the UK, relevant sources of so-called transport biofuels include wheat grain and sugar beet for the production of bioethanol. It is proposed that the production of bioethanol from such biomass sources would provide a number of important benefits, including energy resource conservation, improved fuel security and GHG savings as well as diversification of the agricultural sector and the food industry. Expected energy resource and GHG benefits are based on the fact that biomass, such as wheat grain and sugar beet, is, potentially, a renewable source of energy and that biofuels derived from biomass can be "carbon neutral". This latter characteristic arises from the observation that the amount of carbon dioxide emitted from a biofuel when it is burnt balances the amount of carbon dioxide absorbed by the crop from which was originally produced. The renewable and carbon neutral features of biofuels imply that significant savings can be achieved when they are used to replace conventional fuels derived from fossil fuels such as crude oil. However, it is possible to over-estimate that actual savings that can be realised unless account is taken of the depletable energy resources and GHG emissions associated with the complete life cycle of a biofuel, including cultivation, harvesting and transportation of the crop, and conversion, processing and delivery of the fuel to consumers. As an established technique, life cycle assessment can be adopted to determine the amount of depletable energy resources and GHG emissions associated with the production of bioethanol in order to obtain estimates of the net savings possible when this biofuel replaces conventional fuels such as petrol.

1.2 Aims and Objectives

The main aims of this study are to estimate the amount of energy and GHG emissions associated with possible means of producing bioethanol from wheat grain and sugar beet in the UK using current technology, and to compare subsequent estimates with the amount of energy and GHG emissions associated with the production and use of unleaded petrol derived from crude oil. This involves the following objectives:

- assess data on a combination of wheat grain or sugar beet and power generation processes to form the best opinion on the energy balance, life cycle CO_2 and other GHG emissions for bioethanol as a road transport fuel,
- consider two data sets consisting of published reports and internal technical and financial information provided by British Sugar plc on a confidential basis, and
- evaluate production options comprised of the 8 different models agreed after consultation during the study.

Table 1 Agreed Models for the Production of Bioethanol from Wheat Grain and Sugar Beet

Production Option	Bioethanol from Wheat Grain	Bioethanol from Sugar Beet
Natural Gas-fired Boiler and Grid Electricity	Model 1	Model 2
Natural Gas-fired Combined Heat and Power using a Steam Turbine	Model 3	Model 4a
Natural Gas-fired Combined Heat and Power using a Gas Turbine	Model 3a	Model 4b
Straw-fired Combined Heat and Power using a Steam Turbine	Model 7	Model 8

1.3 Structure of the Report

This report records the work undertaken in this study of the energy and GHG emissions for bioethanol production from wheat grain and sugar beet. Following this introduction, the methodology adopted in the study is outlined in Section 2. The essential aspects of life cycle assessment as the basis for the study are presented in Section 2.1. Key definitions are given in Section 2.2 and allocation procedures for addressing the issue of joint products and related considerations are explained in Section 2.3. The derivation of results is described in Section 3, which begins by introducing baseline results for unleaded petrol and bioethanol production. The main features of the calculation of results for the production of bioethanol from wheat grain and sugar beet are provided in Sections 3.2 and 3.3, respectively. In particular, each selected Model is addressed for bioethanol production from wheat grain in Sections 3.2.1 to 3.2.4, and for bioethanol production from sugar beet in Sections 3.3.1 to 3.3.4. The results of this study are compared with the baseline results in Section 4. The key conclusions of the study are set out in Section 5. The details of the study for each Model of bioethanol production are contained in Appendices A to H.

2. METHODOLOGY

2.1 Life Cycle Assessment

The main basis for this study is life cycle assessment which is specified by the International Standard ISO 14040 Series (Ref. 2). This is a technique which is used to evaluate the complete environmental impacts of any product or service from "cradle to grave". This involves establishing the life cycle of the product or service, including its provision, use and, where relevant, eventual disposal. Environmental impacts are determined by identifying all the inputs and outputs of the life cycle traced through the process chain which is required to provide the product or service from initial natural resources. Energy and GHG emissions are important inputs and outputs, respectively, for the life cycles of many products and services. The means for estimating these inputs and outputs is a significant stage of life cycle assessment known as inventory analysis. As part of inventory analysis, it is necessary to specify the main process chain for the product or service which can be represented by a flow chart. Based on the flow chart, inputs and outputs can be identified and quantified. Subsequently, a systematic and transparent summary of calculations is used to derive and present results. Based on previous work to evaluate the energy and GHG emission associated with a range of biofuel technologies in the UK (Ref. 3), a standard spreadsheet format is adopted here for the production of bioethanol from wheat grain and sugar beet.

In agreement with the ISO 14040 recommendations for reporting the results life cycle assessment studies, basic specifications are recorded at the beginning of each spreadsheet. The first of these specifications is the functional unit which provides a clear definition of the product or service under consideration. The next basic specification is the unit of measurement which indicates quantity of the end point of the process chain. In this study, the chosen final unit of measurement is 1 tonne of bioethanol. Flow charts and spreadsheet results are normalised in this final unit of measurement. However, it should be noted that comparison between bioethanol and petrol is usually made in terms of the energy available from these fuels. Hence, it is also necessary to quote their relevant gross or net calorific values which equal the total amount of heat released during combustion, including or excluding, respectively, the latent heat of condensable vapours, such as water. The next specifications in the spreadsheet are the relevant location and period to which the calculations refer. This is necessary because results can vary between different countries and over time. The final specification is a summary of the allocation procedures (see Section 2.3) applied to the partitioning of energy and GHG emissions between any joint products generated during the provision of the product or service.

2.2 Definitions

Formal definitions of the key terms used in this study provide the essential basis for appreciating the meaning of subsequent results. Energy inputs are measured in terms of primary energy which is the amount of energy available in resources in their natural state, such as coal, natural gas and oil deposits in the ground. As such, primary energy is an indicator of the availability and depletion of finite energy resources, such as fossil and nuclear fuels. The total amount of primary energy consists of the sum of the direct energy due to the consumption of fuels and electricity in specific stages of the main process chain, the indirect energy associated with the provision of materials, equipment, fuels, electricity, etc., used in these stages, and the energy contained in any feedstocks, such as chemicals, especially nitrogen fertiliser, and materials, such as plastics, derived from fossil fuels. Although the energy within a feedstock is not necessarily released, it amounts to a reduction in fossil fuel resources and, as such, must be included in these calculations.

GHG emissions usually consist of the release of CO_2, CH_4 and N_2O from any activities related to the main process chain. Total GHG emissions equal the sum of the direct GHG emissions from the combustion of fuels and the indirect GHG emissions due to the production of these fuels, the generation of electricity and the manufacture of materials, equipment, etc. In addition to GHG emissions from the direct or indirect combustion of fossil fuels, other sources of GHG outputs, particularly CO_2 emissions, such as the manufacture of cement and nitrogen fertiliser, must be taken into account. 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. This is an important consideration for the production of nitrogen fertiliser from natural gas. Similarly, direct N_2O emissions from the application of nitrogen fertiliser to cultivated land are also taken into account in calculations. However, net changes in the carbon content of soils due to the cultivation of crops such as wheat grain and sugar beet are not included in this study. The effect of reference systems in cultivation is included, however. This introduces primary energy and GHG "credits" for the alternative land use if the crop under investigation were not grown.

Although estimates are presented for individual GHG emissions, they can be combined together by means of conversion using quoted values of the global warming potential of each GHG. Global warming potentials are factors which relate other greenhouse gases to an equivalent amount of CO_2. It should be noted that standard values of global warming potential are given for a range of timescales reflecting the different periods of time which each GHG is active as an agent of global warming in the atmosphere (Ref. 4). In this study, it is assumed that the relevant global warming potential for 1 kg of CH_4 is 24.5 kg eq CO_2 and a global warming potential for 1 kg of N_2O is 320 kg eq CO_2.

Although normalisation of the flow chart and spreadsheet is determined by the chosen final unit of measurement, basic results for each stage of the main process chain are initially specified by an appropriate unit of production (recorded in *italics*). For example, results for contributions to cultivation and harvesting are initially presented "per hectare of land used per year" (ha.a). These are then adjusted, by accounting for production ratios, reflected in the flow charts, and any allocation procedures, to provide results specified by the final unit of measurement (reported in **bold**). Total values of direct, indirect and feedstock inputs and outputs for all contributions at each stage of the biofuel technology are summarised within the spreadsheets. Estimated results are presented as typical values and ranges (in the form of "error bars"; ±). The ranges are based on specified levels of uncertainty for individual inputs or outputs with final results derived using a standard propagation of errors routine (Ref. 5). Abbreviations for the particular units of measurement adopted in separate parts of the spreadsheets are explained. Detailed notes on calculations and data used are provided, and appropriate references are specified. It should be noted that results for primary energy inputs, in MJ, and CO_2 and total GHG emissions, in kg, are quoted in whole numbers, whilst results for CH_4 and N_2O outputs, in kg, are quoted to the third decimal place. Results with lower values than these are not recorded.

2.3 Allocation Procedures

Allocation procedures are essential aspects of life cycle assessment. Such procedures are necessary as a means of partitioning inputs and outputs between any joint products which arise during the provision of a product or service. Joint products consist of co-products, by-products and, occasionally, waste products. A number of different joint products are generated when bioethanol is produced from wheat grain and sugar beet. Allocation procedures are needed to avoid the unrealistic and potentially-misleading consequences of accounting all primary energy and GHG emissions in the process chain to bioethanol, as the main product, alone. In general, there are many different allocation procedures which can be adopted in life cycle assessment. These include allocation by substitution, mass, energy content and price. It is important to realise that no single allocation procedure can be used in all situations. The actual choice of allocation procedure depends on specific circumstances.

However, allocation by substitution is the procedure which is often recommended in life cycle assessment (Ref. 2) and it is frequently the most favoured approach considered by practitioners. It involves applying effective primary energy and GHG emission "credits" for co- and by-products derived from separate analysis of their main means of production. The attraction of this approach is that it demonstrates the consequences of displacing alternative products by the co- and by-products from the main process under consideration. However, a major disadvantage of the approach is that considerable more work may be required in investigating and analysing such alternative process in order to derive the correct values for the substitution credits.

Furthermore, this approach cannot be used when the alternative product is only ever available as a by-product. Unfortunately, such instances frequently arise for the co- and by-products of bioethanol production. As will be demonstrated later (Section 3), by-products such as distillers' dark grains, bran and beet pulp are usually sold as animal feed. The alternatives to such animal feed include rape meal and soya meal which are also generated as co- or by-products from other production processes. Consequently, allocation by substitution in these circumstances does not provide a real solution since it only transfers the problem to the analysis of other production processes.

Allocation by substitution can be used justifiably with certain by-products from bioethanol production. In particular, allocation by substitution can be recommended for surplus electricity which is generated and sold to other users from an integrated combined heat and power plant within the bioethanol processing plant. In such cases, credits are based on the primary energy and GHG emissions saved by displacing either specified sources of electricity or average electricity supplies available for the national network or grid. Typically, credits based on national grid electricity are used and, in this study, published data for the UK in 1996 (Ref. 6) were adopted as the latest and most comprehensive information available. It is recognised, however, that the use of such data can only enable a "snapshot" of current circumstances to be evaluated. Ideally, credits for the primary energy and GHG emissions of displaced grid electricity should be based on a "moving average" over the life of the bioethanol plant. The reason for this is that the mix of power plants which provide grid electricity can vary substantially over time. Unfortunately, forecasting the effect on credits for grid electricity is complex, especially for GHG emissions other than CO_2, and introduces a significant element of uncertainty. It should, however, be noted that the primary energy and GHG emissions credits for UK grid electricity are expected to decline further in the future.

Allocation by mass or energy content are often preferred by life cycle assessment practitioners with a background in natural sciences since these are physical characteristics which are relatively easy to establish and remain constant over time. For processes which produce co- and/or by-products which are relatively similar and are effectively sold in terms of mass or energy content, such allocation procedures can be justified. However, allocation by mass presents serious problems in which waste products are produced in comparable or larger quantities than the main product. Unfortunately, this situation can arise in bioethanol production, especially in connection with wheat straw. An important consideration for allocation by energy content is that the co- and by-products must all the used as sources of energy in practice rather than assuming a theoretical possibilities which, in effect, mean that the procedure has been adopted for simple expediency. In this study, allocation by energy content is appropriate for one particular group of joint products, consisting of the steam, hot water and electricity supplied by straw-fired combined heat and power plants integrated with certain bioethanol processing plants (see Sections 3.2.4 and 3.3.4). In such cases, it is necessary to partition the primary energy and GHG emissions associated with the straw-fired combined heat and power plant between the different stages of the bioethanol processing plant. This is required because separate stages of the bioethanol plant also produce joint products which need the application of relevant allocation procedures. It will be appreciated that allocation procedures become extremely complex in such circumstances. However, the complexity can be restricted by allocating the primary energy and GHG emissions associated with the use of steam, hot water and electricity by energy content.

When allocation by substitution, mass or energy content cannot be justified, the procedure usually adopted is to allocate by price. This approach does suffer from the obvious problem that the price of joint products can change over time so that allocation becomes a procedure which derives variable results. However, it should be noted that relative market prices between joint products form the basis for this allocation procedure and these may be subject to less variation than absolute prices. Furthermore, it can be argued that allocation and the results of life cycle assessment should reflect the economic reality of the product or service under consideration. The inherent value of joint products can change relative to each other as circumstances alter. For example, if bioethanol production was undertaken on a significant scale, it would be expected that over-supply of some by-products might occur, resulting in their re-classification from commercial products for sale to waste products for disposal. The relative market prices of such by-products would fall or become zero so that all primary energy and GHG emissions associated with the process would be allocated to the main product. Hence, allocation by price can be justified as a meaningful alternative when other procedures, especially allocation by substitution are impractical. In a number of instances, it has been necessary to adopt allocation by price in this study. However, important adjustments were sometimes required for its actual application. In particular, market prices may not exist for joint products in their intermediate form. In such cases, "shadow prices" have had to be used. These are based on actual market prices for a final saleable product converted by means of physical factors, such as relative concentration, to represent an effective price for the intermediate product. Summaries of the allocation procedures adopted in this study are given in Sections 3.2 and 3.4, with details of original data and methods of calculation presented in Appendices A to H.

3. BASIC RESULTS

3.1 Baseline Results

At the beginning of this study, it was necessary to establish certain baseline results which would provide a basis of comparison and assist the estimation of results for the different means of producing bioethanol under investigation. An essential set of baseline results consists of basic information on unleaded petrol derived from crude oil and bioethanol as its potential replacement transport fuel. Standard specifications for the densities and calorific values of unleaded petrol and bioethanol are presented in Table 2. The designation of calorific values, in either net or gross terms, is important for subsequent comparison of results per unit delivered energy output.

Table 2 Standard Fuel Specifications

Specification	Unleaded Petrol	Bioethanol
Density (kg/l)	0.735[(a)]	0.794[(b)]
Net Calorific Value (MJ/kg)	43.99[(c)]	26.70[(d)]
Gross Calorific Value (MJ/kg)	47.10[(a)]	29.74[(e)]

Notes

(a) From Ref. 7.
(b) From Ref. 8.
(c) From Ref. 9.
(d) From Ref. 10.
(e) From Ref. 11.

Baseline results, in the form of energy and GHG requirements, for unleaded petrol produced from crude oil in the UK in 1996 are presented in Table 3. The energy requirement equals the total primary energy input per unit of delivered energy output.

The total primary energy input includes the direct energy input of crude oil used to produce petrol and indirect energy input of all fossil fuels consumed in oil extraction, transport, refining and distribution. GHG requirements are provided for individual GHG emissions (CO_2, CH_4 and N_2O) and as a total value measured as equivalent carbon dioxide (eq. CO_2) derived using quoted global warming potentials (see Section 2.2). These GHG requirements include both direct (petrol combustion) and indirect (petrol production) emissions.

Table 3 Baseline Results for Unleaded Petrol

Fuel	Energy Requirement[(a)] (MJ/MJ)	Carbon Requirement[(b)] (kg CO_2/MJ)	Methane Requirement[(c)] (g CH_4/MJ)	Nitrous Oxide Requirement[(d)] (g N_2O/MJ)	Total GHG Requirement[(e)] (kg eq. CO_2/MJ)
Unleaded Petrol from Crude Oil	1.19	0.081	0.022	0.000028	0.081

Notes

(a) Primary energy input per unit delivered energy output, based on the net calorific value of petrol.
(b) Specified production and combustion emissions per unit delivered energy output, based on the net calorific value of petrol.
(c) Specified production emissions per unit delivered energy output, based on the net calorific value of petrol, excluding direct methane emissions during combustion due to variations in vehicle engine performance.
(d) Specified production emissions per unit delivered energy output, based on the net calorific value of petrol, excluding direct nitrous oxide emissions during combustion due to variations in vehicle engine performance.
(e) Assuming 24.5 g eq. CO_2/g CH_4 and 320 g eq. CO_2/g N_2O.

During 2003, baseline results for the production of a range of biofuels, including bioethanol from wheat grain and sugar beet, were derived for Future Energy Solutions (formerly the Energy Technology Support Unit) under the Sustainable Energy Programme of the Department of Trade and Industry (Ref. 3). These baseline results were assembled using data from the most relevant and transparent existing studies, adjusted and supplemented, where necessary, for consistency and completeness. The most appropriate source of representative results for the primary energy inputs and GHG emissions for the production of bioethanol from wheat in the UK consisted of a study prepared by the Energy Technology Support Unit in 1996 (ETSU 1996; Ref. 8). The ETSU 1996 study, which provides results in the form of primary energy inputs and specific emissions (carbon dioxide, carbon monoxide, hydrocarbons, oxides of nitrogen, sulphur dioxide and particulates), is a sufficiently transparent basis for deriving a suitable flow chart, as shown in Figure 1. The ETSU 1996 study investigates a number of different allocation procedures for wheat straw and distillers' dark grains. However, none of these procedures are appropriate and it was necessary to adjust the original estimates for allocation by price. Additionally, a correction was needed to the basic data related to derivation of the amount of natural gas used in a boiler for raising steam and hot water for the bioethanol processing plant. Subsequent baseline results for the production of bioethanol from wheat grain in the UK are summarised in Table 4. The breakdown of results by specific contribution from the process chain is presented in Table 5. This shows that, in the baseline case, the most important considerations for primary energy and GHG emissions from the production of bioethanol from wheat grain are hydrolysis, fermentation and distillation, grain drying, the net diesel fuel consumption of wheat cultivation and harvesting, and nitrogen fertiliser and other inputs used in wheat cultivation.

Figure 1 Baseline Flow Chart for the Production of Bioethanol from Wheat Grain in the UK (Ref. 3)

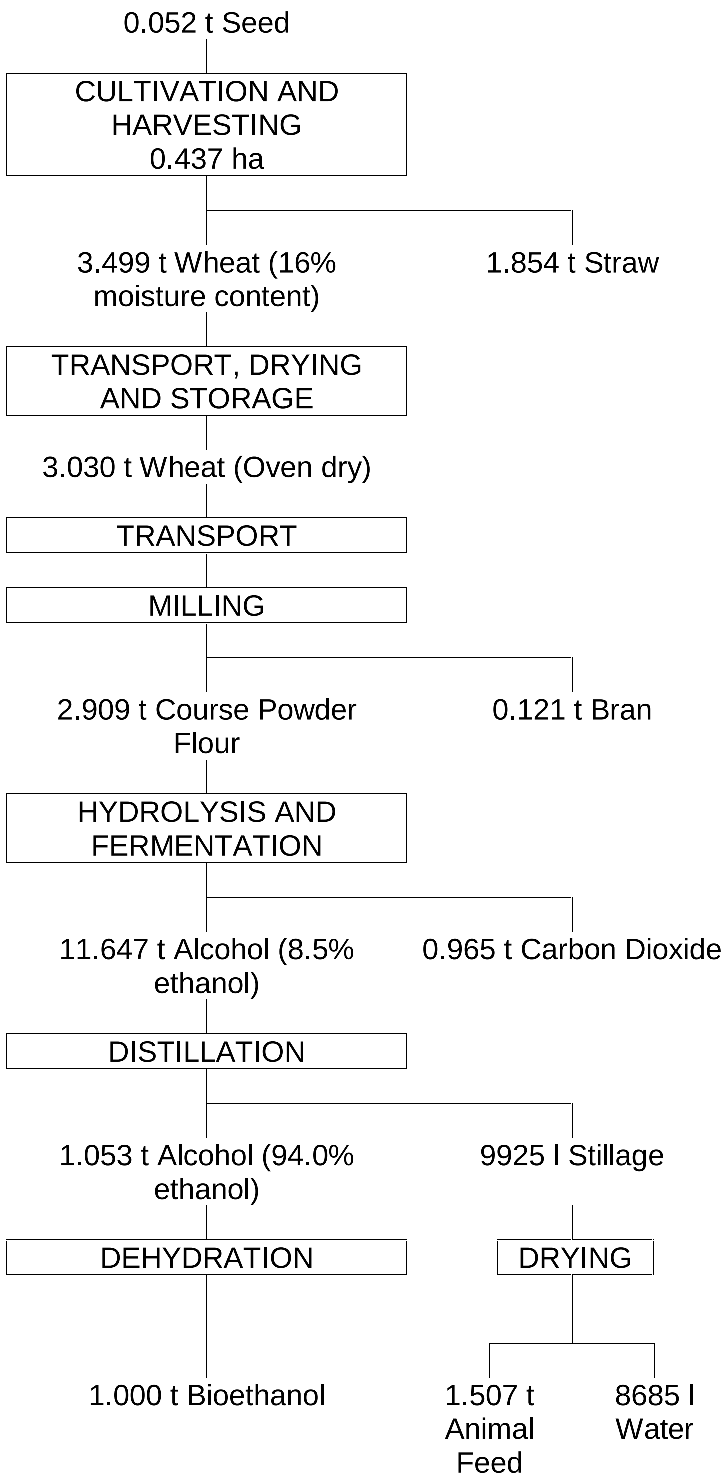


Table 4 Baseline Results for Bioethanol Production from Wheat Grain in the UK (Ref. 3)

Fuel	Energy Requirement[(a)] (MJ/MJ)	Carbon Requirement[(a)] (kg CO_2/MJ)	Methane Requirement[(a)] (g CH_4/MJ)	Nitrous Oxide Requirement[(a)] (g N_2O/MJ)	Total GHG Requirement[(a)] (kg eq. CO_2/MJ)
Bioethanol from Wheat Grain	0.464 ± 0.032	0.024 ± 0.002	0.028 ± 0.003[(b)]	0.012 ± 0.001[(b)]	0.029 ± 0.002[(c)]

Note

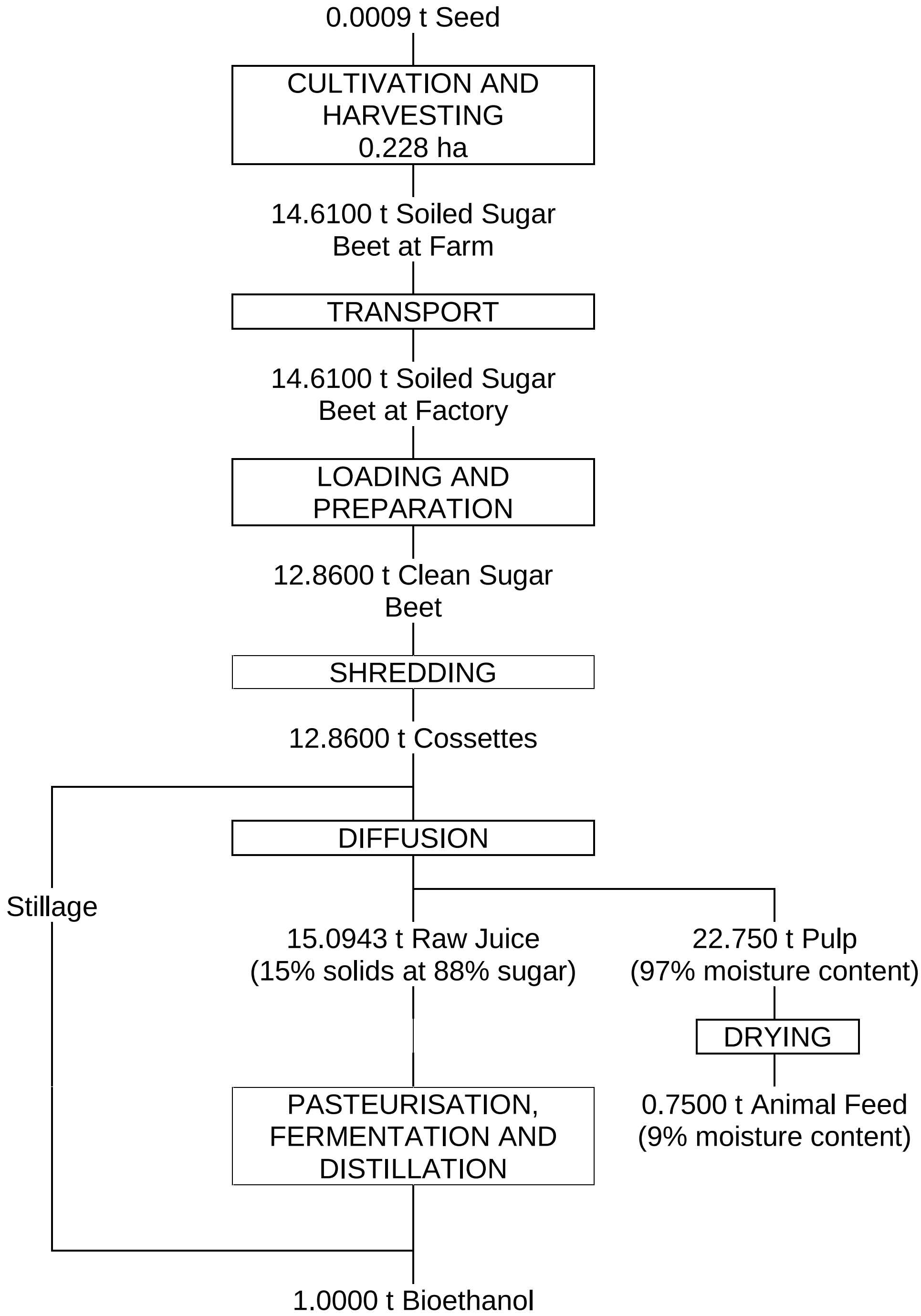
(a) Based on the net calorific value of bioethanol.
(b) Excluding direct methane emissions during the combustion of bioethanol.
(c) Excluding direct nitrous oxide emissions during the combustion of bioethanol.
(d) Excluding the carbon dioxide equivalent of direct methane and nitrous oxide emissions during the combustion of bioethanol.

Table 5 Breakdown of Contributions to Baseline Results for Bioethanol Production from Wheat Grain in the UK (Ref. 3)

Contribution	Primary Energy Inputs (%)	Carbon Dioxide Emissions (%)	Methane Emissions (%)	Nitrous Oxide Emissions (%)	Total GHG Emissions (%)
Cultivation and Harvesting:					
- N fertiliser	5	4	7	88	16
- Net diesel fuel	8	10	2	-	8
- Other inputs	13	8	-	12	8
Transport	6	8	1	-	7
Drying	14	19	5	-	16
Storage	2	2	5	-	2
Milling	3	2	6	-	2
Hydrolysis, Fermentation and Distillation	44	40	72	-	36
Dehydration	-	-	1	-	-
Plant Construction	1	1	-	-	1
Plant Maintenance	-	1	-	-	-
Distribution	4	5	1	-	4

The study produced by the Institut für Energie- und Umweltforschung (Institute for Energy and Environmental Research; IFEU 1997; Ref. 10) was found to be the most appropriate source of baseline results for primary energy and GHG emissions for the production of bioethanol from sugar beet. The IFEU 1997 study is based on the cultivation and possible processing of sugar beet in Germany. Although the IFEU 1997 study is very detailed and examines a considerable range of biofuels, the results for bioethanol production from sugar beet are not wholly transparent. In particular, using this source, it is not possible to identify the quantities of all the important materials involved in the main process chain. Additionally, estimated primary energy inputs and GHG emissions are aggregated for most of the activities involved in bioethanol production. Furthermore, only total GHG emissions are specified clearly and estimates of individual GHG emissions (CO_2, CH_4 and N_2O) cannot be disaggregated with any confidence. Hence, it was necessary to expand the original data, to adjust information to UK conditions and to introduce an allocation procedure based on price for the sugar beet pulp which is sold as animal feed. The subsequent flow chart is shown in Figure 2 and the baseline results are presented in Table 6. The breakdown of results by specific contribution from the process chain is presented in Table 7. This shows that, in the baseline case, the most important

Figure 2 Baseline Flow Chart for the Production of Bioethanol from Sugar Beet in the UK (Ref. 3)



considerations for primary energy and GHG emissions from the production of bioethanol from sugar beet are distillation, beet transport, nitrogen fertiliser used in beet cultivation, and diffusion.

Table 6 Baseline Results for Bioethanol Production from Sugar Beet in the UK (Ref. 3)

Fuel	Energy Requirement[a] (MJ/MJ)	Carbon Requirement[a] (kg CO_2/MJ)	Methane Requirement[a] (g CH_4/MJ)	Nitrous Oxide Requirement[a] (g N_2O/MJ)	Total GHG Requirement[a] (kg eq. CO_2/MJ)
Bioethanol from Sugar Beet	0.496 ± 0.044	0.034 ± 0.003	0.013 ± 0.001[b]	0.018 ± 0.002[c]	0.040 ± 0.003[d]

Note

(a) Based on the net calorific value of bioethanol.
(b) Excluding direct methane emissions during the combustion of bioethanol.
(c) Excluding direct nitrous oxide emissions during the combustion of bioethanol.
(d) Excluding the carbon dioxide equivalent of direct methane and nitrous oxide emissions during the combustion of bioethanol.

Table 7 Breakdown of Contributions to Baseline Results for Bioethanol Production from Sugar Beet in the UK (Ref. 3)

Contribution	Primary Energy Inputs (%)	Carbon Dioxide Emissions (%)	Methane Emissions (%)	Nitrous Oxide Emissions (%)	Total GHG Emissions (%)
Cultivation and Harvesting:					
- N fertiliser	8	5	28	99	19
- Net diesel fuel	3	3	2	-	3
- Other inputs	3	2	1	-	2
Transport	8	7	4	-	6
Loading and Preparation	1	2	-	-	1
Storage	-	-	-	-	-
Shredding	-	-	-	-	-
Diffusion	7	6	8	-	6
Pasteurisation	4	6	5	-	5
Fermentation	1	1	1	-	1
Distillation	59	63	49	1	54
Plant Construction	1	1	-	-	-
Plant Maintenance	1	-	-	-	-
Distribution	4	4	2	-	3

3.2 Bioethanol from Wheat Grain

Against this background of baseline results, this study was undertaken to evaluate the primary energy and GHG emissions associated with specific options to produce bioethanol from wheat grain. First, the main process chains for bioethanol production were agreed with British Sugar plc. The resulting flow chart for bioethanol production from wheat grain using conventional fossil fuels for process steam, hot water and electricity is illustrated in Figure 3. This particular flow chart is specifically relevant to Models 1, 3 and 3a in this study. Originally, the flow chart was delineated into separate sub-systems, mainly to assist with discussions concerning process chain specification and subsequent data collection. The agreed flow chart for the production of bioethanol from wheat grain using wheat straw for combined heat and power generation in the processing plant is shown in Figure 4. It can be seen that

Figure 3 Flow Chart for the Production of Bioethanol from Wheat Grain using Conventional Fossil Fuels (Models 1, 3 and 3a)

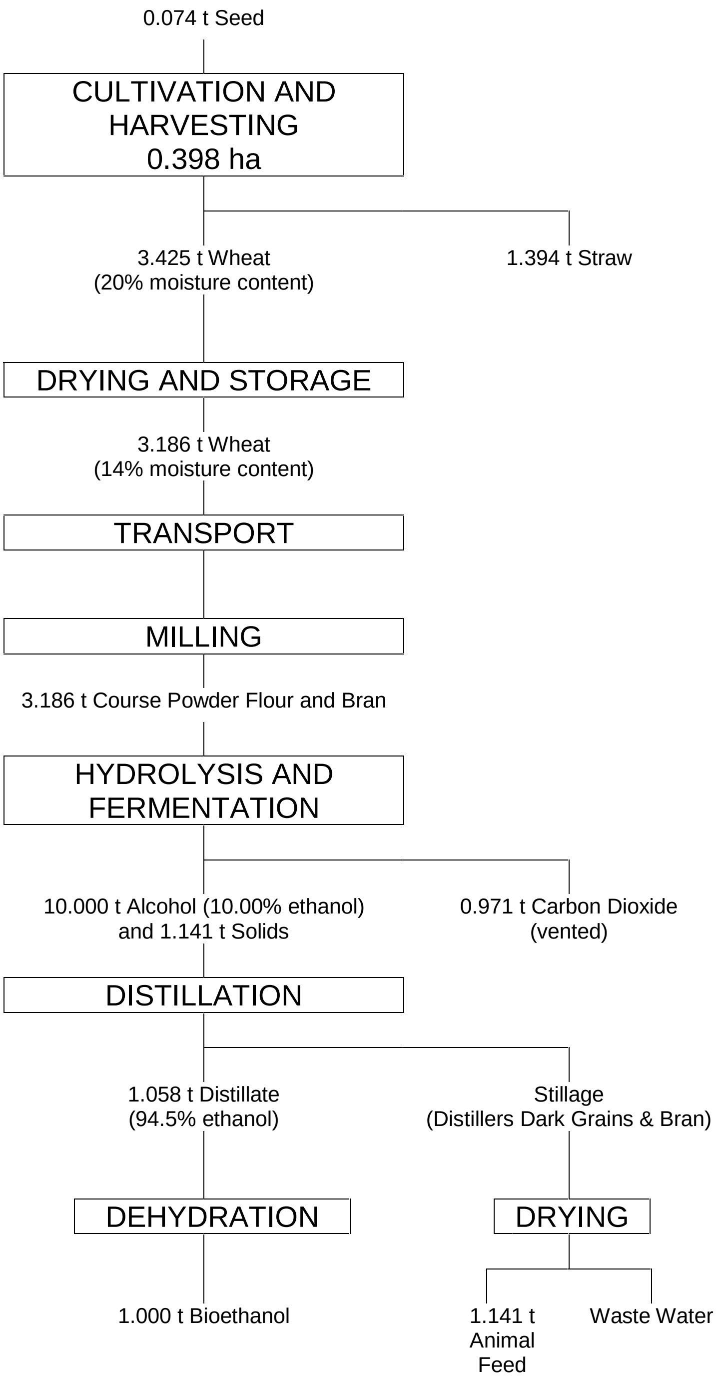
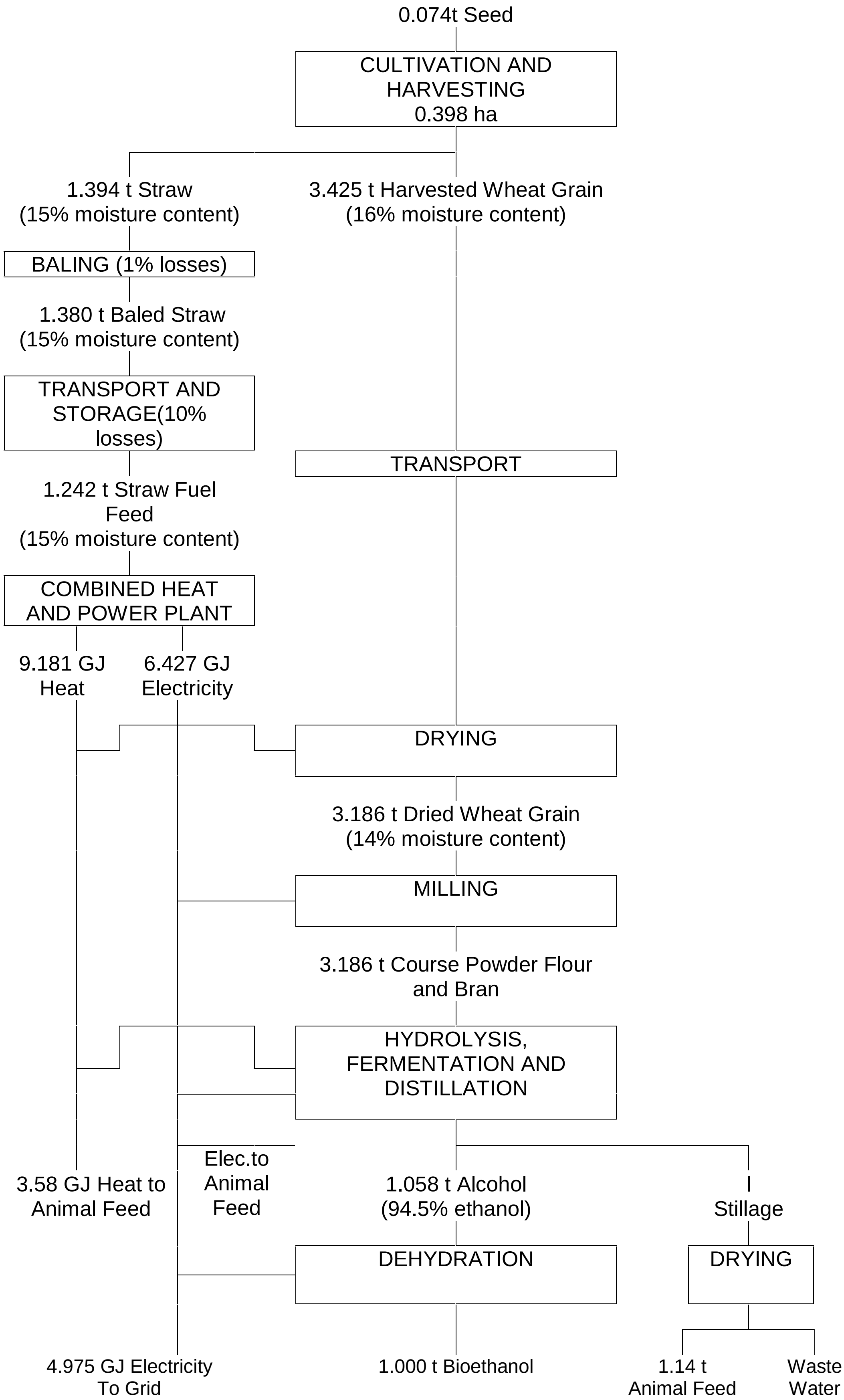


Figure 4 Flow Chart for the Production of Bioethanol from Wheat Grain using Wheat Straw as a Fuel (Models 7)



this flow chart is relatively complex. This is mainly due to the fact that different amounts of heat and electricity, provided by the straw-fired combined heat and power plant, are used in different stages of the bioethanol plant. The wheat straw available from wheat cultivation is sufficient to meet the total heat and electricity requirements of the bioethanol and associated animal feed processing operations. Surplus electricity is "exported" from the bioethanol plant as sales to the national grid. Following confirmation of these flow charts, data were collected to conduct relevant analysis. This required close discussion with British Sugar plc, especially in relation to the details of proposed processing operations, such as major inputs and outputs, heat and electricity demands, and capital and maintenance costs. Such detailed design data were combined with information from existing databases to estimate primary energy inputs and GHG emissions. Price data for certain co- and by-products were also provided by British Sugar plc to assist with allocation procedures.

3.2.1 Bioethanol Production from Wheat Grain with Natural Gas-fired Boiler and Grid Electricity

This particular bioethanol production option is referred to as Model 1 for which detailed results are presented in Appendix A. Wheat cultivation and harvesting assumptions reflect average agricultural inputs and wheat grain yields for the UK in recent years. In particular, a nitrogen fertiliser application rate of 185 kg N/ha.a and a yield of 8.6 t/ha.a for wheat grain at 20% moisture content are assumed. The reference system is fallow set-aside. It is assumed that all the wheat straw would find a separate market as a material. The average round trip distance between the farm and the bioethanol production plant is taken to be 186 km. Steam and hot water are provided by a natural gas-fired boiler, with a thermal efficiency of 80%, in the bioethanol production plant and electricity is supplied by the national grid assuming conditions for the UK in 1996. Allocation procedures for the harvested wheat grain, wheat straw, animal feed and bioethanol are based on recent average market prices.

3.2.2 Bioethanol Production from Wheat Grain with Natural Gas-fired Combined Heat and Power using a Steam Turbine

Model 3 is the designation of this particular bioethanol production option which has detailed results presented in Appendix B. Wheat cultivation and harvesting assumptions reflect average agricultural inputs and wheat grain yields for the UK in recent years. In particular, a nitrogen fertiliser application rate of 185 kg N/ha.a and a yield 8.6 t/ha.a for wheat grain at 20% moisture content are assumed. The reference system is fallow set-aside. It is assumed that all the wheat straw would find a separate market as a material. The average round trip distance between the farm and the bioethanol production plant is taken to be 186 km. Adequate steam, hot water and electricity are provided for the bioethanol plant from a suitably-sized natural gas-fired combined heat and power plant with a steam turbine and an overall thermal efficiency of 84%. Allocation procedures for the harvested wheat grain, wheat straw, animal feed and bioethanol are based on recent average market prices.

3.2.3 Bioethanol Production from Wheat Grain with Natural Gas-fired Combined Heat and Power using a Gas Turbine

The designation of this particular option for bioethanol production is Model 3a and detailed results are presented in Appendix C. Wheat cultivation and harvesting assumptions reflect average agricultural inputs and wheat grain yields for the UK in recent years. In particular, a nitrogen fertiliser application rate of 185 kg N/ha.a and a yield of 8.6 t/ha.a for wheat grain at 20% moisture content are assumed. The reference system is fallow set-aside. It is assumed that all the wheat straw would find a separate market as a material. The average round trip distance between the farm and the bioethanol production plant is taken to be 186 km. A natural gas-fired combined heat and power plant, with a gas turbine and an overall thermal efficiency of 85%, is matched to the steam and hot water requirements of the bioethanol plant. Surplus electricity is "exported" to the national grid. Allocation procedures for the harvested wheat grain, wheat straw, animal feed and bioethanol are based on recent average market prices.

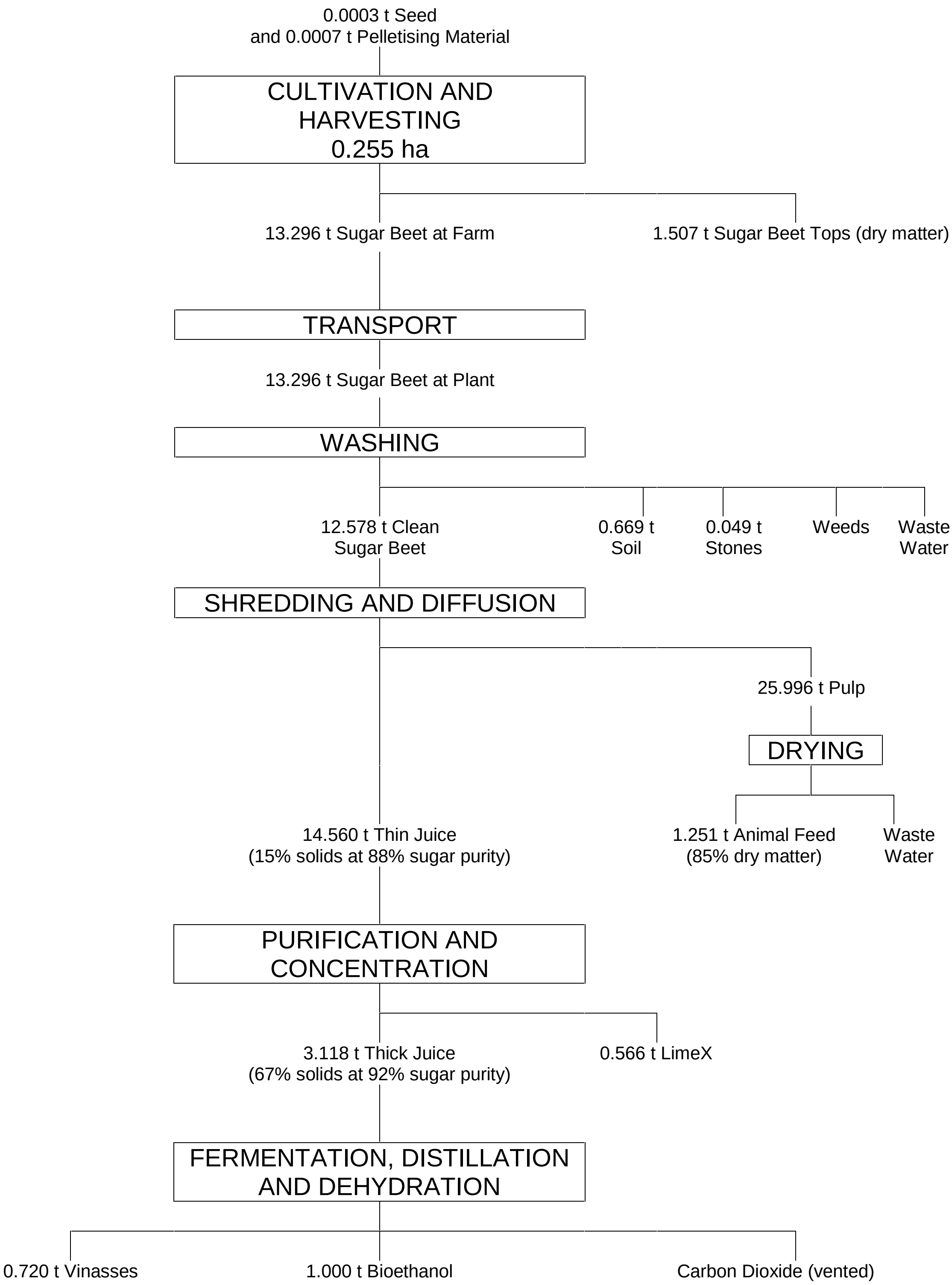
3.2.4 Bioethanol Production from Wheat Grain with Straw-fired Combined Heat and Power using a Steam Turbine

This particular option for producing bioethanol is known as Model 7 for which detailed results are presented in Appendix D. Wheat cultivation and harvesting assumptions reflect average agricultural inputs and wheat grain yields for the UK in recent years. In particular, a nitrogen fertiliser application rate of 185 kg N/ha.a and a yield of 8.6 t/ha.a for wheat grain at 20% moisture content are assumed. The reference system is fallow set-aside. A yield of 3.5 t/ha.a of wheat straw with a moisture content of 15% is adequate for supplying all the heating requirements of the bioethanol plant and associated animal feed plant. However, in order to use this wheat straw, it is necessary to take into account baling and transport operations. Additionally, it is assumed that extra fertiliser inputs, including a nitrogen fertiliser application rate of 59 kg/ha.a, are needed to compensate for straw removal from the soil. Average round trip distances for wheat grain, which is transported via a drying plant to the bioethanol plant, and wheat straw, which travels via separate storage facilities to the bioethanol plant, of 186 km and 80 km, respectively, are assumed. The straw-fired combined heat and power plant, which has an overall thermal efficiency of 85%, generates more electricity than that required by the bioethanol processing plant and the associated animal feed plant, and the surplus is "exported" for sale via the national grid. The "credit" for this electricity is based on displaced average grid electricity supplies for the UK in 1996. The allocation of heat and electricity within the bioethanol plant is simply based on energy content so that 1 unit of heat is equivalent to 1 unit of electricity. The allocation procedure for animal feed and bioethanol is based on recent average market prices.

3.3 Bioethanol from Sugar Beet

It was also possible to undertake the evaluation of the primary energy and GHG emissions associated with the production of bioethanol from sugar beet against the established background of baseline results. Again, the main process chains for bioethanol production were agreed with British Sugar plc. This is shown in Figure 5 which is the relevant flow chart for all the options considered in this study for producing bioethanol from sugar beet (Models 2, 4a, 4b and 8). It should be noted that this basic flow chart does not alter with changes in the means of providing heat and electricity in the bioethanol plant. In particular, it is unchanged for the option with the straw-fired combined heat and power plant (Model 8) because this fuel is obtained from wheat grain cultivation and harvesting rather than sugar beet production. Following confirmation of this flow chart, data were collected to conduct relevant analysis. This required close discussion with British Sugar plc, especially in relation to the details of proposed processing operations, such as major inputs and outputs, heat and electricity demands, and capital and maintenance costs. Such detailed design data were combined with information from existing databases to estimate primary energy inputs and GHG emissions. Price data for certain co- and by-products were also provided by British Sugar plc to assist with allocation procedures.

Figure 5 Flow Chart for the Production of Bioethanol from Sugar Beet (Models 2, 4a, 4b and 8)



3.3.1 Bioethanol Production from Sugar Beet with Natural Gas-fired Boiler and Grid Electricity

This particular bioethanol production option is referred to as Model 2 for which detailed results are presented in Appendix E. Sugar beet cultivation and harvesting assumptions reflect average agricultural inputs and sugar beet yields for the UK in recent years. In particular, a nitrogen fertiliser application rate of 103 kg N/ha.a and a yield of 52 t/ha.a for soiled sugar beet are assumed. The reference system is fallow set-aside. Allocation between sugar beet tops and soiled sugar beet is on the basis of a dry matter equivalent animal feed for the former and a market value for the latter. The average round trip distance between the farm and the bioethanol production plant is taken to be 94 km. Steam and hot water are provided by a natural gas-fired boiler, with a thermal efficiency of 80%, in the bioethanol production plant and electricity is supplied by the national grid assuming conditions for the UK in 1996. Allocation by substitution is assumed for soil and stones recovered from soiled sugar beet washing and sold as landscaping material and aggregate, respectively. Allocation between animal feed derived from sugar beet pulp and thin juice is based on the market price of equivalent animal feed pellets and a shadow price for thin juice based on the equivalent sugar content of thick juice and its respective value. Allocation by substitution is used for Limex. Allocation between bioethanol and vinasses is based on the market price of the former and a shadow price for the latter based on the equivalent sugar content of thick juice and its respective value.

3.3.2 Bioethanol Production from Sugar Beet with Natural Gas-fired Combined Heat and Power using a Steam Turbine

Model 4a is the designation of this particular bioethanol production option which has detailed results presented in Appendix F. Sugar beet cultivation and harvesting assumptions reflect average agricultural inputs and sugar beet yields for the UK in recent years. In particular, a nitrogen fertiliser application rate of 103 kg N/ha.a and a yield of 52 t/ha.a for soiled sugar beet are assumed. The reference system is fallow set-aside. Allocation between sugar beet tops and soiled sugar beet is on the basis of a dry matter equivalent animal feed for the former and a market value for the latter. The average round trip distance between the farm and the bioethanol production plant is taken to be 94 km. Adequate steam, hot water and electricity are provided for the bioethanol plant from a natural gas-fired combined heat and power plant with a steam turbine and an overall thermal efficiency of 84%. The combined heat and power station is sized to match the heat requirements of the bioethanol plant and associated animal feed plant. A small amount of surplus electricity is "exported". Allocation by substitution is assumed for soil and stones recovered from soiled sugar beet washing and sold as landscaping material and aggregate, respectively. Allocation between animal derived from sugar beet pulp and thin juice is based on the market price of equivalent animal feed pellets and a shadow price for thin juice based on the equivalent sugar content of thick juice and its respective value. Allocation by substitution is used for Limex. Allocation between bioethanol and vinasses is based on the market price of the former and a shadow price for the latter based on the equivalent sugar content of thick juice and its respective value.

3.3.3 Bioethanol Production from Sugar Beet with Natural Gas-fired Combined Heat and Power using a Gas Turbine

The designation of this particular option for bioethanol production is Model 4b and detailed results are presented in Appendix G. Sugar beet cultivation and harvesting assumptions reflect average agricultural inputs and sugar beet yields for the UK in recent years. In particular, a nitrogen fertiliser application rate of 103 kg N/ha.a and a yield of 52 t/ha.a for soiled sugar beet are assumed. The reference system is fallow set-aside. Allocation between sugar beet tops and soiled sugar beet is on the basis of a dry matter equivalent animal feed for the former and a market value for the latter. The average round trip distance between the farm and the bioethanol production plant is taken to be 94 km. Adequate steam, hot water and electricity are provided for the bioethanol plant from a natural gas-fired combined heat and power plant with a gas turbine and an overall thermal efficiency of 85%. The combined heat and power station is sized to match the heat requirements of the bioethanol plant and associated animal feed plant. A larger of surplus electricity than that in Model 4a is also "exported". Allocation by substitution is assumed for soil and stones recovered from soiled sugar beet washing and sold as landscaping material and aggregate, respectively. Allocation between animal derived from sugar beet pulp and thin juice is based on the market price of equivalent animal feed pellets and a shadow price for thin juice based on the equivalent sugar content of thick juice and its respective value. Allocation by substitution is used for Limex. Allocation between bioethanol and vinasses is based on the market price of the former and a shadow price for the latter based on the equivalent sugar content of thick juice and its respective value.

3.3.4 Bioethanol Production from Sugar Beet with Straw-fired Combined Heat and Power using a Steam Turbine

This particular option for producing bioethanol is known as Model 8 for which detailed results are presented in Appendix H. Sugar beet cultivation and harvesting assumptions reflect average agricultural inputs and sugar beet yields for the UK in recent years. In particular, a nitrogen fertiliser application rate of 103 kg N/ha.a and a yield of 52 t/ha.a for soiled sugar beet are assumed. The reference system is fallow set-aside. Allocation between sugar beet tops and soiled sugar beet is on the basis of a dry matter equivalent animal feed for the former and a market value for the latter. The average round trip distance between the farm and the bioethanol production plant is taken to be 94 km. The straw-fired combined heat and power plant, with an overall thermal efficiency of 85%, uses enough wheat straw to supply all the heat requirements of the bioethanol plant. Straw baling and transport are taken into account. Additionally, it is assumed that extra fertiliser inputs, including a nitrogen fertiliser application rate of 59 kg/ha.a, are needed to compensate for straw removal from the soil. An average round trip distance for wheat straw, which travels via separate storage facilities to the bioethanol plant, of 80 km is assumed. A significant amount of surplus electricity is generated which is "exported" and forms a credit based on average electricity supplies from the national grid in the UK in 1996. The allocation of heat and electricity within the bioethanol plant is simply based on energy content so that 1 unit of heat is equivalent to 1 unit of electricity. Allocation by substitution is assumed for soil and stones recovered from soiled sugar beet washing and sold as landscaping material and aggregate, respectively. Allocation between animal derived from sugar beet pulp and thin juice is based on the market price of equivalent animal feed pellets and a shadow price for thin juice based on the equivalent sugar content of thick juice and its respective value. Allocation by substitution is used for Limex. Allocation between bioethanol and vinasses is based on the market price of the former and a shadow price for the latter based on the equivalent sugar content of thick juice and its respective value.

4. COMPARISON OF RESULTS

Subsequent estimates of the primary energy and GHG emissions associated with the production of bioethanol from wheat grain (Models 1, 3, 3a and 7) and sugar beet (Models 2, 4a, 4b and 8) are summarised in Tables 8 and 9, respectively. Comparison with the baseline results given in Tables 4 and 6 shows that the

Table 8 Summary of Results for Bioethanol Production from Wheat Grain

Production Option	Energy Requirement[a] (MJ/MJ)	Carbon Requirement[a] (kg CO_2/MJ)	Methane Requirement[a] (g CH_4/MJ)	Nitrous Oxide Requirement[a] (g N_2O/MJ)	Greenhouse Gas Requirement[a] (kg eq CO_2/MJ)
Natural Gas-fired Boiler and Grid Electricity (Model 1)	0.644 ± 0.041	0.031 ± 0.002	0.042 ± 0.003[b]	0.039 ± 0.005[c]	0.044 ± 0.002[d]
Natural Gas-fired Combined Heat and Power Plant with Steam Turbine (Model 3)	0.597 ± 0.042	0.031 ± 0.002	0.040 ± 0.004[b]	0.039 ± 0.005[c]	0.044 ± 0.003[d]
Natural Gas-fired Combined Heat and Power Plant with Gas Turbine (Model 3a)	0.404 ± 0.040	0.021 ± 0.002	0.009 ± 0.004[b]	0.039 ± 0.005[c]	0.033 ± 0.003[d]
Straw-fired Combined Heat and Power Plant with Steam Turbine (Model 7)	-0.070 ± 0.190	-0.002 ± 0.001	-0.046 ± 0.002[b]	0.055 ± 0.005[c]	0.014 ± 0.002[d]

Note

(a) Based on the net calorific value of bioethanol.
(b) Excluding direct methane emissions from the combustion of bioethanol.
(c) Excluding direct nitrous oxide emissions from the combustion of bioethanol.
(d) Excluding direct methane and nitrous oxide emissions from the combustion of bioethanol.

Table 9 Summary of Results for Bioethanol Production from Sugar Beet

Production Option	Energy Requirement[a] (MJ/MJ)	Carbon Requirement[a] (kg CO_2/MJ)	Methane Requirement[a] (g CH_4/MJ)	Nitrous Oxide Requirement[a] (g N_2O/MJ)	Greenhouse Gas Requirement[a] (kg eq CO_2/MJ)
Natural Gas-fired Boiler and Grid Electricity (Model 2)	0.828 ± 0.086	0.041 ± 0.003	0.074 ± 0.006[b]	0.011 ± 0.002[c]	0.047 ± 0.003[d]
Natural Gas-fired Combined Heat and Power Plant with Steam Turbine (Model 4a)	0.678 ± 0.064	0.034 ± 0.003	0.055 ± 0.006[b]	0.011 ± 0.002[c]	0.039 ± 0.003[d]
Natural Gas-fired Combined Heat and Power Plant with Gas Turbine (Model 4b)	0.360 ± 0.130	0.019 ± 0.006	0.007 ± 0.004[b]	0.010 ± 0.002[c]	0.022 ± 0.003[d]
Straw-fired Combined Heat and Power Plant with Steam Turbine (Model 8)	-0.521 ± 0.130	-0.111 ± 0.020	-0.337 ± 0.052[b]	0.032 ± 0.003[c]	-0.109 ± 0.019[d]

Note

(a) Based on the net calorific value of bioethanol.
(b) Excluding direct methane emissions from the combustion of bioethanol.
(c) Excluding direct nitrous oxide emissions from the combustion of bioethanol.
(d) Excluding direct methane and nitrous oxide emissions from the combustion of bioethanol.

estimates derived in this study for equivalent methods of production (Models 1 and 2) are higher for both primary energy and GHG emissions. In the case of bioethanol production from wheat grain, specific reasons for this include a higher nitrogen fertiliser application rate in cultivation and higher natural gas and electricity consumption in the bioethanol plant. With the production of bioethanol from sugar beet, specific reasons consist of higher diesel fuel consumption in cultivation and harvesting and higher natural gas and electricity consumption in the bioethanol plant. In both instances, the evaluations in this study are based on more detailed and complete descriptions of the entire process chain, in general, and the bioethanol production plants, in particular.

Comparison of the results for the separate production options given in Tables 8 and 9 demonstrate a progressive reduction in primary energy and CO_2 and total GHG emissions associated with the options for producing bioethanol. In order of prominence, results improve from a conventional arrangement with a natural gas-fired boiler with "imported" grid electricity (Models 1 and 2), through using natural gas-fired combined heat and power plants with a steam turbine (Models 3 and 4a) and, then, a gas turbine (Models 3a and 4b), finally to utilisation of a straw-fired combined heat and power plant with a steam turbine (Models 7 and 8). Indeed, very substantial reductions in primary energy and GHG emission are achieved by incorporating a straw-fired combined heat and power plant in the bioethanol plant. In these circumstances, results are very close to zero or even negative for primary energy and GHG emissions. In terms of total CO_2 emissions specifically, these bioethanol production options can be considered to be truly "carbon neutral" or "carbon beneficial" which means that CO_2 credits exceed all the associated CO_2 emissions of the entire process chain. Total CH_4 emissions are also negative so that total GHG emissions are either quite small (Model 7) or negative (Model 8) despite positive values for total N_2O emissions. By contrasting Tables 8 and 9, it can be seen that relatively smaller values of results are obtained for bioethanol production from sugar beet (Model 8) compared with bioethanol production from wheat grain (Model 7). This is mainly due to the larger amount of surplus electricity and its subsequent "credit" for the sugar beet plant relative to that for wheat grain plant. This is a consequence of the sizing of the combined heat and power plants to heat requirements and differences in the comparative balances of heat and electricity requirements in each type of bioethanol plant. It should also be noted that procedures adopted for allocation between main and by-products affects bioethanol production from wheat grain and sugar beet differently.

The net savings which could be realised by replacing unleaded petrol from crude oil with bioethanol from wheat grain and sugar beet are summarised in Table 10. These net savings are calculated on the basis that bioethanol can replace unleaded petrol

Table 10 Net Savings by Replacing Unleaded Petrol with Bioethanol from Wheat Grain and Sugar Beet

Production Options	Net Savings[a]				
	Primary Energy (%)	Carbon Dioxide (%)	Methane (%)	Nitrous Oxide (%)	Total Greenhouse Gases (%)
Bioethanol from Wheat Grain: Natural Gas-fired Boiler and Grid Electricity (Model 1)	46	62	- 91	- 139,186	46
Bioethanol from Wheat Grain: Natural Gas-fired Combined Heat and Power Plant with Steam Turbine (Model 3)	50	62	- 82	- 139,186	46
Bioethanol from Wheat Grain: Natural Gas-fired Combined Heat and Power Plant with Gas Turbine (Model 3a)	66	74	59	- 139,186	59
Bioethanol from Wheat Grain: Straw-fired Combined Heat and Power Plant with Steam Turbine (Model 7)	106	102	309	- 196,329	83
Bioethanol from Sugar Beet: Natural Gas-fired Boiler and Grid Electricity (Model 2)	30	49	- 236	- 39,186	42
Bioethanol from Sugar Beet: Natural Gas-fired Combined Heat and Power Plant with Steam Turbine (Model 4a)	43	58	- 150	- 39,186	52
Bioethanol from Sugar Beet: Natural Gas-fired Combined Heat and Power Plant with Gas Turbine (Model 4b)	70	77	68	- 35,614	73
Bioethanol from Sugar Beet: Straw-fired Combined Heat and Power Plant with Steam Turbine (Model 8)	144	237	1,632	- 114,186	235

Note

(a) Based on net calorific values for unleaded petrol and bioethanol.

by the equal amount of energy available from each fuel. Direct emissions of CH_4 and N_2O from the combustion of either fuel are excluded from these calculation due to the lack of comparable standard information on vehicle engine performance. Net savings are apparent in primary energy, and CO_2 and total GHG emissions, especially for bioethanol production incorporating straw-fired combined heat and power plants (Models 7 and 8). Although net savings in CH_4 emissions are achieved with bioethanol production using either natural gas-fired combined heat and power plants with gas turbines and straw-fired combined heat and power plants (Models 3a, 4b, 7 and 8), these emissions actual increase for all the other options (Models 1, 2, 3 and 4a). This is due to the fact that small amounts of CH_4 emissions are associated with the production of unleaded petrol, mainly in crude oil extraction activities, compared with CH_4 emissions from the extraction, processing and transmissions of the relatively large quantities of natural gas consumed in these bioethanol production options. With all bioethanol production options, there are very substantial increases in total N_2O emissions compared with those from the production of unleaded petrol. This occurs because of the manufacture and use of nitrogen fertiliser in the cultivation of wheat grain and sugar beet.

5. CONCLUSIONS

The following key conclusions can be drawn from the results derived in this study:

- Estimated primary energy and GHG emissions for the production of bioethanol from wheat grain and sugar beet using a natural-fired boiler and "imported" grid electricity (Models 1 and 2) are higher that equivalent baseline results obtained from earlier work (Ref. 3). This is due to the use of more detailed, more complete and, probably, more reliable descriptions of the entire process chain, in general, and the bioethanol production plants, in particular.

- Significant reductions in primary energy and GHG emissions can be achieved in comparison with the baseline results by using natural gas-fired combined heat and power plants, with either steam or gas turbines, in the bioethanol plant (Models 3, 3a, 4a and 4b). Of the two types of natural gas-fired combined heat and power plant, that incorporating a gas turbine produces greater reductions in primary energy and GHG emissions than that with a steam turbine.

- The greatest reductions in primary energy and GHG emissions are accomplished by utilising a straw-fired combined heat and power plant with a steam turbine in the bioethanol plant. As such, bioethanol production from sugar beet (Model 8) attains greater reductions than bioethanol production from wheat grain (Model 7).

- Bioethanol produced from wheat grain and sugar beet by all the options considered in this study generate net savings in primary energy, and CO_2 and total GHG emissions when replacing unleaded petrol produced from crude oil.

- Bioethanol produced from wheat grain incorporating a straw-fired combined heat and power plant with a steam turbine (Model 7) more than totally avoids energy resource depletion, is "carbon neutral" in terms of in total CO_2 emissions and reaches a very low level of total GHG emissions.

- Bioethanol produced from sugar beet incorporating a straw-fired combined heat and power plant with a steam turbine (Model 8) more than totally avoids energy resource depletion and is more than "carbon neutral" in terms of total CO_2 emissions and total GHG emissions.

REFERENCES

1. "Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions on Alternative Fuels for Road Transport and on a Set of Measures to Promote the Use of Biofuels" European Commission, COM(2001) 547, Brussels, Belgium, 7 November 2001.

2. "Environmental Management - Life Cycle Assessment" European Standard EN ISO 14040 Series, European Committee for Standardisation, Brussels, Belgium.

3. "Carbon and Energy Balances for a Range of Biofuels Options" by M. A. Elsayed, R. Matthews and N. D. Mortimer, Project Number B/B6/00784/REP, URN 03/836 for the Sustainable Energy Programmes of the Department of Trade and Industry, Resources Research Unit, Sheffield Hallam University, United Kingdom, March 2003.

4. "Third Assessment Report" Intergovernmental Panel on Climate Change, www.grida.no/climate/ipcc_tar/wg1, 2001.

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

6. "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.

7. "Digest of United Kingdom Energy Statistics, 2000" Department of Trade and Industry, London, United Kingdom, 2001.

8. "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.

9. Private communication with M. Watson, United Kingdom Petroleum Industry Association, Department of Trade and Industry, London, United Kingdom, London, 23 March 2003.

10. "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

11. "Handbook of Industrial Energy Analysis" by I. Boustead and G. F. Hancock, Ellis Horwood Ltd., Chichester, United Kingdom, 1979.

APPENDIX A: Model 1

Spreadsheet for Primary Energy Inputs to Bioethanol Production from Wheat using a Natural Gas-fired Boiler and Grid Electricity (Model 1)

Functional Unit:	Bioethanol at point of distribution derived from wheat using a natural gas-fired boiler and grid electricity during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on average market prices, assuming 1.394 tonnes of wheat straw at £25/t (Ref. 1) and 3.425 tonnes of harvested wheat grain with 20% moisture content at £69/t (Ref. 2), giving a 87.1% allocation to bioethanol, and 1.141 tonnes of animal feed at £80/t (Ref. 3) and 1.000 tonnes of bioethanol at £494/t (Ref. 4), giving a 84.4% allocation to bioethanol.

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	*ha.a*	-	-	*2,592*	*±1,036*	*4,920*	*±196*	*7,512*	*±1,054*	(a)
- P Fertiliser	*ha.a*	-	-	*1,484*	*±223*	-	-	*1,484*	*±223*	(b, c)
- K Fertiliser	*ha.a*	-	-	*515*	*±77*	-	-	*515*	*±77*	(c, d)
- Pesticide	*ha.a*	-	-	*548*	*±82*	-	-	*548*	*±82*	(c, e)
- Herbicide	*ha.a*	-	-	*27*	*±4*	-	-	*27*	*±4*	(c, f)
- Insecticide	*ha.a*	-	-	*219*	*±33*	-	-	*219*	*±33*	(c, g)
- Fungicide	*ha.a*	-	-	*274*	*±41*	-	-	*274*	*±41*	(c, h)
- Seed	*ha.a*	-	-	*2,498*	*±375*	-	-	*2,498*	*±375*	(c, i)
- Diesel Fuel	*ha.a*	*5,490*	*±868*	*604*	*±288*	-	-	*6,094*	*±914*	(c, j)
Reference System:										
- Diesel Fuel	*ha.a*	*- 922*	*±146*	*- 101*	*±48*	-	-	*-1,023*	*±154*	(c, k)
Sub-Totals	*ha.a*	*4,568*	*±880*	*8,660*	*±1,168*	*4,920*	*±196*	*18,148*	*±1,477*	
	t be	**1,336**	**±257**	**2,534**	**±342**	**1,439**	**±57**	**5,309**	**±432**	(l)
Drying:										
- Diesel Fuel	*t hwg*	*338*	*±53*	*37*	*±18*	-	-	*375*	*±56*	(c, m)
	t be	**977**	**±153**	**107**	**±52**	**-**	**-**	**1,084**	**±162**	(n)
Transport:										
- Diesel Fuel	*t dwg*	*152*	*±6*	*53*	*±7*	-	-	*205*	*±9*	(o)
	t be	**409**	**±16**	**143**	**±19**	**-**	**-**	**552**	**±25**	(p)
Milling, Hydrolysis, Fermentation and Distillation:										
- Natural Gas	*t de*	*6,455*	*±1,020*	*710*	*±338*	-	-	*7,165*	*±1,075*	(c, q - s)
- Electricity	*t de*	*580*	*±153*	*1,209*	*±221*	-	-	*1,789*	*±268*	(c, q – s)
- Caustic Soda	*t de*	-	-	*836*	*±125*	-	-	*836*	*±125*	(c, t)
- Diam. Phosph.	*t de*	-	-	*55*	*±8*	-	-	*55*	*±8*	(c, u)
- Sulphuric Acid	*t de*	-	-	*66*	*±74*	-	-	*66*	*±74*	(c, v)
- Enzyme AMG	*t de*	-	-	*110*	*±16*	-	-	*110*	*±16*	(c, w)
- Enzyme AA	*t de*	-	-	*43*	*±6*	-	-	*43*	*±6*	(c, x)
- Calcium Chlor.	*t de*	-	-	*6*	*±1*	-	-	*6*	*±1*	(c, y)
Sub-Totals	*t de*	*7,035*	*±1,031*	*3,035*	*±430*	-	-	*10,070*	*±1,118*	
	t be	**6,282**	**±921**	**2,710**	**±384**	**-**	**-**	**8,992**	**±998**	(z)
Dehydration: - Electricity	**t be**	**25**	**±7**	**53**	**±10**	**-**	**-**	**78**	**±12**	(c, q, aa, bb)
Plant Construction	**t be**	**-**	**-**	**541**	**±81**	**-**	**-**	**541**	**±81**	(c, cc)
Plant Maintenance	**t be**	**-**	**-**	**162**	**±24**	**-**	**-**	**162**	**±24**	(c, dd)
Distribution: - Diesel Fuel	**t be**	**369**	**±14**	**129**	**±16**	**-**	**-**	**498**	**±21**	(ee)
Totals	**t be**	**9,398**	**±967**	**6,379**	**±524**	**1,439**	**±57**	**17,216**	**±1,103**	

Biofuel Specifications

Density of bioethanol = 0.79 kg/l
Net calorific value of bioethanol = 26.72 MJ/kg
Gross calorific value of bioethanol = 29.74 MJ/kg

Abbreviations

ha.a = hectare year
t hwg = tonne of harvested wheat grain
t dwg = tonne of dried wheat grain
t de = tonne of distillate ethanol (94.5% alcohol)
t be = tonne of bioethanol

Notes

(a) Nitrogen fertiliser application rate of 185 kg N/ha.a (Ref. 5) 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 nitrogen fertiliser (Ref. 6).

(b) Phosphate fertiliser application rates of 41 kg P/ha.a (Ref. 5), or 93.9 kg P_2O_5/ ha.a assuming 2.290 kg P_2O_5/kg P, and a total energy requirement for phosphate fertiliser of 15.8 MJ/kg P_2O_5 (Ref. 7).

(c) Assuming an error bar of ±15% based on similar analyses (Ref. 8).

(d) Potash fertiliser application rate of 46 kg K/ha.a (Ref. 5), or 55.4 kg K_2O/ha.a assuming 1.205 kg K_2O/kg K, and a total energy requirement for potash fertiliser of 9.3 MJ/ kg K_2O (Ref. 7).

(e) Pesticide application rate of 2.0 kg/ha.a (Ref. 9) and a total energy requirement for general pesticides, herbicides and fungicides of 274.1 MJ/kg (Ref. 7).

(f) Herbicide application rate of 0.1 kg/ha.a (Ref. 9) and a total energy requirement for general pesticides, herbicides and fungicides of 274.1 MJ/kg (Ref. 7).

(g) Insecticide application rate of 0.8 kg/ha.a (Ref. 9) and a total energy requirement for general pesticides, herbicides and fungicides of 274.1 MJ/kg (Ref. 7).

(h) Fungicide application rate of 1.0 kg/ha.a (Ref. 9) and a total energy requirement for general pesticides, herbicides and fungicides of 274.1 MJ/kg (Ref. 7).

(i) Sowing rate of 185 kg/ha.a (Ref. 10) and a total energy requirement of 13.5 MJ/kg of seed (Ref. 11).

(j) Diesel fuel consumption of 5,490 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides, insecticides and fungicides, harvesting, carting and loading (Ref. 12) and a gross energy requirement of 1.110 MJ/MJ for diesel fuel in the UK in 1996 (Ref. 13).

(k) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 7) and a gross energy requirement of 1.110 MJ/MJ for diesel fuel in the UK in 1996 (Ref. 13).

(l) Land requirement of 0.398 ha.a/t of bioethanol and allocation of 87.1% x 84.4% = 73.5% to bioethanol.

(m) Assuming 50% of the harvested wheat grain (1.7125 t/t of bioethanol) dries naturally to a moisture content of 14% and 50% of the harvested wheat grain (1.7125 t/t of bioethanol) requires artificial drying on the farm with a diesel fuel consumption of 677 MJ/t of harvested wheat grain with a moisture content of 19% (Ref. 12), and a gross energy requirement of 1.110 MJ/MJ for diesel fuel in the UK in 1996 (Ref. 13).

(n) Harvested wheat grain requirement of 3.425 t/t of bioethanol and allocation of 84.4% to bioethanol.

(o) Average round trip distance of 186 km (Ref. 12) 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. 14).

(p) Dried wheat grain requirement of 3.186 t/t of bioethanol and allocation of 84.4% to bioethanol.

(q) Steam production with a natural gas-fired boiler with an overall efficiency of 80% (Ref. 12) and a gross energy requirement of 1.110 MJ/MJ for natural gas in the UK in 1996 (Ref. 13), and electricity obtained from the grid with a gross energy requirement of 3.083 MJ/MJ for the UK in 1996 (Ref. 13).

(r) Assuming that milling, hydrolysis, fermentation and distillation consumes steam at a rate of 25.0 t/hr (Ref. 12), accounting for 25.0/44.5 = 56.2% of total steam consumption, or 67,753 MJ/hr, and, based on pro rata power ratings, consumes 1.903/4.500 = 42.3% of total electricity consumption (Ref. 12), or 7,612 MJ/hr.

(s) Total distillate (94.5% alcohol) output rate of 13.12 t/hr, based on an annual output rate of 105,800 t/a of distillate, or 100,000 t/a of bioethanol, and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 12).

(t) Caustic soda (49% concentration) consumption rate of 4,427,136 kg/a (Ref. 12), or 41.8 kg/t of distillate, and an energy requirement of 20 MJ/kg for caustic soda (Ref. 7).

(u) Diammonium phosphate (21% concentration) consumption rate of 2,921,103 kg/a (Ref. 12), or 27.6 kg/t of distillate, and an energy requirement of 2 MJ/kg for diammonium phosphate (Ref. 15).

(v) Sulphuric acid (93% concentration) consumption rate of 2,911,104 kg/a (Ref. 12), or 27.5 kg/t of distillate, and an energy requirement of 2.4 ± 2.7 MJ/kg for sulphuric acid (Ref. 16).

(w) Enzyme AMG consumption rate of 247,176 kg/a (Ref. 12), or 2.3 kg/t of distillate, and an energy requirement of 47 MJ/kg for enzyme AMG (Refs. 17 to 19).

(x) Enzyme Alpha Amylase consumption rate of 137,007 kg/a (Ref. 12), or 1.3 kg/t of distillate, and an energy requirement of 33 MJ/kg for enzyme alpha amylase (Refs. 17 to 19).

(y) Calcium chloride consumption rate of 90,317 kg/a (Ref. 12), or 0.9 kg/t of distillate, and an energy requirement of 7 MJ/kg for calcium chloride (Ref. 20).

(z) Distillate (94.5% alcohol) requirement 1.058 t/t of bioethanol and allocation of 84.4% to bioethanol.

(aa) Assuming dehydration accounts for 78/4,500 = 1.73% of total electricity consumption (Ref. 12), or 312 MJ/hr.

(bb) Total bioethanol output rate of 12.4 t/hr, based on an annual output rate of 100,000 t/a of bioethanol and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 12).

(cc) Primary energy input of 1,282,500 GJ for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £51.3 m (Ref. 12) and an energy intensity of 25 MJ/£ (Ref. 17), and assuming 84.4% contribution to bioethanol by price of co-products.

(dd) Primary energy input of annual plant maintenance assumed to be 1.5% of primary energy input to plant construction (Ref. 12).

(ee) Average round trip distance of 450 km (Ref. 11) 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. 14).

References

1. "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.

2. Annual average ex-farm price of feed wheat, United Kingdom, 2000/02 from www.hgca.com/c-stats accessed 3 February 2003.

3. Private communication with D. Darby, British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication, based on an assumed derogation of fuel duty of 26 p/l and a delivered market price of 39 p/l for bioethanol, with G. Punter, British Sugar plc. Peterborough, United Kingdom, 28 January 2003.

5. "British Survey of Fertiliser Practice 1999", Fertiliser Manufacturers' Association.

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003.

7. "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

8. "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

9. "Pesticide Use Survey" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. "Farm Management Pocket Handbook" by J. Nix, Wye College, University of London, United Kingdom, 2002.

11. "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.

12. Private communication with A. Nixon, British Sugar plc., Peterborough, United Kingdom, 22 January 2003.

13. "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.

14. "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.

15. "Düngemittel – Energie- und Stoffstrombilanzen" (Fertilisers – Energy and Material Balance) by A. Patyk and G. A. Reinhardt, Vieweg Umweltwissenschaften, Braunschweig/Wiesbaden, Germany, 1997.

16. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

17. "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.

18. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

19. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

20. "Interim Report on Energy-Use in Metallurgical and Non-Metallic Mineral Processing, Phase 5" Battelle Columbus Laboratories, PB-246-357, United States of America, 1975.

Spreadsheet for Carbon Dioxide Outputs from Bioethanol Production from Wheat using a Natural Gas-fired Boiler and Grid Electricity (Model 1)

Functional Unit: :	Bioethanol at point of distribution derived from wheat using a natural gas-fired boiler and grid electricity during processing							
Final Unit of Measurement:	1 tonne of bioethanol							
Relevant Location:	United Kingdom							
Relevant Period:	2002							
Allocation Procedures:	Based on average market prices, assuming 1.394 tonnes of wheat straw at £25/t (Ref. 1) and 3.425 tonnes of harvested wheat grain with 20% moisture content at £69/t (Ref. 2), giving a 87.1% allocation to bioethanol, and 1.141 tonnes of animal feed at £80/t (Ref. 3) and 1.000 tonnes of bioethanol at £494/t (Ref. 4), giving a 84.4% allocation to bioethanol.							
Contribution	Per Unit	Carbon Dioxide Output (kg CO_2)						Notes
		Direct		Indirect		Total		
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	*ha.a*	-	-	*352*	*±51*	*352*	*±51*	(a)
- P Fertiliser	*ha.a*	-	-	*66*	*±10*	*66*	*±10*	(b, c)
- K Fertiliser	*ha.a*	-	-	*25*	*±4*	*25*	*±4*	(c, d)
- Pesticide	*ha.a*	-	-	*10*	*±1*	*10*	*±1*	(c, e)
- Herbicide	*ha.a*	-	-	-	-	-	-	(c, f)
- Insecticide	*ha.a*	-	-	*4*	*±1*	*4*	*±1*	(c, g)
- Fungicide	*ha.a*	-	-	*5*	*±1*	*5*	*±1*	(c, h)
- Seed	*ha.a*	-	-	*66*	*±10*	*66*	*±10*	(c, i)
- Diesel Fuel	*ha.a*	*377*	*±60*	*44*	*±20*	*421*	*±63*	(c, j)
Reference System:								
- Diesel Fuel	*ha.a*	*- 63*	*±10*	*- 7*	*±3*	*- 70*	*±11*	(c, k)
Sub-Totals	*ha.a*	*314*	*±61*	*565*	*±57*	*879*	*±83*	
	t be	**92**	**±18**	**165**	**±17**	**257**	**±25**	(l)
Drying:								
- Diesel Fuel	*t hwg*	*23*	*±4*	*3*	-	*26*	*±4*	(c, m)
	t be	**66**	**±12**	**9**	**-**	**75**	**±12**	(n)
Transport:								
- Diesel Fuel	*t dwg*	*10*	-	*3*	-	*13*	-	(o)
	t be	**27**	**±1**	**8**	**-**	**35**	**±1**	(p)
Milling, Hydrolysis, Fermentation and Distillation:								
- Natural Gas	*t de*	*270*	*±41*	*9*	*±8*	*279*	*±42*	(c,q - s)
- Electricity	*t de*	-	-	*87*	*±13*	*87*	*±13*	(c,q – s)
- Caustic Soda	*t de*	-	-	*47*	*±7*	*47*	*±7*	(c, t)
- Diam. Phosph.	*t de*	-	-	*2*	-	*2*	-	(c, u)
- Sulphuric Acid	*t de*	-	-	*4*	*±4*	*4*	*±4*	(c, v)
- Enzyme AMG	*t de*	-	-	*5*	*±1*	*5*	*±1*	(c, w)
- Enzyme AA	*t de*	-	-	*2*	-	*2*	-	(c, x)
- Calcium Chlor.	*t de*	-	-	*1*	-	*1*	-	(c, y)
Sub-Totals	*t de*	*270*	*±41*	*157*	*±17*	*427*	*±45*	
	t be	**241**	**±37**	**140**	**±15**	**381**	**±40**	(z)
Dehydration:								
- Electricity	**t be**	**-**	**-**	**4**	**±1**	**4**	**±1**	(c, q, aa, bb)
Plant Construction	**t be**	**-**	**-**	**27**	**±4**	**27**	**±4**	(c, cc)
Plant Maintenance	**t be**	**-**	**-**	**8**	**±1**	**8**	**±1**	(c, dd)
Distribution:								
- Diesel Fuel	**t be**	**25**	**±1**	**7**	**±1**	**32**	**±1**	(ee)
Totals	**t be**	**451**	**±43**	**368**	**±23**	**819**	**±49**	

Biofuel Specifications

Density of bioethanol = 0.79 kg/l
Net calorific value of bioethanol = 26.72 MJ/kg
Gross calorific value of bioethanol = 29.74 MJ/kg

Abbreviations

ha.a = hectare year
t hwg = tonne of harvested wheat grain
t dwg = tonne of dried wheat grain
t de = tonne of distillate ethanol (94.5% alcohol)
t be = tonne of bioethanol

Notes

(a) Nitrogen fertiliser application rate of 185 kg N/ha.a (Ref. 5) and a total carbon requirement for ammonium nitrate of 1.904 ± 0.275 kg CO_2/kg N (Ref. 6).

(b) Phosphate fertiliser application rates of 41 kg P/ha.a (Ref. 5), or 93.9 kg P_2O_5/ ha.a assuming 2.290 kg P_2O_5/kg P, and a total carbon requirement for phosphate fertiliser of 0.700 kg CO_2/kg P_2O_5 (Ref. 7).

(c) Assuming an error bar of ±15% based on similar analyses (Ref. 8).

(d) Potash fertiliser application rate of 46 kg K/ha.a (Ref. 5), or 55.4 kg K_2O/ha.a assuming 1.205 kg K_2O/kg K, and a total carbon requirement for potash fertiliser of 0.453 kg CO_2/ kg K_2O (Ref. 7).

(e) Pesticide application rate of 2.0 kg/ha.a (Ref. 9) and a total carbon requirement for general pesticides, herbicides and fungicides of 4.921 kg CO_2/kg (Ref. 7).

(f) Herbicide application rate of 0.1 kg/ha.a (Ref. 9) and a total carbon requirement for general pesticides, herbicides and fungicides of 4.921 kg CO_2/kg (Ref. 7).

(g) Insecticide application rate of 0.8 kg/ha.a (Ref. 9) and a total carbon requirement for general pesticides, herbicides and fungicides of 4.921 kg CO_2/kg (Ref. 7).

(h) Fungicide application rate of 1.0 kg/ha.a (Ref. 9) and a total carbon requirement for general pesticides, herbicides and fungicides of 4.921 kg CO_2/kg (Ref. 7).

(i) Sowing rate of 185 kg/ha.a (Ref. 10) and a total carbon requirement of 0.547 kg CO_2/kg of seed based on a ratio of 0.0405 kg CO_2/MJ for oilseed (Ref. 7).

(j) Diesel fuel consumption of 5,490 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides, insecticides and fungicides, harvesting, carting and loading (Ref. 11) 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. 12).

(k) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 7) 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. 12).

(l) Land requirement of 0.398 ha.a/t of bioethanol and allocation of 87.1% x 84.4% = 73.5% to bioethanol.

(m) Assuming 50% of the harvested wheat grain (1.7125 t/t of bioethanol) dries naturally to a moisture content of 14% and 50% of the harvested wheat grain (1.7125 t/t of bioethanol) requires artificial drying on the farm with a diesel fuel consumption of 677 MJ/t of harvested wheat grain with a moisture content of 19% (Ref. 11), 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. 12).

(n) Harvested wheat grain requirement of 3.425 t/t of bioethanol and allocation of 84.4% to bioethanol.

(o) Average round trip distance of 186 km (Ref. 11) 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. 13).

(p) Dried wheat grain requirement of 3.186 t/t of bioethanol and allocation of 84.4% to bioethanol.

(q) Steam production with a natural gas-fired boiler with an overall efficiency of 80% (Ref. 11) 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. 12), and electricity obtained from the grid with an indirect carbon requirement of 0.150 kg CO_2/MJ in the UK in 1996 (Ref. 12).

(r) Assuming that milling, hydrolysis, fermentation and distillation consumes steam at a rate of 25.0 t/hr (Ref. 11), accounting for 25.0/44.5 = 56.2% of total steam consumption, or 67,753 MJ/hr, and, based on pro rata power ratings, consumes 1.903/4.500 = 42.3% of total electricity consumption (Ref. 11), or 7,612 MJ/hr.

(s) Total distillate (94.5% alcohol) output rate of 13.12 t/hr, based on an annual output rate of 105,800 t/a of distillate, or 100,000 t/a of bioethanol, and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 11).

(t) Caustic soda (49% concentration) consumption rate of 4,427,136 kg/a (Ref. 11), or 41.8 kg/t of distillate, and a total carbon requirement of 1.120 kg CO_2/kg for caustic soda (Ref. 7).

(u) Diammonium phosphate (21% concentration) consumption rate of 2,921,103 kg/a (Ref. 11), or 27.6 kg/t of distillate, and a total carbon requirement of 0.06 kg CO_2/kg for diammonium phosphate (Ref. 14).

(v) Sulphuric acid (93% concentration) consumption rate of 2,911,104 kg/a (Ref. 11), or 27.5 kg/t of distillate, and a total carbon requirement of 0.13 ± 0.16 kg CO_2/ kg for sulphuric acid (Ref. 15).

(w) Enzyme AMG consumption rate of 247,176 kg/a (Ref. 11), or 2.3 kg/t of distillate, and a total carbon requirement of 2.25 kg CO_2/ kg for enzyme AMG (Refs. 16 to 18).

(x) Enzyme Alpha Amylase consumption rate of 137,007 kg/a (Ref. 11), or 1.3 kg/t of distillate, and a total carbon requirement of 1.6 kg CO_2/ kg for enzyme alpha amylase (Refs. 16 to 18).

(y) Calcium chloride consumption rate of 90,317 kg/a (Ref. 11), or 0.9 kg/t of distillate, and a total carbon requirement of 0.6 kg CO_2/ kg for (Ref. 19).

(z) Distillate (94.5% alcohol) requirement 1.058 t/t of bioethanol and allocation of 84.4% to bioethanol.

(aa) Assuming dehydration accounts for 78/4,500 = 1.73% of total electricity consumption (Ref. 12), or 312 MJ/hr.

(bb) Total bioethanol output rate of 12.4 t/hr, based on an annual output rate of 100,000 t/a of bioethanol and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 11).

(cc) Carbon dioxide output of 64,125 tonnes of CO_2 for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £51.3 m (Ref. 11) and a carbon intensity of 1.25 kg CO_2/£ (Ref. 16), and assuming 84.4% contribution to bioethanol by price of co-products.

(dd) Carbon dioxide output of annual plant maintenance assumed to be 1.5% of carbon dioxide output from plant construction (Ref. 11).

(ee) Average round trip distance of 450 km (Ref. 20) 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. 13).

References

1. "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.

2. Annual average ex-farm price of feed wheat, United Kingdom, 2000/02 from www.hgca.com/c-stats accessed 3 February 2003.

3. Private communication with D. Darby, British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication, based on an assumed derogation of fuel duty of 26 p/l and a delivered market price of 39 p/l for bioethanol, with G. Punter, British Sugar plc. Peterborough, United Kingdom, 28 January 2003.

5. "British Survey of Fertiliser Practice 1999", Fertiliser Manufacturers' Association.

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003.

7. "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

8. "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

9. "Pesticide Use Survey" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. "Farm Management Pocket Handbook" by J. Nix, Wye College, University of London, United Kingdom, 2002.

11. Private communication with A. Nixon, British Sugar plc., Peterborough, United Kingdom, 22 January 2003.

12. "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.

13. "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.

14. "Düngemittel – Energie- und Stoffstrombilanzen" (Fertilisers – Energy and Material Balance) by A. Patyk and G. A. Reinhardt, Vieweg Umweltwissenschaften, Braunschweig/Wiesbaden, Germany, 1997.

15. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

16. "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.

17. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

18. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

19. "Interim Report on Energy-Use in Metallurgical and Non-Metallic Mineral Processing, Phase 5" Battelle Columbus Laboratories, PB-246-357, United States of America, 1975.

20. "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.

<u>Spreadsheet for Methane Outputs from Bioethanol Production from Wheat using a Natural Gas-fired Boiler and Grid Electricity</u> (Model 1)

Functional Unit: :	Bioethanol at point of distribution derived from wheat using a natural gas-fired boiler and grid electricity during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on average market prices, assuming 1.394 tonnes of wheat straw at £25/t (Ref. 1) and 3.425 tonnes of harvested wheat grain with 20% moisture content at £69/t (Ref. 2), giving a 87.1% allocation to bioethanol, and 1.141 tonnes of animal feed at £80/t (Ref. 3) and 1.000 tonnes of bioethanol at £494/t (Ref. 4), giving a 84.4% allocation to bioethanol.

Contribution	Per Unit	Methane Output (kg CH_4)						Notes
		Direct		Indirect		Total		
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	*ha.a*	-	-	*0.666*	*±0.111*	*0.666*	*±0.111*	(a)
- P Fertiliser	*ha.a*	-	-	*0.002*	-	*0.002*	-	(b, c)
- K Fertiliser	*ha.a*	-	-	*0.001*	-	*0.001*	-	(c, d)
- Pesticide	*ha.a*	-	-	-	-	-	-	(c, e)
- Herbicide	*ha.a*	-	-	-	-	-	-	(c, f)
- Insecticide	*ha.a*	-	-	-	-	-	-	(c, g)
- Fungicide	*ha.a*	-	-	-	-	-	-	(c, h)
- Seed	*ha.a*	-	-	-	-	-	-	(c, i)
- Diesel Fuel	*ha.a*	*0.003*	-	*0.112*	*±0.017*	*0.115*	*±0.017*	(c, j)
Reference System:								
- Diesel Fuel	*ha.a*	*- 0.001*	-	*- 0.019*		*- 0.020*	*±0.003*	(c, k)
Sub-Totals	*ha.a*	*0.002*	-	*0.762*	*±0.112*	*0.764*	*±0.112*	
	t be	**0.001**	**-**	**0.223**	**±0.033**	**0.224**	**±0.033**	(l)
Drying:								
- Diesel Fuel	*t hwg*	*0.001*	-	*0.007*	*±0.001*	*0.008*	*±0.001*	(c, m)
	t be	**0.003**	**-**	**0.020**	**±0.003**	**0.023**	**±0.003**	(n)
Transport:								
- Diesel Fuel	*t dwg*	-	-	*0.003*	-	*0.003*	-	(o)
	t be		**-**	**0.008**	**-**	**0.008**	**-**	(p)
Milling, Hydrolysis, Fermentation and Distillation:								
- Natural Gas	*t de*	*0.019*	*±0.016*	*0.559*	*±0.085*	*0.578*	*±0.087*	(c,q - s)
- Electricity	*t de*	-	-	*0.235*	*±0.035*	*0.235*	*±0.035*	(c,q - s)
- Caustic Soda	*t de*	-	-	*0.136*	*±0.020*	*0.136*	*±0.020*	(c, t)
- Diam. Phosph.	*t de*	-	-	-	-	-	-	(c, u)
- Sulphuric Acid	*t de*	-	-	*0.007*	*±0.008*	*0.007*	*±0.008*	(c, v)
- Enzyme AMG	*t de*	-	-	-	-	-	-	(c, w)
- Enzyme AA	*t de*	-	-	-	-	-	-	(c, x)
- Calcium Chlor.	*t de*	-	-	-		-	-	(c, y)
Sub-Totals	*t de*	*0.019*	*±0.016*	*0.937*	*±0.094*	*0.956*	*±0.096*	
	t be	**0.017**	**±0.014**	**0.837**	**±0.084**	**0.854**	**±0.086**	(z)
Dehydration: - Electricity	**t be**	**-**	**-**	**0.010**	**±0.002**	**0.010**	**±0.002**	(c, q, aa, bb)
Plant Construction	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(c, cc)
Plant Maintenance	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(c, dd)
Distribution: - Diesel Fuel	**t be**	**-**	**-**	**0.008**	**-**	**0.008**	**-**	(ee)
Totals	**t be**	**0.021**	**±0.014**	**1.106**	**±0.090**	**1.127**	**±0.092**	

<u>Biofuel Specifications</u>

Density of bioethanol = 0.79 kg/l
Net calorific value of bioethanol = 26.72 MJ/kg
Gross calorific value of bioethanol = 29.74 MJ/kg

<u>Abbreviations</u>

ha.a = hectare year
t hwg = tonne of harvested wheat grain
t dwg = tonne of dried wheat grain
t de = tonne of distillate ethanol (94.5% alcohol)
t be = tonne of bioethanol

Notes

(a) Nitrogen fertiliser application rate of 185 N/ha.a (Ref. 5) 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 (Ref. 6).

(b) Phosphate fertiliser application rates of 41 kg P/ha.a (Ref. 5), or 93.9 kg P_2O_5/ ha.a assuming 2.290 kg P_2O_5/kg P, and a total methane requirement for phosphate fertiliser of 2.3×10^{-5} kg CH_4/kg P_2O_5 (Ref. 7).

(c) Assuming an error bar of ±15% based on similar analyses (Ref. 8).

(d) Potash fertiliser application rate of 46 kg K/ha.a (Ref. 5), or 55.4 kg K_2O/ha.a assuming 1.205 kg K_2O/kg K, and a total methane requirement for potash fertiliser of 2.1×10^{-5} kg CH_4/ kg K_2O (Ref. 7).

(e) Pesticide application rate of 2.0 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.8×10^{-4} kg CH_4/kg (Ref. 7).

(f) Herbicide application rate of 0.1 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.8×10^{-4} kg CH_4/kg (Ref. 7).

(g) Insecticide application rate of 0.8 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.8×10^{-4} kg CH_4/kg (Ref. 7).

(h) Fungicide application rate of 1.0 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.8×10^{-4} kg CH_4/kg (Ref. 7).

(i) Sowing rate of 185 kg/ha.a (Ref. 10) and a total methane requirement of 0 kg CH_4/kg of seed, assuming similarity with oilseed (Ref. 7).

(j) Diesel fuel consumption of 5,490 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides, insecticides and fungicides, harvesting, carting and loading (Ref. 11) 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. 12).

(k) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 7) 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. 12).

(l) Land requirement of 0.398 ha.a/t of bioethanol and allocation of 87.1% x 84.4% = 73.5% to bioethanol.

(m) Assuming 50% of the harvested wheat grain (1.7125 t/t of bioethanol) dries naturally to a moisture content of 14% and 50% of the harvested wheat grain (1.7125 t/t of bioethanol) requires artificial drying on the farm with a diesel fuel consumption of 677 MJ/t of harvested wheat grain with a moisture content of 19% (Ref. 11), 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. 12).

(n) Harvested wheat grain requirement of 3.425 t/t of bioethanol and allocation of 84.4% to bioethanol.

(o) Average round trip distance of 186 km (Ref. 11) 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. 13).

(p) Dried wheat grain requirement of 3.186 t/t of bioethanol and allocation of 84.4% to bioethanol.

(q) Steam production with a natural gas-fired boiler with an overall efficiency of 80% (Ref. 11) 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. 12), and electricity obtained from the grid with an indirect methane requirement of 4.043×10^{-4} kg CH_4/MJ for the UK in 1996 (Ref. 12).

(r) Assuming that milling, hydrolysis, fermentation and distillation consumes steam at a rate of 25.0 t/hr (Ref. 11), accounting for 25.0/44.5 = 56.2% of total steam consumption, or 67,753 MJ/hr, and, based on pro rata power ratings, consumes 1.903/4.500 = 42.3% of total electricity consumption (Ref. 11), or 7,612 MJ/hr.

(s) Total distillate (94.5% alcohol) output rate of 13.12 t/hr, based on an annual output rate of 105,800 t/a of distillate, or 100,000 t/a of bioethanol, and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 11).

(t) Caustic soda (49% concentration) consumption rate of 4,427,136 kg/a (Ref. 11), or 41.8 kg/t of distillate, and a total methane requirement of 3.25×10^{-3} kg CH_4/kg for caustic soda (Ref. 7).

(u) Diammonium phosphate (21% concentration) consumption rate of 2,921,103 kg/a (Ref. 11), or 27.6 kg/t of distillate, and a total methane requirement of 2×10^{-6} kg CH_4/kg for diammonium phosphate (Ref. 14).

(v) Sulphuric acid (93% concentration) consumption rate of 2,911,104 kg/a (Ref. 11), or 27.5 kg/t of distillate, and a total methane requirement of 2.7 x 10^{-4} ± 3.0 x 10^{-4} kg CH_4/ kg for sulphuric acid (Ref. 15).

(w) Enzyme AMG consumption rate of 247,176 kg/a (Ref. 11), or 2.3 kg/t of distillate, and a total methane requirement of 6 x 10^{-6} kg CH_4/ kg for enzyme AMG (Refs. 16 to 18).

(x) Enzyme Alpha Amylase consumption rate of 137,007 kg/a (Ref. 11), or 1.3 kg/t of distillate, and a total methane requirement of 4 x 10^{-6} kg CH_4/ kg for enzyme alpha amylase (Refs. 16 to 18).

(y) Calcium chloride consumption rate of 90,317 kg/a (Ref. 11), or 0.9 kg/t of distillate, and a total methane requirement of 2 x 10^{-4} kg CO_2/ kg for (Ref. 19).

(z) Distillate (94.5% alcohol) requirement 1.058 t/t of bioethanol and allocation of 84.4% to bioethanol.

(aa) Assuming dehydration accounts for 78/4,500 = 1.73% of total electricity consumption (Ref. 12), or 312 MJ/hr.

(bb) Total bioethanol output rate of 12.4 t/hr, based on an annual output rate of 100,000 t/a of bioethanol and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 11).

(cc) Primary energy input of 1,282,500 GJ for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £51.3 m (Ref. 11) and an energy intensity of 25 MJ/£ (Ref. 16) , and an estimated total methane requirement of 1.192 x 10^{-7} kg CH_4/MJ primary energy input to construction (Ref. 18), assuming 84.4% contribution to bioethanol by price of co-products.

(dd) Methane output of annual plant maintenance assumed to be 1.5% of methane output from plant construction (Ref. 11).

(ee) Average round trip distance of 450 km (Ref. 20) by bulk road carrier transport with a direct methane requirement of 4.900 x 10^{-7} ± 2.000 x 10^{-8} kg CH_4/t-km, an indirect methane requirement of 1.672 x 10^{-5} ± 6.3 x 10^{-7} kg CH_4/t-km and a total methane requirement of 1.721 x 10^{-5} ± 6.5 x 10^{-7} kg CH_4/t-km (Ref. 13).

References

1. "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.

2. Annual average ex-farm price of feed wheat, United Kingdom, 2000/02 from www.hgca.com/c-stats accessed 3 February 2003.

3. Private communication with D. Darby, British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication, based on an assumed derogation of fuel duty of 26 p/l and a delivered market price of 39 p/l for bioethanol, with G. Punter, British Sugar plc. Peterborough, United Kingdom, 28 January 2003.

5. "British Survey of Fertiliser Practice 1999", Fertiliser Manufacturers' Association.

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003.

7. "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

8. "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

9. "Pesticide Use Survey" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. "Farm Management Pocket Handbook" by J. Nix, Wye College, University of London, United Kingdom, 2002.

11. Private communication with A. Nixon, British Sugar plc., Peterborough, United Kingdom, 22 January 2003.

12. "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.

13. "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.

14. "Düngemittel – Energie- und Stoffstrombilanzen" (Fertilisers – Energy and Material Balance) by A. Patyk and G. A. Reinhardt, Vieweg Umweltwissenschaften, Braunschweig/Wiesbaden, Germany, 1997.

15. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

16. "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.

17. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

18. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

19. "Interim Report on Energy-Use in Metallurgical and Non-Metallic Mineral Processing, Phase 5" Battelle Columbus Laboratories, PB-246-357, United States of America, 1975.

20. "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.

<u>Spreadsheet for Nitrous Oxide Outputs from Bioethanol Production from Wheat using a Natural Gas-fired Boiler and Grid Electricity</u> (Model 1)

Functional Unit: :	Bioethanol at point of distribution derived from wheat using a natural gas-fired boiler and grid electricity during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on average market prices, assuming 1.394 tonnes of wheat straw at £25/t (Ref. 1) and 3.425 tonnes of harvested wheat grain with 20% moisture content at £69/t (Ref. 2), giving a 87.1% allocation to bioethanol, and 1.141 tonnes of animal feed at £80/t (Ref. 3) and 1.000 tonnes of bioethanol at £494/t (Ref. 4), giving a 84.4% allocation to bioethanol.

Contribution	Per Unit	Nitrous Oxide Output (kg N_2O)						Notes
		Direct		Indirect		Total		
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	*ha.a*	*0.666*	*±0.100*	*2.720*	*±0.408*	*3.386*	*±0.420*	(a, b)
- P Fertiliser	*ha.a*	-	-	*0.004*	*±0.001*	*0.004*	*±0.001*	(b, c)
- K Fertiliser	*ha.a*	-	-	*0.001*	-	*0.001*	-	(b, d)
- Pesticide	*ha.a*	-	-	*0.003*	-	*0.003*	-	(b, e)
- Herbicide	*ha.a*	-	-	-	-	-	-	(b, f)
- Insecticide	*ha.a*	-	-	*0.001*	-	*0.001*	-	(b, g)
- Fungicide	*ha.a*	-	-	*0.002*	-	*0.002*	-	(b, h)
- Seed	*ha.a*	-	-	*0.185*	*±0.028*	*0.185*	*±0.028*	(b, i)
- Diesel Fuel	*ha.a*	*0.003*	-	-	-	*0.003*	-	(b, j)
Reference System:								
- Diesel Fuel	*ha.a*	*- 0.001*	-	-		*- 0.001*	-	(b, k)
Sub-Totals	*ha.a*	*0.668*	*±0.100*	*2.916*	*±0.409*	*3.584*	*±0.421*	
	t be	**0.195**	**±0.029**	**0.853**	**±0.120**	**1.048**	**±0.123**	(l)
Drying:								
- Diesel Fuel	*t hwg*	-	-	-	-	-	-	(b, m)
	t be	**-**	**-**	**-**	**-**	**-**	**-**	(n)
Transport:								
- Diesel Fuel	*t dwg*	-	-	-	-	-	-	(o)
	t be	**-**	**-**	**-**	**-**	**-**	**-**	(p)
Milling, Hydrolysis, Fermentation and Distillation:								
- Natural Gas	*t de*	-	-	-	-	-	-	(b,q - s)
- Electricity	*t de*	-	-	*0.003*	-	*0.003*	-	(b,q - s)
- Caustic Soda	*t de*	-	-	-	-	-	-	(b, t)
- Diam. Phosph.	*t de*	-	-	-	-	-	-	(b, u)
- Sulphuric Acid	*t de*	-	-	-	-	-	-	(b, v)
- Enzyme AMG	*t de*	-	-	-	-	-	-	(b, w)
- Enzyme AA	*t de*	-	-	-	-	-	-	(b, x)
- Calcium Chlor.	*t de*	-	-	-	-	-	-	(b, y)
Sub-Totals	*t de*	-	-	*0.003*	-	*0.003*	-	
	t be	**-**	**-**	**0.003**	**-**	**0.003**	**-**	(z)
Dehydration:	*t dwg*	-	-	-	-	-	-	(b, q, aa,
- Electricity	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	bb)
Plant Construction	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(b, cc)
Plant Maintenance	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(b, dd)
Distribution:								
- Diesel Fuel	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(ee)
Totals	**t be**	**0.195**	**±0.029**	**0.856**	**±0.120**	**1.051**	**±0.123**	

<u>Biofuel Specifications</u>

Density of bioethanol = 0.79 kg/l
Net calorific value of bioethanol = 26.72 MJ/kg
Gross calorific value of bioethanol = 29.74 MJ/kg

<u>Abbreviations</u>

ha.a = hectare year
t hwg = tonne of harvested wheat grain
t dwg = tonne of dried wheat grain
t de = tonne of distillate ethanol (94.5% alcohol)
t be = tonne of bioethanol

Notes

(a) Nitrogen fertiliser application rate of 185 N/ha.a (Ref. 5) and a direct nitrous oxide requirement of 0.0036 kg N_2O/kg N (Ref. 5), an indirect nitrous oxide requirement of 0.0147 kg N_2O/kg N (Ref. 6) and a total nitrous oxide requirement for ammonium nitrate of 0.0183 kg N_2O/kg N (Ref. 6).

(b) Assuming an error bar of ±15% based on similar analyses (Ref. 7).

(c) Phosphate fertiliser application rates of 41 kg P/ha.a (Ref. 5), or 93.9 kg P_2O_5/ ha.a assuming 2.290 kg P_2O_5/kg P, and a total nitrous oxide requirement for phosphate fertiliser of 4.2 x 10^{-5} kg N_2O/kg P_2O_5 (Ref. 8).

(d) Potash fertiliser application rate of 46 kg K/ha.a (Ref. 5), or 55.4 kg K_2O/ha.a assuming 1.205 kg K_2O/kg K, and a total nitrous oxide requirement for potash fertiliser of 9.4 x 10^{-6} kg N_2O/ kg K_2O (Ref. 5).

(e) Pesticide application rate of 2.0 kg/ha.a (Ref. 9) and a total nitrous oxide requirement for general pesticides, herbicides and fungicides of 1.51 x 10^{-3} kg N_2O/kg (Ref. 8).

(f) Herbicide application rate of 0.1 kg/ha.a (Ref. 9) and a total nitrous oxide requirement for general pesticides, herbicides and fungicides of 1.51 x 10^{-3} kg N_2O/kg (Ref. 8).

(g) Insecticide application rate of 0.8 kg/ha.a (Ref. 9) and a total nitrous oxide requirement for general pesticides, herbicides and fungicides of 1.51 x 10^{-3} kg N_2O/kg (Ref. 8).

(h) Fungicide application rate of 1.0 kg/ha.a (Ref. 9) and a total nitrous oxide requirement for general pesticides, herbicides and fungicides of 1.51 x 10^{-3} kg N_2O/kg (Ref. 8).

(i) Sowing rate of 185 kg/ha.a (Ref. 10) and a total nitrous oxide requirement of 0.001 kg N_2O/kg of seed assuming similarity with oilseed (Ref. 8).

(j) Diesel fuel consumption of 5,490 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides, insecticides and fungicides, harvesting, carting and loading (Ref. 11) 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. 12).

(k) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 8) 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. 12).

(l) Land requirement of 0.398 ha.a/t of bioethanol and allocation of 87.1% x 84.4% = 73.5% to bioethanol.

(m) Assuming 50% of the harvested wheat grain (1.7125 t/t of bioethanol) dries naturally to a moisture content of 14% and 50% of the harvested wheat grain (1.7125 t/t of bioethanol) requires artificial drying on the farm with a diesel fuel consumption of 677 MJ/t of harvested wheat grain with a moisture content of 19% (Ref. 11), 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. 12).

(n) Harvested wheat grain requirement of 3.425 t/t of bioethanol and allocation of 84.4% to bioethanol.

(o) Average round trip distance of 186 km (Ref. 11) 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. 13).

(p) Dried wheat grain requirement of 3.186 t/t of bioethanol and allocation of 84.4% to bioethanol.

(q) Steam production with a natural gas-fired boiler with an overall efficiency of 80% (Ref. 11) 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. 12), and electricity obtained from the grid with an indirect nitrous oxide requirement of 5.577 x 10^{-6} kg N_2O/MJ for the UK in 1996 (Ref. 13).

(r) Assuming that milling, hydrolysis, fermentation and distillation consumes steam at a rate of 25.0 t/hr (Ref. 11), accounting for 25.0/44.5 = 56.2% of total steam consumption, or 67,753 MJ/hr, and, based on pro rata power ratings, consumes 1.903/4.500 = 42.3% of total electricity consumption (Ref. 11), or 7,612 MJ/hr.

(s) Total distillate (94.5% alcohol) output rate of 13.12 t/hr, based on an annual output rate of 105,800 t/a of distillate, or 100,000 t/a of bioethanol, and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 11).

(t) Caustic soda (49% concentration) consumption rate of 4,427,136 kg/a (Ref. 11), or 41.8 kg/t of distillate, and a total nitrous oxide requirement of 0 kg CH_4/kg for caustic soda (Ref. 7).

(u) Diammonium phosphate (21% concentration) consumption rate of 2,921,103 kg/a (Ref. 11), or 27.6 kg/t of distillate, and a total nitrous oxide requirement of 2 x 10^{-6} kg CH_4/kg for diammonium phosphate (Ref. 14).

(v) Sulphuric acid (93% concentration) consumption rate of 2,911,104 kg/a (Ref. 11), or 27.5 kg/t of distillate, and a total nitrous oxide requirement of 2 x 10^{-7} ± 3 x 10^{-7} kg CH_4/ kg for sulphuric acid (Ref. 15).

(w) Enzyme AMG consumption rate of 247,176 kg/a (Ref. 11), or 2.3 kg/t of distillate, and a total nitrous oxide requirement of 9 x 10^{-8} kg CH_4/ kg for enzyme AMG (Refs. 16 to 18).

(x) Enzyme Alpha Amylase consumption rate of 137,007 kg/a (Ref. 11), or 1.3 kg/t of distillate, and a total nitrous oxide requirement of 6 x 10^{-8} kg CH_4/ kg for enzyme alpha amylase (Refs. 16 to 18).

(y) Calcium chloride consumption rate of 90,317 kg/a (Ref. 11), or 0.9 kg/t of distillate, and a total nitrous oxide requirement of 4 x 10^{-7} kg CO_2/ kg for (Ref. 19).

(z) Distillate (94.5% alcohol) requirement 1.058 t/t of bioethanol and allocation of 84.4% to bioethanol.

(aa) Assuming dehydration accounts for 78/4,500 = 1.73% of total electricity consumption (Ref. 12), or 312 MJ/hr.

(bb) Total bioethanol output rate of 12.4 t/hr, based on an annual output rate of 100,000 t/a of bioethanol and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 11).

(cc) Primary energy input of 1,282,500 GJ for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £51.3 m (Ref. 11) and an energy intensity of 25 MJ/£ (Ref. 16) , and an estimated total nitrous oxide requirement of 1.866 x 10^{-9} kg N_2O/MJ of primary energy input to construction (Ref. 18), assuming 84.4% contribution to bioethanol by price of co-products.

(dd) Nitrous oxide output of annual plant maintenance assumed to be 1.5% of nitrous oxide output from plant construction (Ref. 11).

(ee) Average round trip distance of 450 km (Ref. 20) 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. 13).

References

1. "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.

2. Annual average ex-farm price of feed wheat, United Kingdom, 2000/02 from www.hgca.com/c-stats accessed 3 February 2003.

3. Private communication with D. Darby, British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication, based on an assumed derogation of fuel duty of 26 p/l and a delivered market price of 39 p/l for bioethanol, with G. Punter, British Sugar plc. Peterborough, United Kingdom, 28 January 2003.

5. "British Survey of Fertiliser Practice 1999", Fertiliser Manufacturers' Association.

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003.

7. "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

8. "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

9. "Pesticide Use Survey" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. "Farm Management Pocket Handbook" by J. Nix, Wye College, University of London, United Kingdom, 2002.

11. Private communication with A. Nixon, British Sugar plc., Peterborough, United Kingdom, 22 January 2003.

12. "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.

13. "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.

14. "Düngemittel – Energie- und Stoffstrombilanzen" (Fertilisers – Energy and Material Balance) by A. Patyk and G. A. Reinhardt, Vieweg Umweltwissenschaften, Braunschweig/Wiesbaden, Germany, 1997.

15. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

16. "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.

17. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

18. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

19. "Interim Report on Energy-Use in Metallurgical and Non-Metallic Mineral Processing, Phase 5" Battelle Columbus Laboratories, PB-246-357, United States of America, 1975.

20. "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.

<u>Spreadsheet for Greenhouse Gas Outputs from Bioethanol Production from Wheat using a Natural Gas-fired Boiler and Grid Electricity</u> (Model 1)

Functional Unit: :	Bioethanol at point of distribution derived from wheat using a natural gas-fired boiler and grid electricity during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on average market prices, assuming 1.394 tonnes of wheat straw at £25/t (Ref. 1) and 3.425 tonnes of harvested wheat grain with 20% moisture content at £69/t (Ref. 2), giving a 87.1% allocation to bioethanol, and 1.141 tonnes of animal feed at £80/t (Ref. 3) and 1.000 tonnes of bioethanol at £494/t (Ref. 4), giving a 84.4% allocation to bioethanol.

Contribution	Per Unit	Total Greenhouse Gas Output (kg eq CO_2)						Notes
		Direct		Indirect		Total		
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	*ha.a*	*213*	*±32*	*1,239*	*±140*	*1,452*	*±144*	(a)
- P Fertiliser	*ha.a*	-	-	*67*	*±10*	*67*	*±10*	(a)
- K Fertiliser	*ha.a*	-	-	*25*	*±4*	*25*	*±4*	(a)
- Pesticide	*ha.a*	-	-	*11*	*±1*	*11*	*±1*	(a)
- Herbicide	*ha.a*	-	-	-	-	-	-	(a)
- Insecticide	*ha.a*	-	-	*4*	*±1*	*4*	*±1*	(a)
- Fungicide	*ha.a*	-	-	*6*	*±1*	*6*	*±1*	(a)
- Seed	*ha.a*	-	-	*125*	*±13*	*125*	*±13*	(a)
- Diesel Fuel	*ha.a*	*378*	*±60*	*47*	*±20*	*425*	*±63*	(a)
Reference System:								
- Diesel Fuel	*ha.a*	*- 63*	*±10*	*- 7*	*±3*	*- 70*	*±11*	(a)
Sub-Totals	*ha.a*	*528*	*±68*	*1,517*	*±142*	*2,045*	*±158*	
	t be	**154**	**±20**	**444**	**±42**	**598**	**±46**	(b)
Drying:								
- Diesel Fuel	*t hwg*	*23*	*±4*	*3*	-	*26*	*±4*	(a)
	t be	**66**	**±12**	**9**	**-**	**75**	**±12**	(c)
Transport:								
- Diesel Fuel	*t dwg*	*10*	-	*3*	-	*13*	-	(a)
	t be	**27**	**±1**	**8**	**-**	**35**	**±1**	(d)
Milling, Hydrolysis, Fermentation and Distillation:								
- Natural Gas	*t de*	*270*	*±41*	*23*	*±8*	*293*	*±42*	(a)
- Electricity	*t de*	-	-	*94*	*±13*	*94*	*±13*	(a)
- Caustic Soda	*t de*	-	-	*50*	*±7*	*50*	*±7*	(a)
- Diam. Phosph.	*t de*	-	-	*2*	-	*2*	-	(a)
- Sulphuric Acid	*t de*	-	-	*4*	*±4*	*4*	*±4*	(a)
- Enzyme AMG	*t de*	-	-	*5*	*±1*	*5*	*±1*	(a)
- Enzyme AA	*t de*	-	-	*2*	-	*2*	-	(a)
- Calcium Chlor.	*t de*	-	-	*1*	-	*1*	-	(a)
Sub-Totals	*t de*	*270*	*±41*	*181*	*±17*	*451*	*±45*	
	t be	**241**	**±37**	**162**	**±15**	**403**	**±40**	(e)
Dehydration:								(a)
- Electricity	**t be**	**-**	**-**	**4**	**±1**	**4**	**±1**	
Plant Construction	**t be**	**-**	**-**	**27**	**±4**	**27**	**±4**	(a)
Plant Maintenance	**t be**	**-**	**-**	**8**	**±1**	**8**	**±1**	(a)
Distribution:								
- Diesel Fuel	**t be**	**25**	**±1**	**7**	**±1**	**32**	**±1**	(ee)
Totals	**t be**	**513**	**±44**	**669**	**±45**	**1,182**	**±62**	

<u>Biofuel Specifications</u>

Density of bioethanol = 0.79 kg/l
Net calorific value of bioethanol = 26.72 MJ/kg
Gross calorific value of bioethanol = 29.74 MJ/kg

<u>Abbreviations</u>

ha.a = hectare year
t hwg = tonne of harvested wheat grain
t dwg = tonne of dried wheat grain
t de = tonne of distillate ethanol (94.5% alcohol)
t be = tonne of bioethanol

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 0.398 ha.a/t of bioethanol and allocation of 87.1% x 84.4% = 73.5% to bioethanol.

(c) Harvested wheat grain requirement of 3.425 t/t of bioethanol and allocation of 84.4% to bioethanol.

(d) Dried wheat grain requirement of 3.186 t/t of bioethanol and allocation of 84.4% to bioethanol.

(e) Distillate (94.5% alcohol) requirement 1.058 t/t of bioethanol and allocation of 84.4% to bioethanol.

References

1. "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.

2. Annual average ex-farm price of feed wheat, United Kingdom, 2000/02 from www.hgca.com/c-stats accessed 3 February 2003.

3. Private communication with D. Darby, British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication, based on an assumed derogation of fuel duty of 26 p/l and a delivered market price of 39 p/l for bioethanol, with G. Punter, British Sugar plc. Peterborough, United Kingdom, 28 January 2003.

APPENDIX B: Model 3

Spreadsheet for Primary Energy Inputs to Bioethanol Production from Wheat using a Natural Gas-fired Combined Heat and Power Plant with a Steam Turbine (Model 3)

Functional Unit:	Bioethanol at point of distribution derived from wheat using natural gas-fired combined heat and power generation with a steam turbine during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on average market prices, assuming 1.394 tonnes of wheat straw at £25/t (Ref. 1) and 3.425 tonnes of harvested wheat grain with 20% moisture content at £69/t (Ref. 2), giving a 87.1% allocation to bioethanol, and 1.141 tonnes of animal feed at £80/t (Ref. 3) and 1.000 tonnes of bioethanol at £494/t (Ref. 4), giving a 84.4% allocation to bioethanol.

Contribution	Per Unit	Primary Energy Input (MJ)								Notes
		Direct		Indirect		Feedstock		Total		
		Value	Range	Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:										
- N Fertiliser	*ha.a*	-	-	*2,592*	*±1,036*	*4,920*	*±196*	*7,512*	*±1,054*	(a)
- P Fertiliser	*ha.a*	-	-	*1,484*	*±223*	-	-	*1,484*	*±223*	(b, c)
- K Fertiliser	*ha.a*	-	-	*515*	*±77*	-	-	*515*	*±77*	(c, d)
- Pesticide	*ha.a*	-	-	*548*	*±82*	-	-	*548*	*±82*	(c, e)
- Herbicide	*ha.a*	-	-	*27*	*±4*	-	-	*27*	*±4*	(c, f)
- Insecticide	*ha.a*	-	-	*219*	*±33*	-	-	*219*	*±33*	(c, g)
- Fungicide	*ha.a*	-	-	*274*	*±41*	-	-	*274*	*±41*	(c, h)
- Seed	*ha.a*	-	-	*2,498*	*±375*	-	-	*2,498*	*±375*	(c, i)
- Diesel Fuel	*ha.a*	*5,490*	*±868*	*604*	*±288*	-	-	*6,094*	*±914*	(c, j)
Reference System:										
- Diesel Fuel	*ha.a*	*- 922*	*±146*	*- 101*	*±48*	-	-	*-1,023*	*±154*	(c, k)
Sub-Totals	*ha.a*	*4,568*	*±880*	*8,660*	*±1,168*	*4,920*	*±196*	*18,148*	*±1,477*	
	t be	**1,336**	**±257**	**2,534**	**±342**	**1,439**	**±57**	**5,309**	**±432**	(l)
Drying:										
- Diesel Fuel	*t hwg*	*338*	*±53*	*37*	*±18*	-	-	*375*	*±56*	(c, m)
	t be	**977**	**±153**	**107**	**±52**	**-**	**-**	**1,084**	**±162**	(n)
Transport:										
- Diesel Fuel	*t dwg*	*152*	*±6*	*53*	*±7*	-	-	*205*	*±9*	(o)
	t be	**409**	**±16**	**143**	**±19**	**-**	**-**	**552**	**±25**	(p)
Milling, Hydrolysis, Fermentation and Distillation:										
- Natural Gas	*t de*	*6,836*	*±1,080*	*752*	*±358*	-	-	*7,588*	*±1,138*	(c, q - s)
- Caustic Soda	*t de*	-	-	*836*	*±125*	-	-	*836*	*±125*	(c, t)
- Diam. Phosph.	*t de*	-	-	*55*	*±8*	-	-	*55*	*±8*	(c, u)
- Sulphuric Acid	*t de*	-	-	*66*	*±74*	-	-	*66*	*±74*	(c, v)
- Enzyme AMG	*t de*	-	-	*110*	*±16*	-	-	*110*	*±16*	(c, w)
- Enzyme AA	*t de*	-	-	*43*	*±6*	-	-	*43*	*±6*	(c, x)
- Calcium Chlor.	*t de*	-	-	*6*	*±1*	-	-	*6*	*±1*	(c, y)
Sub-Totals	*t de*	*6,836*	*±1,080*	*1,868*	*±387*	-	-	*8,704*	*±1,147*	
	t be	**6,104**	**±964**	**1,668**	**±346**	**-**	**-**	**7,772**	**±1,024**	(z)
Dehydration: - Natural Gas	**t be**	**30**	**±5**	**3**	**±2**	**-**	**-**	**33**	**±5**	(c, q, aa, bb)
Plant Construction	**t be**	**-**	**-**	**541**	**±81**	**-**	**-**	**541**	**±81**	(c, cc)
Plant Maintenance	**t be**	**-**	**-**	**162**	**±24**	**-**	**-**	**162**	**±24**	(c, dd)
Distribution: - Diesel Fuel	**t be**	**369**	**±14**	**129**	**±16**	**-**	**-**	**498**	**±21**	(ee)
Totals	**t be**	**9,225**	**±1,010**	**5,287**	**±497**	**1,439**	**±57**	**15,951**	**±1,127**	

Biofuel Specifications

Density of bioethanol = 0.79 kg/l
Net calorific value of bioethanol = 26.72 MJ/kg
Gross calorific value of bioethanol = 29.74 MJ/kg

Abbreviations

ha.a = hectare year
t hwg = tonne of harvested wheat grain
t dwg = tonne of dried wheat grain
t de = tonne of distillate ethanol (94.5% alcohol)
t be = tonne of bioethanol

Notes

(a) Nitrogen fertiliser application rate of 185 kg N/ha.a (Ref. 5) 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 nitrogen fertiliser (Ref. 6).

(b) Phosphate fertiliser application rates of 41 kg P/ha.a (Ref. 5), or 93.9 kg P_2O_5/ ha.a assuming 2.290 kg P_2O_5/kg P, and a total energy requirement for phosphate fertiliser of 15.8 MJ/kg P_2O_5 (Ref. 7).

(c) Assuming an error bar of ±15% based on similar analyses (Ref. 8).

(d) Potash fertiliser application rate of 46 kg K/ha.a (Ref. 5), or 55.4 kg K_2O/ha.a assuming 1.205 kg K_2O/kg K, and a total energy requirement for potash fertiliser of 9.3 MJ/ kg K_2O (Ref. 7).

(e) Pesticide application rate of 2.0 kg/ha.a (Ref. 9) and a total energy requirement for general pesticides, herbicides and fungicides of 274.1 MJ/kg (Ref. 7).

(f) Herbicide application rate of 0.1 kg/ha.a (Ref. 9) and a total energy requirement for general pesticides, herbicides and fungicides of 274.1 MJ/kg (Ref. 7).

(g) Insecticide application rate of 0.8 kg/ha.a (Ref. 9) and a total energy requirement for general pesticides, herbicides and fungicides of 274.1 MJ/kg (Ref. 7).

(h) Fungicide application rate of 1.0 kg/ha.a (Ref. 9) and a total energy requirement for general pesticides, herbicides and fungicides of 274.1 MJ/kg (Ref. 7).

(i) Sowing rate of 185 kg/ha.a (Ref. 10) and a total energy requirement of 13.5 MJ/kg of seed (Ref. 11).

(j) Diesel fuel consumption of 5,490 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides, insecticides and fungicides, harvesting, carting and loading (Ref. 12) and a gross energy requirement of 1.110 MJ/MJ for diesel fuel in the UK in 1996 (Ref. 13).

(k) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 7) and a gross energy requirement of 1.110 MJ/MJ for diesel fuel in the UK in 1996 (Ref. 13).

(l) Land requirement of 0.398 ha.a/t of bioethanol and allocation of 87.1% x 84.4% = 73.5% to bioethanol.

(m) Assuming 50% of the harvested wheat grain (1.7125 t/t of bioethanol) dries naturally to a moisture content of 14% and 50% of the harvested wheat grain (1.7125 t/t of bioethanol) requires artificial drying on the farm with a diesel fuel consumption of 677 MJ/t of harvested wheat grain with a moisture content of 19% (Ref. 12), and a gross energy requirement of 1.110 MJ/MJ for diesel fuel in the UK in 1996 (Ref. 13).

(n) Harvested wheat grain requirement of 3.425 t/t of bioethanol and allocation of 84.4% to bioethanol.

(o) Average round trip distance of 186 km (Ref. 12) 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. 14).

(p) Dried wheat grain requirement of 3.186 t/t of bioethanol and allocation of 84.4% to bioethanol.

(q) Natural gas-fired combined heat and power plant with an overall efficiency of 84% producing 0.109 MJ of electricity and 0.731 MJ of steam from each MJ of natural gas (Ref. 12), giving a natural gas consumption rate of 1.190 MJ/MJ of energy output in the form of electricity or steam, and a gross energy requirement of 1.110 MJ/MJ for natural gas in the UK in 1996 (Ref. 13).

(r) Assuming that milling, hydrolysis, fermentation and distillation consumes steam at a rate of 25.0 t/hr (Ref. 12), accounting for 25.0/44.5 = 56.2% of total steam consumption, or 67,753 MJ/hr, and, based on pro rata power ratings, consumes 1.903/4.500 = 42.3% of total electricity consumption (Ref. 12), or 7,612 MJ/hr, equivalent to (67,753 = 7,612) x 1.190 = 89,684 MJ/hr of natural gas consumption in the combined heat and power plant.

(s) Total distillate (94.5% alcohol) output rate of 13.12 t/hr, based on an annual output rate of 105,800 t/a of distillate, or 100,000 t/a of bioethanol, and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 12).

(t) Caustic soda (49% concentration) consumption rate of 4,427,136 kg/a (Ref. 12), or 41.8 kg/t of distillate, and an energy requirement of 20 MJ/kg for caustic soda (Ref. 7).

(u) Diammonium phosphate (21% concentration) consumption rate of 2,921,103 kg/a (Ref. 12), or 27.6 kg/t of distillate, and an energy requirement of 2 MJ/kg for diammonium phosphate (Ref. 15).

(v) Sulphuric acid (93% concentration) consumption rate of 2,911,104 kg/a (Ref. 12), or 27.5 kg/t of distillate, and an energy requirement of 2.4 ± 2.7 MJ/kg for sulphuric acid (Ref. 16).

(w) Enzyme AMG consumption rate of 247,176 kg/a (Ref. 12), or 2.3 kg/t of distillate, and an energy requirement of 47 MJ/kg for enzyme AMG (Refs. 17 to 19).

(x) Enzyme Alpha Amylase consumption rate of 137,007 kg/a (Ref. 12), or 1.3 kg/t of distillate, and an energy requirement of 33 MJ/kg for enzyme alpha amylase (Refs. 17 to 19).

(y) Calcium chloride consumption rate of 90,317 kg/a (Ref. 12), or 0.9 kg/t of distillate, and an energy requirement of 7 MJ/kg for calcium chloride (Ref. 20).

(z) Distillate (94.5% alcohol) requirement 1.058 t/t of bioethanol and allocation of 84.4% to bioethanol.

(aa) Assuming dehydration accounts for 78/4,500 = 1.73% of total electricity consumption (Ref. 12), or 312 MJ/hr, equivalent to 312 x 1.190 = 371 MJ/hr of natural gas consumption in the combined heat and power plant.

(bb) Total bioethanol output rate of 12.4 t/hr, based on an annual output rate of 100,000 t/a of bioethanol and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 12).

(cc) Primary energy input of 1,282,500 GJ for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £51.3 m (Ref. 12) and an energy intensity of 25 MJ/£ (Ref. 17), and assuming 84.4% contribution to bioethanol by price of co-products.

(dd) Primary energy input of annual plant maintenance assumed to be 1.5% of primary energy input to plant construction (Ref. 12).

(ee) Average round trip distance of 450 km (Ref. 11) 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. 14).

References

1. "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.

2. Annual average ex-farm price of feed wheat, United Kingdom, 2000/02 from www.hgca.com/c-stats accessed 3 February 2003.

3. Private communication with D. Darby, British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication, based on an assumed derogation of fuel duty of 26 p/l and a delivered market price of 39 p/l for bioethanol, with G. Punter, British Sugar plc. Peterborough, United Kingdom, 28 January 2003.

5. "British Survey of Fertiliser Practice 1999", Fertiliser Manufacturers' Association.

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003.

7. "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

8. "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

9. "Pesticide Use Survey" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. "Farm Management Pocket Handbook" by J. Nix, Wye College, University of London, United Kingdom, 2002.

11. "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.

12. Private communication with A. Nixon, British Sugar plc., Peterborough, United Kingdom, 22 January 2003.

13. "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.

14. "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.

15. "Düngemittel – Energie- und Stoffstrombilanzen" (Fertilisers – Energy and Material Balance) by A. Patyk and G. A. Reinhardt, Vieweg Umweltwissenschaften, Braunschweig/Wiesbaden, Germany, 1997.

16. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

17. "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.

18. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

19. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

20. "Interim Report on Energy-Use in Metallurgical and Non-Metallic Mineral Processing, Phase 5" Battelle Columbus Laboratories, PB-246-357, United States of America, 1975.

Spreadsheet for Carbon Dioxide Outputs from Bioethanol Production from Wheat using a Natural Gas-fired Combined Heat and Power Plant with a Steam Turbine (Model 3)

Functional Unit: :	Bioethanol at point of distribution derived from wheat using natural gas-fired combined heat and power generation with a steam turbine during processing							
Final Unit of Measurement:	1 tonne of bioethanol							
Relevant Location:	United Kingdom							
Relevant Period:	2002							
Allocation Procedures:	Based on average market prices, assuming 1.394 tonnes of wheat straw at £25/t (Ref. 1) and 3.425 tonnes of harvested wheat grain with 20% moisture content at £69/t (Ref. 2), giving a 87.1% allocation to bioethanol, and 1.141 tonnes of animal feed at £80/t (Ref. 3) and 1.000 tonnes of bioethanol at £494/t (Ref. 4), giving a 84.4% allocation to bioethanol.							
Contribution	Per Unit	Carbon Dioxide Output (kg CO_2)						
		Direct		Indirect		Total		Notes
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	*ha.a*	-	-	*352*	*±51*	*352*	*±51*	(a)
- P Fertiliser	*ha.a*	-	-	*66*	*±10*	*66*	*±10*	(b, c)
- K Fertiliser	*ha.a*	-	-	*25*	*±4*	*25*	*±4*	(c, d)
- Pesticide	*ha.a*	-	-	*10*	*±1*	*10*	*±1*	(c, e)
- Herbicide	*ha.a*	-	-	-	-	-	-	(c, f)
- Insecticide	*ha.a*	-	-	*4*	*±1*	*4*	*±1*	(c, g)
- Fungicide	*ha.a*	-	-	*5*	*±1*	*5*	*±1*	(c, h)
- Seed	*ha.a*	-	-	*66*	*±10*	*66*	*±10*	(c, i)
- Diesel Fuel	*ha.a*	*377*	*±60*	*44*	*±20*	*421*	*±63*	(c, j)
Reference System:								
- Diesel Fuel	*ha.a*	*- 63*	*±10*	*- 7*	*±3*	*- 70*	*±11*	(c, k)
Sub-Totals	*ha.a*	*314*	*±61*	*565*	*±57*	*879*	*±83*	
	t be	**92**	**±18**	**165**	**±17**	**257**	**±25**	(l)
Drying:								
- Diesel Fuel	*t hwg*	*23*	*±4*	*3*	-	*26*	*±4*	(c, m)
	t be	**66**	**±12**	**9**	**-**	**75**	**±12**	(n)
Transport:								
- Diesel Fuel	*t dwg*	*10*	-	*3*	-	*13*	-	(o)
	t be	**27**	**±1**	**8**	**-**	**35**	**±1**	(p)
Milling, Hydrolysis, Fermentation and Distillation:								
- Natural Gas	*t de*	*357*	*±54*	*12*	*±10*	*369*	*±55*	(c,q - s)
- Caustic Soda	*t de*	-	-	*47*	*±7*	*47*	*±7*	(c, t)
- Diam. Phosph.	*t de*	-	-	*2*	-	*2*	-	(c, u)
- Sulphuric Acid	*t de*	-	-	*4*	*±4*	*4*	*±4*	(c, v)
- Enzyme AMG	*t de*	-	-	*5*	*±1*	*5*	*±1*	(c, w)
- Enzyme AA	*t de*	-	-	*2*	-	*2*	-	(c, x)
- Calcium Chlor.	*t de*	-	-	*1*	-	*1*	-	(c, y)
Sub-Totals	*t de*	*357*	*±54*	*73*	*±13*	*430*	*±56*	
	t be	**319**	**±48**	**65**	**±12**	**384**	**±50**	(z)
Dehydration: - Natural Gas	**t be**	**2**	**-**	**-**	**-**	**2**	**-**	(c, q, aa, bb)
Plant Construction	**t be**	**-**	**-**	**27**	**±4**	**27**	**±4**	(c, cc)
Plant Maintenance	**t be**	**-**	**-**	**8**	**±1**	**8**	**±1**	(c, dd)
Distribution: - Diesel Fuel	**t be**	**25**	**±1**	**7**	**±1**	**32**	**±1**	(ee)
Totals	**t be**	**531**	**±53**	**289**	**±21**	**820**	**±57**	

Biofuel Specifications

Density of bioethanol = 0.79 kg/l
Net calorific value of bioethanol = 26.72 MJ/kg
Gross calorific value of bioethanol = 29.74 MJ/kg

Abbreviations

ha.a = hectare year
t hwg = tonne of harvested wheat grain
t dwg = tonne of dried wheat grain
t de = tonne of distillate ethanol (94.5% alcohol)
t be = tonne of bioethanol

Notes

(a) Nitrogen fertiliser application rate of 185 kg N/ha.a (Ref. 5) and a total carbon requirement for ammonium nitrate of 1.904 ± 0.275 kg CO_2/kg N (Ref. 6).

(b) Phosphate fertiliser application rates of 41 kg P/ha.a (Ref. 5), or 93.9 kg P_2O_5/ ha.a assuming 2.290 kg P_2O_5/kg P, and a total carbon requirement for phosphate fertiliser of 0.700 kg CO_2/kg P_2O_5 (Ref. 7).

(c) Assuming an error bar of ±15% based on similar analyses (Ref. 8).

(d) Potash fertiliser application rate of 46 kg K/ha.a (Ref. 5), or 55.4 kg K_2O/ha.a assuming 1.205 kg K_2O/kg K, and a total carbon requirement for potash fertiliser of 0.453 kg CO_2/ kg K_2O (Ref. 7).

(e) Pesticide application rate of 2.0 kg/ha.a (Ref. 9) and a total carbon requirement for general pesticides, herbicides and fungicides of 4.921 kg CO_2/kg (Ref. 7).

(f) Herbicide application rate of 0.1 kg/ha.a (Ref. 9) and a total carbon requirement for general pesticides, herbicides and fungicides of 4.921 kg CO_2/kg (Ref. 7).

(g) Insecticide application rate of 0.8 kg/ha.a (Ref. 9) and a total carbon requirement for general pesticides, herbicides and fungicides of 4.921 kg CO_2/kg (Ref. 7).

(h) Fungicide application rate of 1.0 kg/ha.a (Ref. 9) and a total carbon requirement for general pesticides, herbicides and fungicides of 4.921 kg CO_2/kg (Ref. 7).

(i) Sowing rate of 185 kg/ha.a (Ref. 10) and a total carbon requirement of 0.547 kg CO_2/kg of seed based on a ratio of 0.0405 kg CO_2/MJ for oilseed (Ref. 7).

(j) Diesel fuel consumption of 5,490 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides, insecticides and fungicides, harvesting, carting and loading (Ref. 11) 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. 12).

(k) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 7) 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. 12).

(l) Land requirement of 0.398 ha.a/t of bioethanol and allocation of 87.1% x 84.4% = 73.5% to bioethanol.

(m) Assuming 50% of the harvested wheat grain (1.7125 t/t of bioethanol) dries naturally to a moisture content of 14% and 50% of the harvested wheat grain (1.7125 t/t of bioethanol) requires artificial drying on the farm with a diesel fuel consumption of 677 MJ/t of harvested wheat grain with a moisture content of 19% (Ref. 11), 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. 12).

(n) Harvested wheat grain requirement of 3.425 t/t of bioethanol and allocation of 84.4% to bioethanol.

(o) Average round trip distance of 186 km (Ref. 11) 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. 13).

(p) Dried wheat grain requirement of 3.186 t/t of bioethanol and allocation of 84.4% to bioethanol.

(q) Natural gas-fired combined heat and power plant with an overall efficiency of 84% producing 0.109 MJ of electricity and 0.731 MJ of steam from each MJ of natural gas (Ref. 11), giving a natural gas consumption rate of 1.190 MJ/MJ of energy output in the form of electricity or 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. 12).

(r) Assuming that milling, hydrolysis, fermentation and distillation consumes steam at a rate of 25.0 t/hr (Ref. 11), accounting for 25.0/44.5 = 56.2% of total steam consumption, or 67,753 MJ/hr, and, based pro rata on power ratings, consumes 1.903/4.500 = 42.3% of total electricity consumption (Ref. 11), or 7,612 MJ/hr, equivalent to (67,753 = 7,612) x 1.190 = 89,684 MJ/hr of natural gas consumption in the combined heat and power plant.

(s) Total distillate (94.5% alcohol) output rate of 13.12 t/hr, based on an annual output rate of 105,800 t/a of distillate, or 100,000 t/a of bioethanol, and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 11).

(t) Caustic soda (49% concentration) consumption rate of 4,427,136 kg/a (Ref. 11), or 41.8 kg/t of distillate, and a total carbon requirement of 1.120 kg CO_2/kg for caustic soda (Ref. 7).

(u) Diammonium phosphate (21% concentration) consumption rate of 2,921,103 kg/a (Ref. 11), or 27.6 kg/t of distillate, and a total carbon requirement of 0.06 kg CO_2/kg for diammonium phosphate (Ref. 14).

(v) Sulphuric acid (93% concentration) consumption rate of 2,911,104 kg/a (Ref. 11), or 27.5 kg/t of distillate, and a total carbon requirement of 0.13 ± 0.16 kg CO_2/kg for sulphuric acid (Ref. 15).

(w) Enzyme AMG consumption rate of 247,176 kg/a (Ref. 11), or 2.3 kg/t of distillate, and a total carbon requirement of 2.25 kg CO_2/kg for enzyme AMG (Refs. 16 to 18).

(x) Enzyme Alpha Amylase consumption rate of 137,007 kg/a (Ref. 11), or 1.3 kg/t of distillate, and a total carbon requirement of 1.6 kg CO_2/ kg for enzyme alpha amylase (Refs. 16 to 18).

(y) Calcium chloride consumption rate of 90,317 kg/a (Ref. 11), or 0.9 kg/t of distillate, and a total carbon requirement of 0.6 kg CO_2/kg for (Ref. 19).

(z) Distillate (94.5% alcohol) requirement 1.058 t/t of bioethanol and allocation of 84.4% to bioethanol.

(aa) Assuming dehydration accounts for 78/4,500 = 1.73% of total electricity consumption (Ref. 11), or 312 MJ/hr, equivalent to 312 x 1.190 = 371 MJ/hr of natural gas consumption in the combined heat and power plant.

(bb) Total bioethanol output rate of 12.4 t/hr, based on an annual output rate of 100,000 t/a of bioethanol and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 11).

(cc) Carbon dioxide output of 64,125 tonnes of CO_2 for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £51.3 m (Ref. 11) and a carbon intensity of 1.25 kg CO_2/£ (Ref. 16), and assuming 84.4% contribution to bioethanol by price of co-products.

(dd) Carbon dioxide output of annual plant maintenance assumed to be 1.5% of carbon dioxide output from plant construction (Ref. 11).

(ee) Average round trip distance of 450 km (Ref. 20) 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. 13).

References

1. "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.

2. Annual average ex-farm price of feed wheat, United Kingdom, 2000/02 from www.hgca.com/c-stats accessed 3 February 2003.

3. Private communication with D. Darby, British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication, based on an assumed derogation of fuel duty of 26 p/l and a delivered market price of 39 p/l for bioethanol, with G. Punter, British Sugar plc. Peterborough, United Kingdom, 28 January 2003.

5. "British Survey of Fertiliser Practice 1999", Fertiliser Manufacturers' Association.

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003.

7. "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

8. "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

9. "Pesticide Use Survey" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. "Farm Management Pocket Handbook" by J. Nix, Wye College, University of London, United Kingdom, 2002.

11. Private communication with A. Nixon, British Sugar plc., Peterborough, United Kingdom, 22 January 2003.

12. "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.

13. "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.

14. "Düngemittel – Energie- und Stoffstrombilanzen" (Fertilisers – Energy and Material Balance) by A. Patyk and G. A. Reinhardt, Vieweg Umweltwissenschaften, Braunschweig/Wiesbaden, Germany, 1997.

15. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

16. "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.

17. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

18. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

19. "Interim Report on Energy-Use in Metallurgical and Non-Metallic Mineral Processing, Phase 5" Battelle Columbus Laboratories, PB-246-357, United States of America, 1975.

20. "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.

Spreadsheet for Methane Outputs from Bioethanol Production from Wheat using a Natural Gas-fired Combined Heat and Power Plant with a Steam Turbine (Model 3)

Functional Unit: :	Bioethanol at point of distribution derived from wheat using natural gas-fired combined heat and power generation with a steam turbine during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on average market prices, assuming 1.394 tonnes of wheat straw at £25/t (Ref. 1) and 3.425 tonnes of harvested wheat grain with 20% moisture content at £69/t (Ref. 2), giving a 87.1% allocation to bioethanol, and 1.141 tonnes of animal feed at £80/t (Ref. 3) and 1.000 tonnes of bioethanol at £494/t (Ref. 4), giving a 84.4% allocation to bioethanol.

Contribution	Per Unit	Methane Output (kg CH_4)						Notes
		Direct		Indirect		Total		
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	*ha.a*	-	-	*0.666*	*±0.111*	*0.666*	*±0.111*	(a)
- P Fertiliser	*ha.a*	-	-	*0.002*	-	*0.002*	-	(b, c)
- K Fertiliser	*ha.a*	-	-	*0.001*	-	*0.001*	-	(c, d)
- Pesticide	*ha.a*	-	-	-	-	-	-	(c, e)
- Herbicide	*ha.a*	-	-	-	-	-	-	(c, f)
- Insecticide	*ha.a*	-	-	-	-	-	-	(c, g)
- Fungicide	*ha.a*	-	-	-	-	-	-	(c, h)
- Seed	*ha.a*	-	-	-	-	-	-	(c, i)
- Diesel Fuel	*ha.a*	*0.003*	-	*0.112*	*±0.017*	*0.115*	*±0.017*	(c, j)
Reference System:								
- Diesel Fuel	*ha.a*	*- 0.001*	-	*- 0.019*		*- 0.020*	*±0.003*	(c, k)
Sub-Totals	*ha.a*	*0.002*	-	*0.762*	*±0.112*	*0.764*	*±0.112*	
	t be	**0.001**	**-**	**0.223**	**±0.033**	**0.224**	**±0.033**	(l)
Drying:								
- Diesel Fuel	*t hwg*	*0.001*	-	*0.007*	*±0.001*	*0.008*	*±0.001*	(c, m)
	t be	**0.003**	**-**	**0.020**	**±0.003**	**0.023**	**±0.003**	(n)
Transport:								
- Diesel Fuel	*t dwg*	-	-	*0.003*	-	*0.003*	-	(o)
	t be		**-**	**0.008**	**-**	**0.008**	**-**	(p)
Milling, Hydrolysis, Fermentation and Distillation:								
- Natural Gas	*t de*	*0.025*	*±0.021*	*0.740*	*±0.113*	*0.765*	*±0.115*	(c,q - s)
- Caustic Soda	*t de*	-	-	*0.136*	*±0.020*	*0.136*	*±0.020*	(c, t)
- Diam. Phosph.	*t de*	-	-	-	-	-	-	(c, u)
- Sulphuric Acid	*t de*	-	-	*0.007*	*±0.008*	*0.007*	*±0.008*	(c, v)
- Enzyme AMG	*t de*	-	-	-	-	-	-	(c, w)
- Enzyme AA	*t de*	-	-	-	-	-	-	(c, x)
- Calcium Chlor.	*t de*	-	-	-		-	-	(c, y)
Sub-Totals	*t de*	*0.025*	*±0.021*	*0.883*	*±0.115*	*0.908*	*±0.117*	
	t be	**0.022**	**±0.019**	**0.788**	**±0.103**	**0.810**	**±0.104**	(z)
Dehydration:								
- Natural Gas	**t be**	**-**	**-**	**0.003**	**-**	**0.003**	**-**	(c, q, aa, bb)
Plant Construction	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(c, cc)
Plant Maintenance	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(c, dd)
Distribution:								
- Diesel Fuel	**t be**	**-**	**-**	**0.008**	**-**	**0.008**	**-**	(ee)
Totals	**t be**	**0.026**	**±0.019**	**1.050**	**±0.108**	**1.076**	**±0.109**	

Biofuel Specifications

Density of bioethanol = 0.79 kg/l
Net calorific value of bioethanol = 26.72 MJ/kg
Gross calorific value of bioethanol = 29.74 MJ/kg

Abbreviations

ha.a = hectare year
t hwg = tonne of harvested wheat grain
t dwg = tonne of dried wheat grain
t de = tonne of distillate ethanol (94.5% alcohol)
t be = tonne of bioethanol

Notes

(a) Nitrogen fertiliser application rate of 185 N/ha.a (Ref. 5) 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 (Ref. 6).

(b) Phosphate fertiliser application rates of 41 kg P/ha.a (Ref. 5), or 93.9 kg P_2O_5/ ha.a assuming 2.290 kg P_2O_5/kg P, and a total methane requirement for phosphate fertiliser of 2.3×10^{-5} kg CH_4/kg P_2O_5 (Ref. 7).

(c) Assuming an error bar of ±15% based on similar analyses (Ref. 8).

(d) Potash fertiliser application rate of 46 kg K/ha.a (Ref. 5), or 55.4 kg K_2O/ha.a assuming 1.205 kg K_2O/kg K, and a total methane requirement for potash fertiliser of 2.1×10^{-5} kg CH_4/ kg K_2O (Ref. 7).

(e) Pesticide application rate of 2.0 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.8×10^{-4} kg CH_4/kg (Ref. 7).

(f) Herbicide application rate of 0.1 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.8×10^{-4} kg CH_4/kg (Ref. 7).

(g) Insecticide application rate of 0.8 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.8×10^{-4} kg CH_4/kg (Ref. 7).

(h) Fungicide application rate of 1.0 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.8×10^{-4} kg CH_4/kg (Ref. 7).

(i) Sowing rate of 185 kg/ha.a (Ref. 10) and a total methane requirement of 0 kg CH_4/kg of seed, assuming similarity with oilseed (Ref. 7).

(j) Diesel fuel consumption of 5,490 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides, insecticides and fungicides, harvesting, carting and loading (Ref. 11) 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. 12).

(k) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 7) 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. 12).

(l) Land requirement of 0.398 ha.a/t of bioethanol and allocation of 87.1% x 84.4% = 73.5% to bioethanol.

(m) Assuming 50% of the harvested wheat grain (1.7125 t/t of bioethanol) dries naturally to a moisture content of 14% and 50% of the harvested wheat grain (1.7125 t/t of bioethanol) requires artificial drying on the farm with a diesel fuel consumption of 677 MJ/t of harvested wheat grain with a moisture content of 19% (Ref. 11), 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. 12).

(n) Harvested wheat grain requirement of 3.425 t/t of bioethanol and allocation of 84.4% to bioethanol.

(o) Average round trip distance of 186 km (Ref. 11) 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. 13).

(p) Dried wheat grain requirement of 3.186 t/t of bioethanol and allocation of 84.4% to bioethanol.

(q) Natural gas-fired combined heat and power plant with an overall efficiency of 84% producing 0.109 MJ of electricity and 0.731 MJ of steam from each MJ of natural gas (Ref. 11), giving a natural gas consumption rate of 1.190 MJ/MJ of energy output in the form of electricity or steam, 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. 12).

(r) Assuming that milling, hydrolysis, fermentation and distillation consumes steam at a rate of 25.0 t/hr (Ref. 11), accounting for 25.0/44.5 = 56.2% of total steam consumption, or 67,753 MJ/hr, and, based pro rata on power ratings, consumes 1.903/4.500 = 42.3% of total electricity consumption (Ref. 11), or 7,612 MJ/hr, equivalent to (67,753 = 7,612) x 1.190 = 89,684 MJ/hr of natural gas consumption in the combined heat and power plant.

(s) Total distillate (94.5% alcohol) output rate of 13.12 t/hr, based on an annual output rate of 105,800 t/a of distillate, or 100,000 t/a of bioethanol, and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 11).

(t) Caustic soda (49% concentration) consumption rate of 4,427,136 kg/a (Ref. 11), or 41.8 kg/t of distillate, and a total methane requirement of 3.25×10^{-3} kg CH_4/kg for caustic soda (Ref. 7).

(u) Diammonium phosphate (21% concentration) consumption rate of 2,921,103 kg/a (Ref. 11), or 27.6 kg/t of distillate, and a total methane requirement of 2×10^{-6} kg CH_4/kg for diammonium phosphate (Ref. 14).

(v) Sulphuric acid (93% concentration) consumption rate of 2,911,104 kg/a (Ref. 11), or 27.5 kg/t of distillate, and a total methane requirement of $2.7 \times 10^{-4} \pm 3.0 \times 10^{-4}$ kg CH_4/kg for sulphuric acid (Ref. 15).

(w) Enzyme AMG consumption rate of 247,176 kg/a (Ref. 11), or 2.3 kg/t of distillate, and a total methane requirement of 6×10^{-6} kg CH_4/kg for enzyme AMG (Refs. 16 to 18).

(x) Enzyme Alpha Amylase consumption rate of 137,007 kg/a (Ref. 11), or 1.3 kg/t of distillate, and a total methane requirement of 4×10^{-6} kg CH_4/kg for enzyme alpha amylase (Refs. 16 to 18).

(y) Calcium chloride consumption rate of 90,317 kg/a (Ref. 11), or 0.9 kg/t of distillate, and a total methane requirement of 2×10^{-4} kg CH_4/kg for (Ref. 19).

(z) Distillate (94.5% alcohol) requirement 1.058 t/t of bioethanol and allocation of 84.4% to bioethanol.

(aa) Assuming dehydration accounts for 78/4,500 = 1.73% of total electricity consumption (Ref. 11), or 312 MJ/hr, equivalent to 312 x 1.190 = 371 MJ/hr of natural gas consumption in the combined heat and power plant.

(bb) Total bioethanol output rate of 12.4 t/hr, based on an annual output rate of 100,000 t/a of bioethanol and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 11).

(cc) Primary energy input of 1,282,500 GJ for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £51.3 m (Ref. 11) and an energy intensity of 25 MJ/£ (Ref. 16) , and an estimated total methane requirement of 1.192×10^{-7} kg CH_4/MJ primary energy input to construction (Ref. 18), assuming 84.4% contribution to bioethanol by price of co-products.

(dd) Methane output of annual plant maintenance assumed to be 1.5% of methane output from plant construction (Ref. 11).

(ee) Average round trip distance of 450 km (Ref. 20) 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. 13).

<u>References</u>

1. "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.

2. Annual average ex-farm price of feed wheat, United Kingdom, 2000/02 from www.hgca.com/c-stats accessed 3 February 2003.

3. Private communication with D. Darby, British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication, based on an assumed derogation of fuel duty of 26 p/l and a delivered market price of 39 p/l for bioethanol, with G. Punter, British Sugar plc. Peterborough, United Kingdom, 28 January 2003.

5. "British Survey of Fertiliser Practice 1999", Fertiliser Manufacturers' Association.

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003.

7. "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

8. "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

9. "Pesticide Use Survey" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. "Farm Management Pocket Handbook" by J. Nix, Wye College, University of London, United Kingdom, 2002.

11. Private communication with A. Nixon, British Sugar plc., Peterborough, United Kingdom, 22 January 2003.

12. "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.

13. "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.

14. "Düngemittel – Energie- und Stoffstrombilanzen" (Fertilisers – Energy and Material Balance) by A. Patyk and G. A. Reinhardt, Vieweg Umweltwissenschaften, Braunschweig/Wiesbaden, Germany, 1997.

15. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

16. "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.

17. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

18. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

19. "Interim Report on Energy-Use in Metallurgical and Non-Metallic Mineral Processing, Phase 5" Battelle Columbus Laboratories, PB-246-357, United States of America, 1975.

20. "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.

Spreadsheet for Nitrous Oxide Outputs from Bioethanol Production from Wheat using a Natural Gas-fired Combined Heat and Power Plant with a Steam Turbine (Model 3)

Functional Unit: :	Bioethanol at point of distribution derived from wheat using natural gas-fired combined heat and power generation with a steam turbine during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on average market prices, assuming 1.394 tonnes of wheat straw at £25/t (Ref. 1) and 3.425 tonnes of harvested wheat grain with 20% moisture content at £69/t (Ref. 2), giving a 87.1% allocation to bioethanol, and 1.141 tonnes of animal feed at £80/t (Ref. 3) and 1.000 tonnes of bioethanol at £494/t (Ref. 4), giving a 84.4% allocation to bioethanol.

Contribution	Per Unit	Nitrous Oxide Output (kg N_2O)						Notes
		Direct		Indirect		Total		
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	*ha.a*	*0.666*	*±0.100*	*2.720*	*±0.408*	*3.386*	*±0.420*	(a, b)
- P Fertiliser	*ha.a*	-	-	*0.004*	*±0.001*	*0.004*	*±0.001*	(b, c)
- K Fertiliser	*ha.a*	-	-	*0.001*	-	*0.001*	-	(b, d)
- Pesticide	*ha.a*	-	-	*0.003*	-	*0.003*	-	(b, e)
- Herbicide	*ha.a*	-	-	-	-	-	-	(b, f)
- Insecticide	*ha.a*	-	-	*0.001*	-	*0.001*	-	(b, g)
- Fungicide	*ha.a*	-	-	*0.002*	-	*0.002*	-	(b, h)
- Seed	*ha.a*	-	-	*0.185*	*±0.028*	*0.185*	*±0.028*	(b, i)
- Diesel Fuel	*ha.a*	*0.003*	-	-	-	*0.003*	-	(b, j)
Reference System:								
- Diesel Fuel	*ha.a*	*- 0.001*	-	-		*- 0.001*	-	(b, k)
Sub-Totals	*ha.a*	*0.668*	*±0.100*	*2.916*	*±0.409*	*3.584*	*±0.421*	
	t be	**0.195**	**±0.029**	**0.853**	**±0.120**	**1.048**	**±0.123**	(l)
Drying:								
- Diesel Fuel	*t hwg*	-	-	-	-	-	-	(b, m)
	t be	**-**	**-**	**-**	**-**	**-**	**-**	(n)
Transport:								
- Diesel Fuel	*t dwg*	-	-	-	-	-	-	(o)
	t be	**-**	**-**	**-**	**-**	**-**	**-**	(p)
Milling, Hydrolysis, Fermentation and Distillation:								
- Natural Gas	*t de*	*0.001*	-	-	-	*0.001*	-	(b,q - s)
- Caustic Soda	*t de*	-	-	-	-	-	-	(b, t)
- Diam. Phosph.	*t de*	-	-	-	-	-	-	(b, u)
- Sulphuric Acid	*t de*	-	-	-	-	-	-	(b, v)
- Enzyme AMG	*t de*	-	-	-	-	-	-	(b, w)
- Enzyme AA	*t de*	-	-	-	-	-	-	(b, x)
- Calcium Chlor.	*t de*	-	-	-	-	-	-	(b, y)
Sub-Totals	*t de*	*0.001*	-	-	-	*0.001*	-	(z)
	t be	**0.001**	**-**	**-**	**-**	**0.001**	**-**	
Dehydration:	*t dwg*	-	-	-	-	-	-	(b, q, aa,
- Natural Gas	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	bb)
Plant Construction	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(b, cc)
Plant Maintenance	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(b, dd)
Distribution:								
- Diesel Fuel	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(ee)
Totals	**t be**	**0.196**	**±0.029**	**0.853**	**±0.120**	**1.049**	**±0.123**	

Biofuel Specifications

Density of bioethanol = 0.79 kg/l
Net calorific value of bioethanol = 26.72 MJ/kg
Gross calorific value of bioethanol = 29.74 MJ/kg

Abbreviations

ha.a = hectare year
t hwg = tonne of harvested wheat grain
t dwg = tonne of dried wheat grain
t de = tonne of distillate ethanol (94.5% alcohol)
t be = tonne of bioethanol

Notes

(a) Nitrogen fertiliser application rate of 185 N/ha.a (Ref. 5) and a direct nitrous oxide requirement of 0.0036 kg N_2O/kg N (Ref. 5), an indirect nitrous oxide requirement of 0.0147 kg N_2O/kg N (Ref. 6) and a total nitrous oxide requirement for ammonium nitrate of 0.0183 kg N_2O/kg N (Ref. 6).

(b) Assuming an error bar of ±15% based on similar analyses (Ref. 7).

(c) Phosphate fertiliser application rates of 41 kg P/ha.a (Ref. 5), or 93.9 kg P_2O_5/ ha.a assuming 2.290 kg P_2O_5/kg P, and a total nitrous oxide requirement for phosphate fertiliser of 4.2×10^{-5} kg N_2O/kg P_2O_5 (Ref. 8).

(d) Potash fertiliser application rate of 46 kg K/ha.a (Ref. 5), or 55.4 kg K_2O/ha.a assuming 1.205 kg K_2O/kg K, and a total nitrous oxide requirement for potash fertiliser of 9.4×10^{-6} kg N_2O/ kg K_2O (Ref. 5).

(e) Pesticide application rate of 2.0 kg/ha.a (Ref. 9) and a total nitrous oxide requirement for general pesticides, herbicides and fungicides of 1.51×10^{-3} kg N_2O/kg (Ref. 8).

(f) Herbicide application rate of 0.1 kg/ha.a (Ref. 9) and a total nitrous oxide requirement for general pesticides, herbicides and fungicides of 1.51×10^{-3} kg N_2O/kg (Ref. 8).

(g) Insecticide application rate of 0.8 kg/ha.a (Ref. 9) and a total nitrous oxide requirement for general pesticides, herbicides and fungicides of 1.51×10^{-3} kg N_2O/kg (Ref. 8).

(h) Fungicide application rate of 1.0 kg/ha.a (Ref. 9) and a total nitrous oxide requirement for general pesticides, herbicides and fungicides of 1.51×10^{-3} kg N_2O/kg (Ref. 8).

(i) Sowing rate of 185 kg/ha.a (Ref. 10) and a total nitrous oxide requirement of 0.001 kg N_2O/kg of seed assuming similarity with oilseed (Ref. 8).

(j) Diesel fuel consumption of 5,490 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides, insecticides and fungicides, harvesting, carting and loading (Ref. 11) and a direct nitrous oxide requirement of 5.64×10^{-7} kg N_2O/MJ, an indirect nitrous oxide requirement of 2.60×10^{-8} kg N_2/MJ and a total nitrous oxide requirement of 5.90×10^{-7} kg N_2O/MJ for diesel fuel in the UK in 1996 (Ref. 12).

(k) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 8) and a direct nitrous oxide requirement of 5.64×10^{-7} kg N_2O/MJ, an indirect nitrous oxide requirement of 2.60×10^{-8} kg N_2/MJ and a total nitrous oxide requirement of 5.90×10^{-7} kg N_2O/MJ for diesel fuel in the UK in 1996 (Ref. 12).

(l) Land requirement of 0.398 ha.a/t of bioethanol and allocation of 87.1% x 84.4% = 73.5% to bioethanol.

(m) Assuming 50% of the harvested wheat grain (1.7125 t/t of bioethanol) dries naturally to a moisture content of 14% and 50% of the harvested wheat grain (1.7125 t/t of bioethanol) requires artificial drying on the farm with a diesel fuel consumption of 677 MJ/t of harvested wheat grain with a moisture content of 19% (Ref. 11), and a direct nitrous oxide requirement of 5.64×10^{-7} kg N_2O/MJ, an indirect nitrous oxide requirement of 2.60×10^{-8} kg N_2/MJ and a total nitrous oxide requirement of 5.90×10^{-7} kg N_2O/MJ for diesel fuel in the UK in 1996 (Ref. 12).

(n) Harvested wheat grain requirement of 3.425 t/t of bioethanol and allocation of 84.4% to bioethanol.

(o) Average round trip distance of 186 km (Ref. 11) by bulk road carrier transport with a direct nitrous oxide requirement of $4.6 \times 10^{-7} \pm 1.7 \times 10^{-8}$ kg N_2O/t-km, an indirect nitrous oxide requirement of $2.1 \times 10^{-8} \pm 8 \times 10^{-10}$ kg N_2O/t-km and a total nitrous oxide requirement of $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8}$ kg N_2O/t-km (Ref. 13).

(p) Dried wheat grain requirement of 3.186 t/t of bioethanol and allocation of 84.4% to bioethanol.

(q) Natural gas-fired combined heat and power plant with an overall efficiency of 84% producing 0.109 MJ of electricity and 0.731 MJ of steam from each MJ of natural gas (Ref. 11), giving a natural gas consumption rate of 1.190 MJ/MJ of energy output in the form of electricity or steam, and a direct nitrous requirement of 8.9×10^{-8} kg N_2O/MJ, an indirect nitrous oxide requirement of 1.1×10^{-8} kg N_2O/MJ and a total nitrous oxide requirement of 1.0×10^{-7} kg N_2O/MJ for natural gas in the UK in 1996 (Ref. 12).

(r) Assuming that milling, hydrolysis, fermentation and distillation consumes steam at a rate of 25.0 t/hr (Ref. 11), accounting for 25.0/44.5 = 56.2% of total steam consumption, or 67,753 MJ/hr, and, based pro rata on power ratings, consumes 1.903/4.500 = 42.3% of total electricity consumption (Ref. 11), or 7,612 MJ/hr, equivalent to (67,753 = 7,612) x 1.190 = 89,684 MJ/hr of natural gas consumption in the combined heat and power plant.

(s) Total distillate (94.5% alcohol) output rate of 13.12 t/hr, based on an annual output rate of 105,800 t/a of distillate, or 100,000 t/a of bioethanol, and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 11).

(t) Caustic soda (49% concentration) consumption rate of 4,427,136 kg/a (Ref. 11), or 41.8 kg/t of distillate, and a total nitrous oxide requirement of 0 kg N_2O/kg for caustic soda (Ref. 7).

(u) Diammonium phosphate (21% concentration) consumption rate of 2,921,103 kg/a (Ref. 11), or 27.6 kg/t of distillate, and a total nitrous oxide requirement of 2×10^{-6} kg N_2O/kg for diammonium phosphate (Ref. 14).

(v) Sulphuric acid (93% concentration) consumption rate of 2,911,104 kg/a (Ref. 11), or 27.5 kg/t of distillate, and a total nitrous oxide requirement of $2 \times 10^{-7} \pm 3 \times 10^{-7}$ kg N_2O/kg for sulphuric acid (Ref. 15).

(w) Enzyme AMG consumption rate of 247,176 kg/a (Ref. 11), or 2.3 kg/t of distillate, and a total nitrous oxide requirement of 9×10^{-8} kg N_2O/kg for enzyme AMG (Refs. 16 to 18).

(x) Enzyme Alpha Amylase consumption rate of 137,007 kg/a (Ref. 11), or 1.3 kg/t of distillate, and a total nitrous oxide requirement of 6×10^{-8} kg N_2O/kg for enzyme alpha amylase (Refs. 16 to 18).

(y) Calcium chloride consumption rate of 90,317 kg/a (Ref. 11), or 0.9 kg/t of distillate, and a total nitrous oxide requirement of 4×10^{-7} kg N_2O/kg for (Ref. 19).

(z) Distillate (94.5% alcohol) requirement 1.058 t/t of bioethanol and allocation of 84.4% to bioethanol.

(aa) Assuming dehydration accounts for 78/4,500 = 1.73% of total electricity consumption (Ref. 11), or 312 MJ/hr, equivalent to 312 x 1.190 = 371 MJ/hr of natural gas consumption in the combined heat and power plant.

(bb) Total bioethanol output rate of 12.4 t/hr, based on an annual output rate of 100,000 t/a of bioethanol and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 11).

(cc) Primary energy input of 1,282,500 GJ for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £51.3 m (Ref. 11) and an energy intensity of 25 MJ/£ (Ref. 16) , and an estimated total nitrous oxide requirement of 1.866×10^{-9} kg N_2O/MJ of primary energy input to construction (Ref. 18), assuming 84.4% contribution to bioethanol by price of co-products.

(dd) Nitrous oxide output of annual plant maintenance assumed to be 1.5% of nitrous oxide output from plant construction (Ref. 11).

(ee) Average round trip distance of 450 km (Ref. 20) by bulk road carrier transport with a direct nitrous oxide requirement of $4.6 \times 10^{-7} \pm 1.7 \times 10^{-8}$ kg N_2O/t-km, an indirect nitrous oxide requirement of $2.1 \times 10^{-8} \pm 8 \times 10^{-10}$ kg N_2O/t-km and a total nitrous oxide requirement of $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8}$ kg N_2O/t-km (Ref. 13).

References

1. "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.

2. Annual average ex-farm price of feed wheat, United Kingdom, 2000/02 from www.hgca.com/c-stats accessed 3 February 2003.

3. Private communication with D. Darby, British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication, based on an assumed derogation of fuel duty of 26 p/l and a delivered market price of 39 p/l for bioethanol, with G. Punter, British Sugar plc. Peterborough, United Kingdom, 28 January 2003.

5. "British Survey of Fertiliser Practice 1999", Fertiliser Manufacturers' Association.

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003.

7. "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

8. "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

9. "Pesticide Use Survey" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. "Farm Management Pocket Handbook" by J. Nix, Wye College, University of London, United Kingdom, 2002.

11. Private communication with A. Nixon, British Sugar plc., Peterborough, United Kingdom, 22 January 2003.

12. "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.

13. "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.

14. "Düngemittel – Energie- und Stoffstrombilanzen" (Fertilisers – Energy and Material Balance) by A. Patyk and G. A. Reinhardt, Vieweg Umweltwissenschaften, Braunschweig/Wiesbaden, Germany, 1997.

15. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

16. "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.

17. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

18. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

19. "Interim Report on Energy-Use in Metallurgical and Non-Metallic Mineral Processing, Phase 5" Battelle Columbus Laboratories, PB-246-357, United States of America, 1975.

20. "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.

Spreadsheet for Greenhouse Gas Outputs from Bioethanol Production from Wheat using a Natural Gas-fired Combined Heat and Power Plant with a Steam Turbine (Model 3)

Functional Unit: :	Bioethanol at point of distribution derived from wheat using natural gas-fired combined heat and power generation with a steam turbine during processing							
Final Unit of Measurement:	1 tonne of bioethanol							
Relevant Location:	United Kingdom							
Relevant Period:	2002							
Allocation Procedures:	Based on average market prices, assuming 1.394 tonnes of wheat straw at £25/t (Ref. 1) and 3.425 tonnes of harvested wheat grain with 20% moisture content at £69/t (Ref. 2), giving a 87.1% allocation to bioethanol, and 1.141 tonnes of animal feed at £80/t (Ref. 3) and 1.000 tonnes of bioethanol at £494/t (Ref. 4), giving a 84.4% allocation to bioethanol.							
Contribution	Per Unit	Total Greenhouse Gas Output (kg eq CO_2)						Notes
		Direct		Indirect		Total		
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	*ha.a*	*213*	*±32*	*1,239*	*±140*	*1,452*	*±144*	(a)
- P Fertiliser	*ha.a*	-	-	*67*	*±10*	*67*	*±10*	(a)
- K Fertiliser	*ha.a*	-	-	*25*	*±4*	*25*	*±4*	(a)
- Pesticide	*ha.a*	-	-	*11*	*±1*	*11*	*±1*	(a)
- Herbicide	*ha.a*	-	-	-	-	-	-	(a)
- Insecticide	*ha.a*	-	-	*4*	*±1*	*4*	*±1*	(a)
- Fungicide	*ha.a*	-	-	*6*	*±1*	*6*	*±1*	(a)
- Seed	*ha.a*	-	-	*125*	*±13*	*125*	*±13*	(a)
- Diesel Fuel	*ha.a*	*378*	*±60*	*47*	*±20*	*425*	*±63*	(a)
Reference System:								
- Diesel Fuel	*ha.a*	*- 63*	*±10*	*- 7*	*±3*	*- 70*	*±11*	(a)
Sub-Totals	*ha.a*	*528*	*±68*	*1,517*	*±142*	*2,045*	*±158*	
	t be	**154**	**±20**	**444**	**±42**	**598**	**±46**	(b)
Drying:								
- Diesel Fuel	*t hwg*	*23*	*±4*	*3*	-	*26*	*±4*	(a)
	t be	**66**	**±12**	**9**	**-**	**75**	**±12**	(c)
Transport:								
- Diesel Fuel	*t dwg*	*10*	-	*3*	-	*13*	-	(a)
	t be	**27**	**±1**	**8**	**-**	**35**	**±1**	(d)
Milling, Hydrolysis, Fermentation and Distillation:								
- Natural Gas	*t de*	*358*	*±55*	*30*	*±10*	*388*	*±55*	(a)
- Caustic Soda	*t de*	-	-	*50*	*±7*	*50*	*±7*	(a)
- Diam. Phosph.	*t de*	-	-	*2*	-	*2*	-	(a)
- Sulphuric Acid	*t de*	-	-	*4*	*±4*	*4*	*±4*	(a)
- Enzyme AMG	*t de*	-	-	*5*	*±1*	*5*	*±1*	(a)
- Enzyme AA	*t de*	-	-	*2*	-	*2*	-	(a)
- Calcium Chlor.	*t de*	-	-	*1*	-	*1*	-	(a)
Sub-Totals	*t de*	*358*	*±55*	*94*	*±13*	*452*	*±56*	
	t be	**320**	**±48**	**84**	**±12**	**404**	**±50**	(e)
Dehydration:								(a)
- Natural Gas	**t be**	**2**	**-**	**-**	**-**	**2**	**-**	
Plant Construction	**t be**	**-**	**-**	**27**	**±4**	**27**	**±4**	(a)
Plant Maintenance	**t be**	**-**	**-**	**8**	**±1**	**8**	**±1**	(a)
Distribution:								
- Diesel Fuel	**t be**	**25**	**±1**	**7**	**±1**	**32**	**±1**	(ee)
Totals	**t be**	**594**	**±53**	**587**	**±44**	**1,181**	**±69**	

Biofuel Specifications

Density of bioethanol = 0.79 kg/l
Net calorific value of bioethanol = 26.72 MJ/kg
Gross calorific value of bioethanol = 29.74 MJ/kg

Abbreviations

ha.a = hectare year
t hwg = tonne of harvested wheat grain
t dwg = tonne of dried wheat grain
t de = tonne of distillate ethanol (94.5% alcohol)
t be = tonne of bioethanol

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 0.398 ha.a/t of bioethanol and allocation of 87.1% x 84.4% = 73.5% to bioethanol.

(c) Harvested wheat grain requirement of 3.425 t/t of bioethanol and allocation of 84.4% to bioethanol.

(d) Dried wheat grain requirement of 3.186 t/t of bioethanol and allocation of 84.4% to bioethanol.

(e) Distillate (94.5% alcohol) requirement 1.058 t/t of bioethanol and allocation of 84.4% to bioethanol.

References

1. "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.

2. Annual average ex-farm price of feed wheat, United Kingdom, 2000/02 from www.hgca.com/c-stats accessed 3 February 2003.

3. Private communication with D. Darby, British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication, based on an assumed derogation of fuel duty of 26 p/l and a delivered market price of 39 p/l for bioethanol, with G. Punter, British Sugar plc. Peterborough, United Kingdom, 28 January 2003.

APPENDIX C: Model 3a

Spreadsheet for Primary Energy Inputs to Bioethanol Production from Wheat (Model 3a)

Functional Unit:	Bioethanol at point of distribution derived from beet using natural gas-fired combined heat and power generation during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on average market prices, assuming 12.578 t clean sugar beet 394 tonnes of wheat straw at £25/t (Ref. 1) and 3.425 tonnes of harvested wheat grain with 20% moisture content at £69/t (Ref. 2), giving a 87.1% allocation to bioethanol, and 1.141 tonnes of animal feed at £80/t (Ref. 3) and 1.000 tonnes of bioethanol at £494/t (Ref. 4), giving a 84.4% allocation to bioethanol.

Contribution	Per Unit	Primary Energy Input (MJ)								Notes
		Direct		Indirect		Feedstock		Total		
		Value	Range	Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:										
- N Fertiliser	*ha.a*	-	-	*2,592*	*±1,036*	*4,920*	*±196*	*7,512*	*±1,054*	(a)
- P Fertiliser	*ha.a*	-	-	*1,484*	*±223*	-	-	*1,484*	*±223*	(b, c)
- K Fertiliser	*ha.a*	-	-	*515*	*±77*	-	-	*515*	*±77*	(c, d)
- Pesticide	*ha.a*	-	-	*548*	*±82*	-	-	*548*	*±82*	(c, e)
- Herbicide	*ha.a*	-	-	*27*	*±4*	-	-	*27*	*±4*	(c, f)
- Insecticide	*ha.a*	-	-	*219*	*±33*	-	-	*219*	*±33*	(c, g)
- Fungicide	*ha.a*	-	-	*274*	*±41*	-	-	*274*	*±41*	(c, h)
- Seed	*ha.a*	-	-	*2,498*	*±375*	-	-	*2,498*	*±375*	(c, i)
- Diesel Fuel	*ha.a*	*5,490*	*±868*	*604*	*±288*	-	-	*6,094*	*±914*	(c, j)
Reference System:										
- Diesel Fuel	*ha.a*	*- 922*	*±146*	*- 101*	*±48*	-	-	*- 1,023*	*±154*	(c, k)
Sub-Totals	*ha.a*	*4,568*	*±880*	*8,660*	*±1,168*	*4,920*	*±196*	*18,148*	*±1,477*	
	t be	**1,336**	**±257**	**2,534**	**±342**	**1,439**	**±57**	**5,309**	**±432**	(l)
Drying:										
- Diesel Fuel	*t hwg*	*338*	*±53*	*37*	*±18*	-	-	*375*	*±56*	(c, m)
	t be	**977**	**±153**	**107**	**±52**	**-**	**-**	**1,084**	**±162**	(n)
Transport:										
- Diesel Fuel	*t dwg*	*152*	*±6*	*53*	*±7*	-	-	*205*	*±9*	(o)
	t be	**409**	**±16**	**143**	**±19**	**-**	**-**	**552**	**±25**	(p)
Milling, Hydrolysis, Fermentation and Distillation:										
- Natural Gas	*t de*	*6,875*	*±1,031*	*756*	*±113*	-	-	*7,631*	*±1,037*	(c, q - s)
- Caustic Soda	*t de*	-	-	*836*	*±125*	-	-	*836*	*±125*	(c, t)
- Diam. Phosph.	*t de*	-	-	*55*	*±8*	-	-	*55*	*±8*	(c, u)
- Sulphuric Acid	*t de*	-	-	*66*	*±74*	-	-	*66*	*±74*	(c, v)
- Enzyme AMG	*t de*	-	-	*110*	*±16*	-	-	*110*	*±16*	(c, w)
- Enzyme AA	*t de*	-	-	*43*	*±6*	-	-	*43*	*±6*	(c, x)
- Calcium Chlor.	*t de*	-	-	*6*	*±1*	-	-	*6*	*±1*	(c, y)
Sub-Totals	*t de*	*6,875*	*±1,031*	*1,872*	*±185*	-	-	*8,747*	*±1,047*	
	t be	**6,430**	**±920**	**1,751**	**±165**	**-**	**-**	**8,181**	**±935**	(z)
Dehydration:										
- Natural Gas	**t be**	**30**	**±5**	**3**	**-**	**-**	**-**	**33**	**± 5**	(c, q, aa, bb)
Surplus Electricity	**t be**	**-5,574**	**-**	**-**	**-**	**-**	**-**	**-5,574**	**-**	(cc)
Plant Construction	**t be**	**-**	**-**	**541**	**±81**	**-**	**-**	**541**	**±81**	(c, dd)
Plant Maintenance	**t be**	**-**	**-**	**162**	**±24**	**-**	**-**	**162**	**±24**	(c, ee)
Distribution:										
- Diesel Fuel	**t be**	**369**	**±14**	**129**	**±16**	**-**	**-**	**498**	**±21**	(ff)
Totals	**t be**	**3,977**	**±968**	**5,370**	**±393**	**1,439**	**±57**	**10,786**	**± 1,046**	

Biofuel Specifications

Density of bioethanol = 0.79 kg/l
Net calorific value of bioethanol = 26.72 MJ/kg
Gross calorific value of bioethanol = 29.74 MJ/kg

Abbreviations

ha.a = hectare year
t hwg = tonne of harvested wheat grain
t dwg = tonne of dried wheat grain
t de = tonne of distillate ethanol (94.5% alcohol)
t be = tonne of bioethanol

Notes

(a) Nitrogen fertiliser application rate of 185 kg N/ha.a (Ref. 5) 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 nitrogen fertiliser (Ref. 6).

(b) Phosphate fertiliser application rates of 41 kg P/ha.a (Ref. 5), or 93.9 kg P_2O_5/ ha.a assuming 2.290 kg P_2O_5/kg P, and a total energy requirement for phosphate fertiliser of 15.8 MJ/kg P_2O_5 (Ref. 7).

(c) Assuming an error bar of ±15% based on similar analyses (Ref. 8).

(d) Potash fertiliser application rate of 46 kg K/ha.a (Ref. 5), or 55.4 kg K_2O/ha.a assuming 1.205 kg K_2O/kg K, and a total energy requirement for potash fertiliser of 9.3 MJ/ kg K_2O (Ref. 7).

(e) Pesticide application rate of 2.0 kg/ha.a (Ref. 9) and a total energy requirement for general pesticides, herbicides and fungicides of 274.1 MJ/kg (Ref. 7).

(f) Herbicide application rate of 0.1 kg/ha.a (Ref. 9) and a total energy requirement for general pesticides, herbicides and fungicides of 274.1 MJ/kg (Ref. 7).

(g) Insecticide application rate of 0.8 kg/ha.a (Ref. 9) and a total energy requirement for general pesticides, herbicides and fungicides of 274.1 MJ/kg (Ref. 7).

(h) Fungicide application rate of 1.0 kg/ha.a (Ref. 9) and a total energy requirement for general pesticides, herbicides and fungicides of 274.1 MJ/kg (Ref. 7).

(i) Sowing rate of 185 kg/ha.a (Ref. 10) and a total energy requirement of 13.5 MJ/kg of seed (Ref. 11).

(j) Diesel fuel consumption of 5,490 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides, insecticides and fungicides, harvesting, carting and loading (Ref. 12) and a gross energy requirement of 1.110 MJ/MJ for diesel fuel in the UK in 1996 (Ref. 13).

(k) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 7) and a gross energy requirement of 1.110 MJ/MJ for diesel fuel in the UK in 1996 (Ref. 13).

(l) Land requirement of 0.398 ha.a/t of bioethanol and allocation of 87.1% x 84.4% = 73.5% to bioethanol.

(m) Assuming 50% of the harvested wheat grain (1.7125 t/t of bioethanol) dries naturally to a moisture content of 14% and 50% of the harvested wheat grain (1.7125 t/t of bioethanol) requires artificial drying on the farm with a diesel fuel consumption of 677 MJ/t of harvested wheat grain with a moisture content of 19% (Ref. 12), and a gross energy requirement of 1.110 MJ/MJ for diesel fuel in the UK in 1996 (Ref. 13).

(n) Harvested wheat grain requirement of 3.425 t/t of bioethanol and allocation of 84.4% to bioethanol.

(o) Average round trip distance of 186 km (Ref. 12) 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. 14).

(p) Dried wheat grain requirement of 3.186 t/t of bioethanol and allocation of 84.4% to bioethanol.

(q) Natural gas-fired combined heat and power plant with a gas turbine and overall efficiency of 85% producing 0.29 MJ of electricity and 0.56 MJ of steam from each MJ of natural gas (Ref. 12), giving a natural gas consumption rate of 1.180 MJ/MJ of energy output in the form of electricity or steam, and a gross energy requirement of 1.110 MJ/MJ for natural gas in the UK in 1996 (Ref. 13).

(r) Assuming that milling, hydrolysis, fermentation and distillation accounts for all the steam provided from the combined heat and power plant, at a rate of 25.0 t/hr, accounting for 25.0/44.5 = 56.2% of total steam consumption, or 69,056 MJ/hr, and electricity consumption of 7,612 MJ/hr from the combined heat and power plant, based pro-rata on the power requirement of all milling, hydrolysis, fermentation and distillation electrical equipment (1,903 kWh/hr) compared to the total power requirement of the bioethanol plant (4,500 kWh/hr), or 42.3% of the total electrical output (Ref. 12).

(s) Total distillate (94.5% alcohol) output rate of 13.12 t/hr, based on an annual output rate of 105,800 t/a of distillate, or 100,000 t/a of bioethanol, and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 12).

(t) Caustic soda (49% concentration) consumption rate of 4,427,136 kg/a (Ref. 12), or 41.8 kg/t of distillate, and an energy requirement of 20 MJ/kg for caustic soda (Ref. 7).

(u) Diammonium phosphate (21% concentration) consumption rate of 2,921,103 kg/a (Ref. 12), or 27.6 kg/t of distillate, and an energy requirement of 2 MJ/kg for diammonium phosphate (Ref. 15).

(v) Sulphuric acid (93% concentration) consumption rate of 2,911,104 kg/a (Ref. 12), or 27.5 kg/t of distillate, and an energy requirement of 2.4 ± 2.7 MJ/kg for sulphuric acid (Ref. 16).

(w) Enzyme AMG consumption rate of 247,176 kg/a (Ref. 12), or 2.3 kg/t of distillate, and an energy requirement of 47 MJ/kg for enzyme AMG (Refs. 17 to 19).

(x) Enzyme Alpha Amylase consumption rate of 137,007 kg/a (Ref. 12), or 1.3 kg/t of distillate, and an energy requirement of 33 MJ/kg for enzyme alpha amylase (Refs. 17 to 19).

(y) Calcium chloride consumption rate of 90,317 kg/a (Ref. 12), or 0.9 kg/t of distillate, and an energy requirement of 7 MJ/kg for calcium chloride (Ref. 20).

(z) Distillate (94.5% alcohol) requirement 1.058 t/t of bioethanol and allocation of 84.4% to bioethanol.

(aa) Assuming dehydration accounts for electricity consumption of 312 MJ/hr from the combined heat and power plant, based pro-rata on the power requirement of dehydration electrical equipment (78 kWh/hr) compared to the total power requirement of the bioethanol plant (4,500 kWh/hr), or 1.7% of the total electrical output (Ref. 12).

(bb) Total bioethanol output rate of 12.4 t/hr, based on an annual output rate of 100,000 t/a of bioethanol and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 12).

(cc) Surplus electricity for sale equal to 3,716 MJ/t of bioethanol which displaces average electricity supplies with a gross energy requirement of 3.083 MJ/MJ for the UK in 1996 (Ref. 8).

(dd) Primary energy input of 1,282,500 GJ for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £51.3 m (Ref. 12) and an energy intensity of 25 MJ/£ (Ref. 17), and assuming 84.4% contribution to bioethanol by price of co-products.

(ee) Primary energy input of annual plant maintenance assumed to be 1.5% of primary energy input to plant construction (Ref. 12).

(ff) Average round trip distance of 450 km (Ref. 11) 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. 14).

References

1. "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.

2. Annual average ex-farm price of feed wheat, United Kingdom, 2000/02 from www.hgca.com/c-stats accessed 3 February 2003.

3. Private communication with D. Darby, British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication, based on an assumed derogation of fuel duty of 26 p/l and a delivered market price of 39 p/l for bioethanol, with G. Punter, British Sugar plc. Peterborough, United Kingdom, 28 January 2003.

5. "British Survey of Fertiliser Practice 1999", Fertiliser Manufacturers' Association.

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003.

7. "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

8. "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

9. "Pesticide Use Survey" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. "Farm Management Pocket Handbook" by J. Nix, Wye College, University of London, United Kingdom, 2002.

11. "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.

12. Private communication with A. Nixon, British Sugar plc., Peterborough, United Kingdom, 22 January 2003.

13. "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.

14. "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.

15. "Düngemittel – Energie- und Stoffstrombilanzen" (Fertilisers – Energy and Material Balance) by A. Patyk and G. A. Reinhardt, Vieweg Umweltwissenschaften, Braunschweig/Wiesbaden, Germany, 1997.

16. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

17. "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.

18. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

19. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

20. "Interim Report on Energy-Use in Metallurgical and Non-Metallic Mineral Processing, Phase 5" Battelle Columbus Laboratories, PB-246-357, United States of America, 1975.

Spreadsheet for Carbon Dioxide Outputs from Bioethanol Production from Wheat (Model 3a)

Functional Unit: :	Bioethanol at point of distribution derived from wheat using natural gas-fired combined heat and power generation during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on average market prices, assuming 1.394 tonnes of wheat straw at £25/t (Ref. 1) and 3.425 tonnes of harvested wheat grain with 20% moisture content at £69/t (Ref. 2), giving a 87.1% allocation to bioethanol, and 1.141 tonnes of animal feed at £80/t (Ref. 3) and 1.000 tonnes of bioethanol at £494/t (Ref. 4), giving a 84.4% allocation to bioethanol.

Contribution	Per Unit	Carbon Dioxide Output (kg CO_2)						Notes
		Direct		Indirect		Total		
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	*ha.a*	-	-	*352*	*±51*	*352*	*±51*	(a)
- P Fertiliser	*ha.a*	-	-	*66*	*±10*	*66*	*±10*	(b, c)
- K Fertiliser	*ha.a*	-	-	*25*	*±4*	*25*	*±4*	(c, d)
- Pesticide	*ha.a*	-	-	*10*	*±1*	*10*	*±1*	(c, e)
- Herbicide	*ha.a*	-	-	-	-	-	-	(c, f)
- Insecticide	*ha.a*	-	-	*4*	*±1*	*4*	*±1*	(c, g)
- Fungicide	*ha.a*	-	-	*5*	*±1*	*5*	*±1*	(c, h)
- Seed	*ha.a*	-	-	*66*	*±10*	*66*	*±10*	(c, i)
- Diesel Fuel	*ha.a*	*377*	*±60*	*44*	*±20*	*421*	*±63*	(c, j)
Reference System:								
- Diesel Fuel	*ha.a*	*- 63*	*±10*	*- 7*	*±3*	*- 70*	*±11*	(c, k)
Sub-Totals	*ha.a*	*314*	*±61*	*565*	*±57*	*879*	*±83*	
	t be	**92**	**±18**	**165**	**±17**	**257**	**±25**	(l)
Drying:								
- Diesel Fuel	*t hwg*	*23*	*±4*	*3*	-	*26*	*±4*	(c, m)
	t be	**66**	**±12**	**9**	**-**	**75**	**±12**	(n)
Transport:								
- Diesel Fuel	*t dwg*	*10*	-	*3*	-	*13*	-	(o)
	t be	**27**	**±1**	**8**	**-**	**35**	**±1**	(p)
Milling, Hydrolysis, Fermentation and Distillation:								
- Natural Gas	*t de*	*359*	*±54*	*12*	*±10*	*371*	*±55*	(c,q - s)
- Caustic Soda	*t de*	-	-	*47*	*±7*	*47*	*±7*	(c, t)
- Diam. Phosph.	*t de*	-	-	*2*	-	*2*	-	(c, u)
- Sulphuric Acid	*t de*	-	-	*4*	*±4*	*4*	*±4*	(c, v)
- Enzyme AMG	*t de*	-	-	*5*	*±1*	*5*	*±1*	(c, w)
- Enzyme AA	*t de*	-	-	*2*	-	*2*	-	(c, x)
- Calcium Chlor.	*t de*	-	-	*1*	-	*1*	-	(c, y)
Sub-Totals	*t de*	*359*	*±54*	*73*	*±13*	*431*	*±56*	
	t be	**320**	**±48**	**65**	**±12**	**385**	**±50**	(z)
Dehydration:								
- Natural Gas	**t be**	**2**	**-**	**-**	**-**	**2**	**-**	(c, q, aa, bb)
Surplus Electricity	**t be**	**-272**	**-**	**-**	**-**	**-272**	**-**	(cc)
Plant Construction	**t be**	**-**	**-**	**27**	**±4**	**27**	**±4**	(c, dd)
Plant Maintenance	**t be**	**-**	**-**	**8**	**±1**	**8**	**±1**	(c, ee)
Distribution:								
- Diesel Fuel	**t be**	**25**	**±1**	**7**	**±1**	**32**	**±1**	(ff)
Totals	**t be**	**260**	**±53**	**289**	**±21**	**549**	**±57**	

Biofuel Specifications

Density of bioethanol	= 0.79 kg/l
Net calorific value of bioethanol	= 26.72 MJ/kg
Gross calorific value of bioethanol	= 29.74 MJ/kg

Abbreviations

ha.a	= hectare year
t hwg	= tonne of harvested wheat grain
t dwg	= tonne of dried wheat grain
t de	= tonne of distillate ethanol (94.5% alcohol)
t be	= tonne of bioethanol

Notes

(a) Nitrogen fertiliser application rate of 185 kg N/ha.a (Ref. 5) and a total carbon requirement for ammonium nitrate of 1.904 ± 0.275 kg CO_2/kg N (Ref. 6).

(b) Phosphate fertiliser application rates of 41 kg P/ha.a (Ref. 5), or 93.9 kg P_2O_5/ ha.a assuming 2.290 kg P_2O_5/kg P, and a total carbon requirement for phosphate fertiliser of 0.700 kg CO_2/kg P_2O_5 (Ref. 7).

(c) Assuming an error bar of ±15% based on similar analyses (Ref. 8).

(d) Potash fertiliser application rate of 46 kg K/ha.a (Ref. 5), or 55.4 kg K_2O/ha.a assuming 1.205 kg K_2O/kg K, and a total carbon requirement for potash fertiliser of 0.453 kg CO_2/ kg K_2O (Ref. 7).

(e) Pesticide application rate of 2.0 kg/ha.a (Ref. 9) and a total carbon requirement for general pesticides, herbicides and fungicides of 4.921 kg CO_2/kg (Ref. 7).

(f) Herbicide application rate of 0.1 kg/ha.a (Ref. 9) and a total carbon requirement for general pesticides, herbicides and fungicides of 4.921 kg CO_2/kg (Ref. 7).

(g) Insecticide application rate of 0.8 kg/ha.a (Ref. 9) and a total carbon requirement for general pesticides, herbicides and fungicides of 4.921 kg CO_2/kg (Ref. 7).

(h) Fungicide application rate of 1.0 kg/ha.a (Ref. 9) and a total carbon requirement for general pesticides, herbicides and fungicides of 4.921 kg CO_2/kg (Ref. 7).

(i) Sowing rate of 185 kg/ha.a (Ref. 10) and a total carbon requirement of 0.547 kg CO_2/kg of seed based on a ratio of 0.0405 kg CO_2/MJ for oilseed (Ref. 7).

(j) Diesel fuel consumption of 5,490 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides, insecticides and fungicides, harvesting, carting and loading (Ref. 11) 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. 12).

(k) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 7) 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. 12).

(l) Land requirement of 0.398 ha.a/t of bioethanol and allocation of 87.1% x 84.4% = 73.5% to bioethanol.

(m) Assuming 50% of the harvested wheat grain (1.7125 t/t of bioethanol) dries naturally to a moisture content of 14% and 50% of the harvested wheat grain (1.7125 t/t of bioethanol) requires artificial drying on the farm with a diesel fuel consumption of 677 MJ/t of harvested wheat grain with a moisture content of 19% (Ref. 11), 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. 12).

(n) Harvested wheat grain requirement of 3.425 t/t of bioethanol and allocation of 84.4% to bioethanol.

(o) Average round trip distance of 186 km (Ref. 11) 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. 13).

(p) Dried wheat grain requirement of 3.186 t/t of bioethanol and allocation of 84.4% to bioethanol.

(q) Natural gas-fired combined heat and power plant with a gas turbine and overall efficiency of 85% producing 0.29 MJ of electricity and 0.56 MJ of steam from each MJ of natural gas (Ref. 11), giving a natural gas consumption rate of 1.180 MJ/MJ of energy output in the form of electricity or 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. 12).

(r) Assuming that milling, hydrolysis, fermentation and distillation accounts for all the steam provided from the combined heat and power plant, at a rate of 25.0 t/hr, accounting for 25.0/44.5 = 56.2% of total steam consumption, or 69,056 MJ/hr, and electricity consumption of 7,612 MJ/hr from the combined heat and power plant, based pro-rata on the power requirement of all milling, hydrolysis, fermentation and distillation electrical equipment (1,903 kWh/hr) compared to the total power requirement of the bioethanol plant (4,500 kWh/hr), or 42.3% of the total electrical output (Ref. 11).

(s) Total distillate (94.5% alcohol) output rate of 13.12 t/hr, based on an annual output rate of 105,800 t/a of distillate, or 100,000 t/a of bioethanol, and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 11).

(t) Caustic soda (49% concentration) consumption rate of 4,427,136 kg/a (Ref. 11), or 41.8 kg/t of distillate, and a total carbon requirement of 1.120 kg CO_2/kg for caustic soda (Ref. 7).

(u) Diammonium phosphate (21% concentration) consumption rate of 2,921,103 kg/a (Ref. 11), or 27.6 kg/t of distillate, and a total carbon requirement of 0.06 kg CO_2/kg for diammonium phosphate (Ref. 14).

(v) Sulphuric acid (93% concentration) consumption rate of 2,911,104 kg/a (Ref. 11), or 27.5 kg/t of distillate, and a total carbon requirement of 0.13 ± 0.16 kg CO_2/ kg for sulphuric acid (Ref. 15).

(w) Enzyme AMG consumption rate of 247,176 kg/a (Ref. 11), or 2.3 kg/t of distillate, and a total carbon requirement of 2.25 kg CO_2/ kg for enzyme AMG (Refs. 16 to 18).

(x) Enzyme Alpha Amylase consumption rate of 137,007 kg/a (Ref. 11), or 1.3 kg/t of distillate, and a total carbon requirement of 1.6 kg CO_2/ kg for enzyme alpha amylase (Refs. 16 to 18).

(y) Calcium chloride consumption rate of 90,317 kg/a (Ref. 11), or 0.9 kg/t of distillate, and a total carbon requirement of 0.6 kg CO_2/ kg for (Ref. 19).

(z) Distillate (94.5% alcohol) requirement 1.058 t/t of bioethanol and allocation of 84.4% to bioethanol.

(aa) Assuming dehydration accounts for electricity consumption of 373 MJ/hr from the combined heat and power plant, based pro-rata on the power requirement of dehydration electrical equipment (78 kWh/hr) compared to the total power requirement of the bioethanol plant (4,512 kWh/hr), or 1.7% of the total electrical output (Ref. 11).

(bb) Total bioethanol output rate of 12.4 t/hr, based on an annual output rate of 100,000 t/a of bioethanol and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 11).

(cc) Surplus electricity for sale equal to 3,716 MJ/t of bioethanol which displaces average electricity supplies with a carbon requirement of
0.150 kg CO_2/MJ for the UK in 1996 (Ref. 8).

(dd) Carbon dioxide output of 64,125 tonnes of CO_2 for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £51.3 m (Ref. 11) and a carbon intensity of 1.25 kg CO_2/£ (Ref. 16), and assuming 84.4% contribution to bioethanol by price of co-products.

(ee) Carbon dioxide output of annual plant maintenance assumed to be 1.5% of carbon dioxide output from plant construction (Ref. 11).

(ff) Average round trip distance of 450 km (Ref. 20) 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. 13).

References

1. "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.

2. Annual average ex-farm price of feed wheat, United Kingdom, 2000/02 from www.hgca.com/c-stats accessed 3 February 2003.

3. Private communication with D. Darby, British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication, based on an assumed derogation of fuel duty of 26 p/l and a delivered market price of 39 p/l for bioethanol, with G. Punter, British Sugar plc. Peterborough, United Kingdom, 28 January 2003.

5. "British Survey of Fertiliser Practice 1999", Fertiliser Manufacturers' Association.

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003.

7. "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

8. "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

9. "Pesticide Use Survey" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. "Farm Management Pocket Handbook" by J. Nix, Wye College, University of London, United Kingdom, 2002.

11. Private communication with A. Nixon, British Sugar plc., Peterborough, United Kingdom, 22 January 2003.

12. "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.

13. "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.

14. "Düngemittel – Energie- und Stoffstrombilanzen" (Fertilisers – Energy and Material Balance) by A. Patyk and G. A. Reinhardt, Vieweg Umweltwissenschaften, Braunschweig/Wiesbaden, Germany, 1997.

15. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

16. "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.

17. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

18. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

19. "Interim Report on Energy-Use in Metallurgical and Non-Metallic Mineral Processing, Phase 5" Battelle Columbus Laboratories, PB-246-357, United States of America, 1975.

20. "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.

Spreadsheet for Methane Outputs from Bioethanol Production from Wheat (Model 3a)

Functional Unit: :	Bioethanol at point of distribution derived from wheat using natural gas-fired combined heat and power generation during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on average market prices, assuming 1.394 tonnes of wheat straw at £25/t (Ref. 1) and 3.425 tonnes of harvested wheat grain with 20% moisture content at £69/t (Ref. 2), giving a 87.1% allocation to bioethanol, and 1.141 tonnes of animal feed at £80/t (Ref. 3) and 1.000 tonnes of bioethanol at £494/t (Ref. 4), giving a 84.4% allocation to bioethanol.

Contribution	Per Unit	Methane Output (kg CH_4)						Notes
		Direct		Indirect		Total		
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	*ha.a*	-	-	*0.666*	*±0.111*	*0.666*	*±0.111*	(a)
- P Fertiliser	*ha.a*	-	-	*0.002*	-	*0.002*	-	(b, c)
- K Fertiliser	*ha.a*	-	-	*0.001*	-	*0.001*	-	(c, d)
- Pesticide	*ha.a*	-	-	-	-	-	-	(c, e)
- Herbicide	*ha.a*	-	-	-	-	-	-	(c, f)
- Insecticide	*ha.a*	-	-	-	-	-	-	(c, g)
- Fungicide	*ha.a*	-	-	-	-	-	-	(c, h)
- Seed	*ha.a*	-	-	-	-	-	-	(c, i)
- Diesel Fuel	*ha.a*	*0.003*	-	*0.112*	*±0.017*	*0.115*	*±0.017*	(c, j)
Reference System:								
- Diesel Fuel	*ha.a*	*- 0.001*	-	*- 0.019*		*- 0.020*	*±0.003*	(c, k)
Sub-Totals	*ha.a*	*0.002*	-	*0.762*	*±0.112*	*0.764*	*±0.112*	
	t be	**0.001**	**-**	**0.223**	**±0.033**	**0.224**	**±0.033**	(l)
Drying:								
- Diesel Fuel	*t hwg*	*0.001*	-	*0.007*	*±0.001*	*0.008*	*±0.001*	(c, m)
	t be	**0.003**	**-**	**0.020**	**±0.003**	**0.023**	**±0.003**	(n)
Transport:								
- Diesel Fuel	*t dwg*	-	-	*0.003*	-	*0.003*	-	(o)
	t be		**-**	**0.008**	**-**	**0.008**	**-**	(p)
Milling, Hydrolysis, Fermentation and Distillation:								
- Natural Gas	*t de*	*0.025*	*±0.021*	*0.745*	*±0.112*	*0.770*	*±0.114*	(c,q - s)
- Caustic Soda	*t de*	-	-	*0.136*	*±0.020*	*0.136*	*±0.020*	(c, t)
- Diam. Phosph.	*t de*	-	-	-	-	-	-	(c, u)
- Sulphuric Acid	*t de*	-	-	*0.007*	*±0.008*	*0.007*	*±0.008*	(c, v)
- Enzyme AMG	*t de*	-	-	-	-	-	-	(c, w)
- Enzyme AA	*t de*	-	-	-	-	-	-	(c, x)
- Calcium Chlor.	*t de*	-	-	-		-	-	(c, y)
Sub-Totals	*t de*	*0.025*	*±0.021*	*0.888*	*±0.114*	*0.913*	*±0.116*	
	t be	**0.023**	**±0.019**	**0.793**	**±0.102**	**0.815**	**±0.104**	(z)
Dehydration:								
- Natural Gas	**t be**	**-**	**-**	**0.004**	**-**	**0.004**	**-**	(c, q, aa, bb)
Surplus Electricity	**t be**	**-0.855**	**-**	**-**	**-**	**-0.855**	**-**	(cc)
Plant Construction	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(c, dd)
Plant Maintenance	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(c, ee)
Distribution:								
- Diesel Fuel	**t be**	**-**	**-**	**0.008**	**-**	**0.008**	**-**	(ff)
Totals	**t be**	**- 0.828**	**±0.019**	**1.056**	**±0.107**	**0.228**	**±0.109**	

Biofuel Specifications

Density of bioethanol = 0.79 kg/l
Net calorific value of bioethanol = 26.72 MJ/kg
Gross calorific value of bioethanol = 29.74 MJ/kg

Abbreviations

ha.a = hectare year
t hwg = tonne of harvested wheat grain
t dwg = tonne of dried wheat grain
t de = tonne of distillate ethanol (94.5% alcohol)
t be = tonne of bioethanol

Notes

(a) Nitrogen fertiliser application rate of 185 N/ha.a (Ref. 5) 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 (Ref. 6).

(b) Phosphate fertiliser application rates of 41 kg P/ha.a (Ref. 5), or 93.9 kg P_2O_5/ ha.a assuming 2.290 kg P_2O_5/kg P, and a total methane requirement for phosphate fertiliser of 2.3×10^{-5} kg CH_4/kg P_2O_5 (Ref. 7).

(c) Assuming an error bar of ±15% based on similar analyses (Ref. 8).

(d) Potash fertiliser application rate of 46 kg K/ha.a (Ref. 5), or 55.4 kg K_2O/ha.a assuming 1.205 kg K_2O/kg K, and a total methane requirement for potash fertiliser of 2.1×10^{-5} kg CH_4/ kg K_2O (Ref. 7).

(e) Pesticide application rate of 2.0 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.8×10^{-4} kg CH_4/kg (Ref. 7).

(f) Herbicide application rate of 0.1 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.8×10^{-4} kg CH_4/kg (Ref. 7).

(g) Insecticide application rate of 0.8 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.8×10^{-4} kg CH_4/kg (Ref. 7).

(h) Fungicide application rate of 1.0 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.8×10^{-4} kg CH_4/kg (Ref. 7).

(i) Sowing rate of 185 kg/ha.a (Ref. 10) and a total methane requirement of 0 kg CH_4/kg of seed, assuming similarity with oilseed (Ref. 7).

(j) Diesel fuel consumption of 5,490 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides, insecticides and fungicides, harvesting, carting and loading (Ref. 11) 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. 12).

(k) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 7) 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. 12).

(l) Land requirement of 0.398 ha.a/t of bioethanol and allocation of 87.1% x 84.4% = 73.5% to bioethanol.

(m) Assuming 50% of the harvested wheat grain (1.7125 t/t of bioethanol) dries naturally to a moisture content of 14% and 50% of the harvested wheat grain (1.7125 t/t of bioethanol) requires artificial drying on the farm with a diesel fuel consumption of 677 MJ/t of harvested wheat grain with a moisture content of 19% (Ref. 11), 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. 12).

(n) Harvested wheat grain requirement of 3.425 t/t of bioethanol and allocation of 84.4% to bioethanol.

(o) Average round trip distance of 186 km (Ref. 11) 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. 13).

(p) Dried wheat grain requirement of 3.186 t/t of bioethanol and allocation of 84.4% to bioethanol.

(q) Natural gas-fired combined heat and power plant with a gas turbine and overall efficiency of 85% producing 0.29 MJ of electricity and 0.56 MJ of steam from each MJ of natural gas (Ref. 11), giving a natural gas consumption rate of 1.180 MJ/MJ of energy output in the form of electricity or steam, 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. 12).

(r) Assuming that milling, hydrolysis, fermentation and distillation accounts for all the steam provided from the combined heat and power plant, at a rate of 25.0 t/hr, accounting for 25.0/44.5 = 56.2% of total steam consumption, or 69,056 MJ/hr, and electricity consumption of 7,612 MJ/hr from the combined heat and power plant, based pro-rata on the power requirement of all milling, hydrolysis, fermentation and distillation electrical equipment (1,903 kWh/hr) compared to the total power requirement of the bioethanol plant (4,500 kWh/hr), or 42.3% of the total electrical output (Ref. 11).

(s) Total distillate (94.5% alcohol) output rate of 13.12 t/hr, based on an annual output rate of 105,800 t/a of distillate, or 100,000 t/a of bioethanol, and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 11).

(t) Caustic soda (49% concentration) consumption rate of 4,427,136 kg/a (Ref. 11), or 41.8 kg/t of distillate, and a total methane requirement of 3.25×10^{-3} kg CH_4/kg for caustic soda (Ref. 7).

(u) Diammonium phosphate (21% concentration) consumption rate of 2,921,103 kg/a (Ref. 11), or 27.6 kg/t of distillate, and a total methane requirement of 2 x 10^{-6} kg CH_4/kg for diammonium phosphate (Ref. 14).

(v) Sulphuric acid (93% concentration) consumption rate of 2,911,104 kg/a (Ref. 11), or 27.5 kg/t of distillate, and a total methane requirement of 2.7 x 10^{-4} ± 3.0 x 10^{-4} kg CH_4/ kg for sulphuric acid (Ref. 15).

(w) Enzyme AMG consumption rate of 247,176 kg/a (Ref. 11), or 2.3 kg/t of distillate, and a total methane requirement of 6 x 10^{-6} kg CH_4/ kg for enzyme AMG (Refs. 16 to 18).

(x) Enzyme Alpha Amylase consumption rate of 137,007 kg/a (Ref. 11), or 1.3 kg/t of distillate, and a total methane requirement of 4 x 10^{-6} kg CH_4/ kg for enzyme alpha amylase (Refs. 16 to 18).

(y) Calcium chloride consumption rate of 90,317 kg/a (Ref. 11), or 0.9 kg/t of distillate, and a total methane requirement of 2 x 10^{-4} kg CO_2/ kg for (Ref. 19).

(z) Distillate (94.5% alcohol) requirement 1.058 t/t of bioethanol and allocation of 84.4% to bioethanol.

(aa) Assuming dehydration accounts for electricity consumption of 373 MJ/hr from the combined heat and power plant, based pro-rata on the power requirement of dehydration electrical equipment (78 kWh/hr) compared to the total power requirement of the bioethanol plant (4,512 kWh/hr), or 1.7% of the total electrical output (Ref. 11).

(bb) Total bioethanol output rate of 12.4 t/hr, based on an annual output rate of 100,000 t/a of bioethanol and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 11).

(cc) Surplus electricity for sale equal to 3,716 MJ/t of bioethanol which displaces average electricity supplies with a methane requirement of 4.043 x 10^{-4} kg CH_4/MJ for the UK in 1996 (Ref. 8).

(dd) Primary energy input of 1,282,500 GJ for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £51.3 m (Ref. 11) and an energy intensity of 25 MJ/£ (Ref. 16) , and an estimated total methane requirement of 1.192 x 10^{-7} kg CH_4/MJ primary energy input to construction (Ref. 18), assuming 84.4% contribution to bioethanol by price of co-products.

(ee) Methane output of annual plant maintenance assumed to be 1.5% of methane output from plant construction (Ref. 11).

(ff) Average round trip distance of 450 km (Ref. 20) by bulk road carrier transport with a direct methane requirement of 4.900 x 10^{-7} ± 2.000 x 10^{-8} kg CH_4/t-km, an indirect methane requirement of 1.672 x 10^{-5} ± 6.3 x 10^{-7} kg CH_4/t-km and a total methane requirement of 1.721 x 10^{-5} ± 6.5 x 10^{-7} kg CH_4/t-km (Ref. 13).

References

1. "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.

2. Annual average ex-farm price of feed wheat, United Kingdom, 2000/02 from www.hgca.com/c-stats accessed 3 February 2003.

3. Private communication with D. Darby, British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication, based on an assumed derogation of fuel duty of 26 p/l and a delivered market price of 39 p/l for bioethanol, with G. Punter, British Sugar plc. Peterborough, United Kingdom, 28 January 2003.

5. "British Survey of Fertiliser Practice 1999", Fertiliser Manufacturers' Association.

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003.

7. "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

8. "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

9. "Pesticide Use Survey" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. "Farm Management Pocket Handbook" by J. Nix, Wye College, University of London, United Kingdom, 2002.

11. Private communication with A. Nixon, British Sugar plc., Peterborough, United Kingdom, 22 January 2003.

12. "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.

13. "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.

14. "Düngemittel – Energie- und Stoffstrombilanzen" (Fertilisers – Energy and Material Balance) by A. Patyk and G. A. Reinhardt, Vieweg Umweltwissenschaften, Braunschweig/Wiesbaden, Germany, 1997.

15. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

16. "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.

17. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

18. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

19. "Interim Report on Energy-Use in Metallurgical and Non-Metallic Mineral Processing, Phase 5" Battelle Columbus Laboratories, PB-246-357, United States of America, 1975.

20. "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.

Spreadsheet for Nitrous Oxide Outputs from Bioethanol Production from Wheat (Model 3a)

Functional Unit: :	Bioethanol at point of distribution derived from wheat
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on average market prices, assuming 1.394 tonnes of wheat straw at £25/t (Ref. 1) and 3.425 tonnes of harvested wheat grain with 20% moisture content at £69/t (Ref. 2), giving a 87.1% allocation to bioethanol, and 1.141 tonnes of animal feed at £80/t (Ref. 3) and 1.000 tonnes of bioethanol at £494/t (Ref. 4), giving a 84.4% allocation to bioethanol.

Contribution	Per Unit	Nitrous Oxide Output (kg N_2O)						Notes
		Direct		Indirect		Total		
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	*ha.a*	*0.666*	*±0.100*	*2.720*	*±0.408*	*3.386*	*±0.420*	(a, b)
- P Fertiliser	*ha.a*	-	-	*0.004*	*±0.001*	*0.004*	*±0.001*	(b, c)
- K Fertiliser	*ha.a*	-	-	*0.001*	-	*0.001*	-	(b, d)
- Pesticide	*ha.a*	-	-	*0.003*	-	*0.003*	-	(b, e)
- Herbicide	*ha.a*	-	-	-	-	-	-	(b, f)
- Insecticide	*ha.a*	-	-	*0.001*	-	*0.001*	-	(b, g)
- Fungicide	*ha.a*	-	-	*0.002*	-	*0.002*	-	(b, h)
- Seed	*ha.a*	-	-	*0.185*	*±0.028*	*0.185*	*±0.028*	(b, i)
- Diesel Fuel	*ha.a*	*0.003*	-	-	-	*0.003*	-	(b, j)
Reference System:								
- Diesel Fuel	*ha.a*	*- 0.001*	-	-		*- 0.001*	-	(b, k)
Sub-Totals	*ha.a*	*0.668*	*±0.100*	*2.916*	*±0.409*	*3.584*	*±0.421*	
	t be	**0.195**	**±0.029**	**0.853**	**±0.120**	**1.048**	**±0.123**	(l)
Drying:								
- Diesel Fuel	*t hwg*	-	-	-	-	-	-	(b, m)
	t be	**-**	**-**	**-**	**-**	**-**	**-**	(n)
Transport:								
- Diesel Fuel	*t dwg*	-	-	-	-	-	-	(o)
	t be	**-**	**-**	**-**	**-**	**-**	**-**	(p)
Milling, Hydrolysis, Fermentation and Distillation:								
- Natural Gas	*t de*	*0.001*	-	-	-	*0.001*	-	(b,q - s)
- Caustic Soda	*t de*	-	-	-	-	-	-	(b, t)
- Diam. Phosph.	*t de*	-	-	-	-	-	-	(b, u)
- Sulphuric Acid	*t de*	-	-	-	-	-	-	(b, v)
- Enzyme AMG	*t de*	-	-	-	-	-	-	(b, w)
- Enzyme AA	*t de*	-	-	-	-	-	-	(b, x)
- Calcium Chlor.	*t de*	-	-	-	-	-	-	(b, y)
Sub-Totals	*t de*	*0.001*	-	-	-	*0.001*	-	(z)
	t be	**0.001**	**-**	**-**	**-**	**0.001**	**-**	
Dehydration:	*t dwg*	-	-	-	-	-	-	(b, q, aa,
- Natural Gas	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	bb)
Surplus Electricity	**t be**	**-0.017**	**-**	**-**	**-**	**-0.017**	**-**	(cc)
Plant Construction	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(b, dd)
Plant Maintenance	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(b, ee)
Distribution:								
- Diesel Fuel	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(ff)
Totals	**t be**	**0.179**	**±0.029**	**0.853**	**±0.120**	**1.032**	**±0.123**	

Biofuel Specifications

Density of bioethanol = 0.79 kg/l
Net calorific value of bioethanol = 26.72 MJ/kg
Gross calorific value of bioethanol = 29.74 MJ/kg

Abbreviations

ha.a = hectare year
t hwg = tonne of harvested wheat grain
t dwg = tonne of dried wheat grain
t de = tonne of distillate ethanol (94.5% alcohol)
t be = tonne of bioethanol

Notes

(a) Nitrogen fertiliser application rate of 185 N/ha.a (Ref. 5) and a direct nitrous oxide requirement of 0.0036 kg N_2O/kg N (Ref. 5), an indirect nitrous oxide requirement of 0.0147 kg N_2O/kg N (Ref. 6) and a total nitrous oxide requirement for ammonium nitrate of 0.0183 kg N_2O/kg N (Ref. 6).

(b) Assuming an error bar of ±15% based on similar analyses (Ref. 7).

(c) Phosphate fertiliser application rates of 41 kg P/ha.a (Ref. 5), or 93.9 kg P_2O_5/ ha.a assuming 2.290 kg P_2O_5/kg P, and a total nitrous oxide requirement for phosphate fertiliser of 4.2×10^{-5} kg N_2O/kg P_2O_5 (Ref. 8).

(d) Potash fertiliser application rate of 46 kg K/ha.a (Ref. 5), or 55.4 kg K_2O/ha.a assuming 1.205 kg K_2O/kg K, and a total nitrous oxide requirement for potash fertiliser of 9.4×10^{-6} kg N_2O/ kg K_2O (Ref. 5).

(e) Pesticide application rate of 2.0 kg/ha.a (Ref. 9) and a total nitrous oxide requirement for general pesticides, herbicides and fungicides of 1.51×10^{-3} kg N_2O/kg (Ref. 8).

(f) Herbicide application rate of 0.1 kg/ha.a (Ref. 9) and a total nitrous oxide requirement for general pesticides, herbicides and fungicides of 1.51×10^{-3} kg N_2O/kg (Ref. 8).

(g) Insecticide application rate of 0.8 kg/ha.a (Ref. 9) and a total nitrous oxide requirement for general pesticides, herbicides and fungicides of 1.51×10^{-3} kg N_2O/kg (Ref. 8).

(h) Fungicide application rate of 1.0 kg/ha.a (Ref. 9) and a total nitrous oxide requirement for general pesticides, herbicides and fungicides of 1.51×10^{-3} kg N_2O/kg (Ref. 8).

(i) Sowing rate of 185 kg/ha.a (Ref. 10) and a total nitrous oxide requirement of 0.001 kg N_2O/kg of seed assuming similarity with oilseed (Ref. 8).

(j) Diesel fuel consumption of 5,490 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides, insecticides and fungicides, harvesting, carting and loading (Ref. 11) and a direct nitrous oxide requirement of 5.64×10^{-7} kg N_2O/MJ, an indirect nitrous oxide requirement of 2.60×10^{-8} kg N_2/MJ and a total nitrous oxide requirement of 5.90×10^{-7} kg N_2O/MJ for diesel fuel in the UK in 1996 (Ref. 12).

(k) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 8) and a direct nitrous oxide requirement of 5.64×10^{-7} kg N_2O/MJ, an indirect nitrous oxide requirement of 2.60×10^{-8} kg N_2/MJ and a total nitrous oxide requirement of 5.90×10^{-7} kg N_2O/MJ for diesel fuel in the UK in 1996 (Ref. 12).

(l) Land requirement of 0.398 ha.a/t of bioethanol and allocation of 87.1% x 84.4% = 73.5% to bioethanol.

(m) Assuming 50% of the harvested wheat grain (1.7125 t/t of bioethanol) dries naturally to a moisture content of 14% and 50% of the harvested wheat grain (1.7125 t/t of bioethanol) requires artificial drying on the farm with a diesel fuel consumption of 677 MJ/t of harvested wheat grain with a moisture content of 19% (Ref. 11), and a direct nitrous oxide requirement of 5.64×10^{-7} kg N_2O/MJ, an indirect nitrous oxide requirement of 2.60×10^{-8} kg N_2/MJ and a total nitrous oxide requirement of 5.90×10^{-7} kg N_2O/MJ for diesel fuel in the UK in 1996 (Ref. 12).

(n) Harvested wheat grain requirement of 3.425 t/t of bioethanol and allocation of 84.4% to bioethanol.

(o) Average round trip distance of 186 km (Ref. 11) by bulk road carrier transport with a direct nitrous oxide requirement of $4.6 \times 10^{-7} \pm 1.7 \times 10^{-8}$ kg N_2O/t-km, an indirect nitrous oxide requirement of $2.1 \times 10^{-8} \pm 8 \times 10^{-10}$ kg N_2O/t-km and a total nitrous oxide requirement of $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8}$ kg N_2O/t-km (Ref. 13).

(p) Dried wheat grain requirement of 3.186 t/t of bioethanol and allocation of 84.4% to bioethanol.

(q) Natural Natural gas-fired combined heat and power plant with a gas turbine and overall efficiency of 85% producing 0.29 MJ of electricity and 0.52 MJ of steam from each MJ of natural gas (Ref. 11), giving a natural gas consumption rate of 1.180 MJ/MJ of energy output in the form of electricity or steam, and a direct nitrous requirement of 8.9×10^{-8} kg N_2O/MJ, an indirect nitrous oxide requirement of 1.1×10^{-8} kg N_2O/MJ and a total nitrous oxide requirement of 1.0×10^{-7} kg N_2O/MJ for natural gas in the UK in 1996 (Ref. 12).

(r) Assuming that milling, hydrolysis, fermentation and distillation accounts for all the steam provided from the combined heat and power plant, at a rate of 25.0 t/hr, accounting for 25.0/44.5 = 56.2% of total steam consumption, or 69,056 MJ/hr, and electricity consumption of 7,612 MJ/hr from the combined heat and power plant, based pro-rata on the power requirement of all milling, hydrolysis, fermentation and distillation electrical equipment (1,903 kWh/hr) compared to the total power requirement of the bioethanol plant (4,500 kWh/hr), or 42.3% of the total electrical output (Ref. 11).

(s) Total distillate (94.5% alcohol) output rate of 13.12 t/hr, based on an annual output rate of 105,800 t/a of distillate, or 100,000 t/a of bioethanol, and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 11).

(t) Caustic soda (49% concentration) consumption rate of 4,427,136 kg/a (Ref. 11), or 41.8 kg/t of distillate, and a total nitrous oxide requirement of 0 kg N_2O/kg for caustic soda (Ref. 7).

(u) Diammonium phosphate (21% concentration) consumption rate of 2,921,103 kg/a (Ref. 11), or 27.6 kg/t of distillate, and a total nitrous oxide requirement of 2×10^{-6} kg N_2O/kg for diammonium phosphate (Ref. 14).

(v) Sulphuric acid (93% concentration) consumption rate of 2,911,104 kg/a (Ref. 11), or 27.5 kg/t of distillate, and a total nitrous oxide requirement of $2 \times 10^{-7} \pm 3 \times 10^{-7}$ kg N_2O/ kg for sulphuric acid (Ref. 15).

(w) Enzyme AMG consumption rate of 247,176 kg/a (Ref. 11), or 2.3 kg/t of distillate, and a total nitrous oxide requirement of 9×10^{-8} kg N_2O/ kg for enzyme AMG (Refs. 16 to 18).

(x) Enzyme Alpha Amylase consumption rate of 137,007 kg/a (Ref. 11), or 1.3 kg/t of distillate, and a total nitrous oxide requirement of 6×10^{-8} kg N_2O / kg for enzyme alpha amylase (Refs. 16 to 18).

(y) Calcium chloride consumption rate of 90,317 kg/a (Ref. 11), or 0.9 kg/t of distillate, and a total nitrous oxide requirement of 4×10^{-7} kg kg N_2O / kg for (Ref. 19).

(z) Distillate (94.5% alcohol) requirement 1.058 t/t of bioethanol and allocation of 84.4% to bioethanol.

(aa) Assuming dehydration accounts for electricity consumption of 312 MJ/hr from the combined heat and power plant, based pro-rata on the power requirement of dehydration electrical equipment (78 kWh/hr) compared to the total power requirement of the bioethanol plant (4,500 kWh/hr), or 1.7% of the total electrical output (Ref. 11).

(bb) Total bioethanol output rate of 12.4 t/hr, based on an annual output rate of 100,000 t/a of bioethanol and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 11).

(cc) Surplus electricity for sale equal to 3,716 MJ/t of bioethanol which displaces average electricity supplies with a nitrous oxide requirement of 5.577×10^{-6} kg N_2O /MJ for the UK in 1996 (Ref. 8).

(dd) Primary energy input of 1,282,500 GJ for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £51.3 m (Ref. 11) and an energy intensity of 25 MJ/£ (Ref. 16) , and an estimated total nitrous oxide requirement of 1.866×10^{-9} kg N_2O/MJ of primary energy input to construction (Ref. 18), assuming 84.4% contribution to bioethanol by price of co-products.

(ee) Nitrous oxide output of annual plant maintenance assumed to be 1.5% of nitrous oxide output from plant construction (Ref. 11).

(ff) Average round trip distance of 450 km (Ref. 20) by bulk road carrier transport with a direct nitrous oxide requirement of $4.6 \times 10^{-7} \pm 1.7 \times 10^{-8}$ kg N_2O/t-km, an indirect nitrous oxide requirement of $2.1 \times 10^{-8} \pm 8 \times 10^{-10}$ kg N_2O/t-km and a total nitrous oxide requirement of $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8}$ kg N_2O/t-km (Ref. 13).

References

1. "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.

2. Annual average ex-farm price of feed wheat, United Kingdom, 2000/02 from www.hgca.com/c-stats accessed 3 February 2003.

3. Private communication with D. Darby, British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication, based on an assumed derogation of fuel duty of 26 p/l and a delivered market price of 39 p/l for bioethanol, with G. Punter, British Sugar plc. Peterborough, United Kingdom, 28 January 2003.

5. "British Survey of Fertiliser Practice 1999", Fertiliser Manufacturers' Association.

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003.

7. "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

8. "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

9. "Pesticide Use Survey" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. "Farm Management Pocket Handbook" by J. Nix, Wye College, University of London, United Kingdom, 2002.

11. Private communication with A. Nixon, British Sugar plc., Peterborough, United Kingdom, 22 January 2003.

12. "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.

13. "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.

14. "Düngemittel – Energie- und Stoffstrombilanzen" (Fertilisers – Energy and Material Balance) by A. Patyk and G. A. Reinhardt, Vieweg Umweltwissenschaften, Braunschweig/Wiesbaden, Germany, 1997.

15. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

16. "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.

17. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

18. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

19. "Interim Report on Energy-Use in Metallurgical and Non-Metallic Mineral Processing, Phase 5" Battelle Columbus Laboratories, PB-246-357, United States of America, 1975.

20. "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.

Spreadsheet for Greenhouse Gas Outputs from Bioethanol Production from Wheat (Model 3a)

Functional Unit: :	Bioethanol at point of distribution derived from wheat
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on average market prices, assuming 1.394 tonnes of wheat straw at £25/t (Ref. 1) and 3.425 tonnes of harvested wheat grain with 20% moisture content at £69/t (Ref. 2), giving a 87.1% allocation to bioethanol, and 1.141 tonnes of animal feed at £80/t (Ref. 3) and 1.000 tonnes of bioethanol at £494/t (Ref. 4), giving a 84.4% allocation to bioethanol.

Contribution	Per Unit	Total Greenhouse Gas Output (kg eq CO_2)						Notes
		Direct		Indirect		Total		
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	*ha.a*	*213*	*±32*	*1,239*	*±140*	*1,452*	*±144*	(a)
- P Fertiliser	*ha.a*	-	-	*67*	*±10*	*67*	*±10*	(a)
- K Fertiliser	*ha.a*	-	-	*25*	*±4*	*25*	*±4*	(a)
- Pesticide	*ha.a*	-	-	*11*	*±1*	*11*	*±1*	(a)
- Herbicide	*ha.a*	-	-	-	-	-	-	(a)
- Insecticide	*ha.a*	-	-	*4*	*±1*	*4*	*±1*	(a)
- Fungicide	*ha.a*	-	-	*6*	*±1*	*6*	*±1*	(a)
- Seed	*ha.a*	-	-	*125*	*±13*	*125*	*±13*	(a)
- Diesel Fuel	*ha.a*	*378*	*±60*	*47*	*±20*	*425*	*±63*	(a)
Reference System:								
- Diesel Fuel	*ha.a*	*- 63*	*±10*	*- 7*	*±3*	*- 70*	*±11*	(a)
Sub-Totals	*ha.a*	*528*	*±68*	*1,517*	*±142*	*2,045*	*±158*	
	t be	**154**	**±20**	**444**	**±42**	**598**	**±46**	(b)
Drying:								
- Diesel Fuel	*t hwg*	*23*	*±4*	*3*	-	*26*	*±4*	(a)
	t be	**66**	**±12**	**9**	**-**	**75**	**±12**	(c)
Transport:								
- Diesel Fuel	*t dwg*	*10*	-	*3*	-	*13*	-	(a)
	t be	**27**	**±1**	**8**	**-**	**35**	**±1**	(d)
Milling, Hydrolysis, Fermentation and Distillation:								
- Natural Gas	*t de*	*360*	*±54*	*30*	*±10*	*390*	*±55*	(a)
- Caustic Soda	*t de*	-	-	*50*	*±7*	*50*	*±7*	(a)
- Diam. Phosph.	*t de*	-	-	*2*	-	*2*	-	(a)
- Sulphuric Acid	*t de*	-	-	*4*	*±4*	*4*	*±4*	(a)
- Enzyme AMG	*t de*	-	-	*5*	*±1*	*5*	*±1*	(a)
- Enzyme AA	*t de*	-	-	*2*	-	*2*	-	(a)
- Calcium Chlor.	*t de*	-	-	*1*	-	*1*	-	(a)
Sub-Totals	*t de*	*360*	*±54*	*94*	*±13*	*454*	*±56*	
	t be	**321**	**±48**	**84**	**±12**	**405**	**±50**	(e)
Dehydration:								(a)
- Natural Gas	**t be**	**2**	**-**	**-**	**-**	**2**	**-**	
Surplus Electricity	**t be**	**-298**	**-**	**-**	**-**	**-298**	**-**	(a)
Plant Construction	**t be**	**-**	**-**	**27**	**±4**	**27**	**±4**	(a)
Plant Maintenance	**t be**	**-**	**-**	**8**	**±1**	**8**	**±1**	(a)
Distribution:								
- Diesel Fuel	**t be**	**25**	**±1**	**7**	**±1**	**32**	**±1**	(a)
Totals	**t be**	**297**	**±53**	**587**	**±44**	**884**	**±69**	

Biofuel Specifications

Density of bioethanol = 0.79 kg/l
Net calorific value of bioethanol = 26.72 MJ/kg
Gross calorific value of bioethanol = 29.74 MJ/kg

Abbreviations

ha.a = hectare year
t hwg = tonne of harvested wheat grain
t dwg = tonne of dried wheat grain
t de = tonne of distillate ethanol (94.5% alcohol)
t be = tonne of bioethanol

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 0.398 ha.a/t of bioethanol and allocation of 87.1% x 84.4% = 73.5% to bioethanol.

(c) Harvested wheat grain requirement of 3.425 t/t of bioethanol and allocation of 84.4% to bioethanol.

(d) Dried wheat grain requirement of 3.186 t/t of bioethanol and allocation of 84.4% to bioethanol.

(e) Distillate (94.5% alcohol) requirement 1.058 t/t of bioethanol and allocation of 84.4% to bioethanol.

References

1. "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.

2. Annual average ex-farm price of feed wheat, United Kingdom, 2000/02 from www.hgca.com/c-stats accessed 3 February 2003.

3. Private communication with D. Darby, British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication, based on an assumed derogation of fuel duty of 26 p/l and a delivered market price of 39 p/l for bioethanol, with G. Punter, British Sugar plc. Peterborough, United Kingdom, 28 January 2003.

APPENDIX D: Model 7

Spreadsheet for Primary Energy Inputs to Bioethanol Production from Wheat Using Straw as Fuel (Model 7)

Functional Unit:	Bioethanol at point of distribution derived from wheat using straw-fired combined heat and power generation during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on average market prices, assuming 1.394 tonnes of wheat straw at £25/t (Ref. 1) and 3.425 tonnes of harvested wheat grain with 20% moisture content at £69/t (Ref. 2), giving a 87.1% allocation to bioethanol, and 1.141 tonnes of animal feed at £80/t (Ref. 3) and 1.000 tonnes of bioethanol at £494/t (Ref. 4), giving a 84.4% allocation to bioethanol.

Contribution	Per Unit	Primary Energy Input (MJ)								
		Direct		Indirect		Feedstock		Total		Notes
		Value	Range	Value	Range	Value	Range	Value	Range	
Cult. & Harvest:										
- N Fertiliser	ha.a	-	-	2,592	±1,036	4,920	±196	7,512	±1,054	(a)
- P Fertiliser	ha.a	-	-	1,484	±223	-	-	1,484	±223	(b, c)
- K Fertiliser	ha.a	-	-	515	±77	-	-	515	±77	(c, d)
- Pesticide	ha.a	-	-	548	±82	-	-	548	±82	(c, e)
- Herbicide	ha.a	-	-	27	±4	-	-	27	±4	(c, f)
- Insecticide	ha.a	-	-	219	±33	-	-	219	±33	(c, g)
- Fungicide	ha.a	-	-	274	±41	-	-	274	±41	(c, h)
- Seed	ha.a	-	-	2,498	±375	-	-	2,498	±375	(c, i)
- Diesel Fuel	ha.a	5,490	±868	604	±288	-	-	6,094	±914	(c, j)
Reference System:										
- Diesel Fuel	ha.a	-922	±146	- 101	±48	-	-	-1,023	±154	(c, k)
Sub-Totals	ha.a	4,568	±880	8,660	±1,168	4,920	±196	18,148	±1,477	
	t be	1,336	±257	2,534	±342	1,439	±57	5,309	±432	(l)
Straw Baling:										
- N Fertiliser	ha.a	-	-	830	±332	1,577	±63	2,407	±338	(m)
- P Fertiliser	ha.a	-	-	387	±58	-	-	381	±58	(c, n)
- K Fertiliser	ha.a	-	-	1,151	±173	-	-	1,129	±173	(c, o)
- Diesel Fuel	ha.a	343	±51	25	±4	-	-	368	±51	(c, p)
- Machinery	ha.a	-	-	403	±60	-	-	403	±60	(c, q)
- Twine	ha.a	-	-	-	-	94	±14	94	±14	(c, r)
- Maintenance	ha.a	-	-	175	±26	-	-	175	±26	(c, s)
Sub-Totals	ha.a	343	±51	2971	±512	1,671	±63	4,985	±518	
	t be	115	±17	999	±172	562	±21	1,676	±174	(t)
Straw Transport:										
- Diesel Fuel	t bws	66	±2	23	±3	-	-	89	±4	(u)
	t be	77	±1	27	±2	-	-	104	±2	(v)
Straw Storage:										
- Diesel Fuel	t bws	66	±10	7	±3	-	-	73	±11	(c,w)
- Sheeting	t bws	-	-	94	±14	92	±14	186	±20	(c, x)
- Machinery	t bws	-	-	21	±3	-	-	21	±3	(c, y)
- Maintenance	t bws	-	-	7	±1	-	-	7	±1	(c, z)
Sub-Totals	t bws	66	±10	129	±15	92	±14	287	±23	
	t be	77	±5	150	±8	107	±8	334	±12	(v)
Wheat Transport:										
- Diesel Fuel	thwgt	152	±6	53	±7	-	-	205	±9	(aa)
	be	440	±18	154	±20	-	-	594	±25	(bb)
Wheat Drying:	t be	-	-	-	-	-	-	-	-	(bb) (cc)
Mill., Hydro., Ferm. and Distill.:										(dd) (ee)
- Caustic Soda	t de	-	-	836	±125	-	-	836	±125	(ff)
- Diam. Phosph.	t de	-	-	55	±8	-	-	55	±8	(gg)
- Sulphuric Acid	t de	-	-	66	±74	-	-	66	±74	(hh)
- Enzyme AMG	t de	-	-	110	±16	-	-	110	±16	(ii)
- Enzyme AA	t de	-	-	43	±6	-	-	43	±6	(jj)
- Calcium Chlor.	t de	-	-	6	±1	-	-	6	±1	(kk)
Sub-Totals	t de	-	-	1116	±146	-	-	1116	±146	
	t be	-	-	1,044	±130	-	-	1,044	±130	(ll)
Dehydration:	t be	-	-	-	-	-	-	-	-	(c)(mm)(nn)
Surplus Electric.	t be	-12,945	-	-	-	-	-	-12,945	-	(oo)
Plant Construct.	t be	32	-	1,044	-	-	-	1,076	±156	(pp)-(rr)
Plant Mainten.	t be	-	-	430	-	-	-	430	±65	(ss)
Ash Disposal:	t ash	66	±2	23	±3	-	-	89	±4	(tt)
	t be	3	-	1	-	-	-	4	-	(uu)
Distribution:										
- Diesel Fuel	t be	369	±14	129	±16	-	-	498	±21	(vv)
Totals	t be	10,496	±259	6,512	±439	2,108	±61	-1,876	±513	

Biofuel Specifications

Density of bioethanol	= 0.79 kg/l
Net calorific value of bioethanol	= 26.72 MJ/kg
Gross calorific value of bioethanol	= 29.74 MJ/kg

Abbreviations

ha.a	= hectare year
t bws	= tonne of baled wheat straw
t hwg	= tonne of harvested wheat grain
t dwg	= tonne of dried wheat grain
t ash	= tonne of ash
t be	= tonne of bioethanol

Notes

(a) Nitrogen fertiliser application rate of 185 kg N/ha.a (Ref. 5) 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 nitrogen fertiliser (Ref. 6).

(b) Phosphate fertiliser application rates of 41 kg P/ha.a (Ref. 5), or 93.9 kg P_2O_5/ ha.a assuming 2.290 kg P_2O_5/kg P, and a total energy requirement for phosphate fertiliser of 15.8 MJ/kg P_2O_5 (Ref. 7).

(c) Assuming an error bar of ±15% based on similar analyses (Ref. 8).

(d) Potash fertiliser application rate of 46 kg K/ha.a (Ref. 5), or 55.4 kg K_2O/ha.a assuming 1.205 kg K_2O/kg K, and a total energy requirement for potash fertiliser of 9.3 MJ/ kg K_2O (Ref. 7).

(e) Pesticide application rate of 2.0 kg/ha.a (Ref. 9) and a total energy requirement for general pesticides, herbicides and fungicides of 274.1 MJ/kg (Ref. 7).

(f) Herbicide application rate of 0.1 kg/ha.a (Ref. 9) and a total energy requirement for general pesticides, herbicides and fungicides of 274.1 MJ/kg (Ref. 7).

(g) Insecticide application rate of 0.8 kg/ha.a (Ref. 9) and a total energy requirement for general pesticides, herbicides and fungicides of 274.1 MJ/kg (Ref. 7).

(h) Fungicide application rate of 1.0 kg/ha.a (Ref. 9) and a total energy requirement for general pesticides, herbicides and fungicides of 274.1 MJ/kg (Ref. 7).

(i) Sowing rate of 185 kg/ha.a (Ref. 10) and a total energy requirement of 13.5 MJ/kg of seed (Ref. 11).

(j) Diesel fuel consumption of 5,490 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides, insecticides and fungicides, harvesting, carting and loading (Ref. 12) and a gross energy requirement of 1.110 MJ/MJ for diesel fuel in the UK in 1996 (Ref. 13).

(k) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 7) and a gross energy requirement of 1.110 MJ/MJ for diesel fuel in the UK in 1996 (Ref. 13).

(l) Land requirement of 0.398 ha.a/t of bioethanol and allocation of 87.1% x 84.4% = 73.5% to bioethanol.

(m) Ammonium nitrate fertiliser application rate of 59.31 kg N /ha.a to replace straw removal, based on Canadian data (Ref. 21) adjusted pro rata to an average wheat straw yield of 3.5 t/ha.a (Ref. 12) with 1.394 t straw collected for fuel from 0.398ha.a/t bioethanol, 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 (Ref. 6).

(n) Phosphate fertiliser application rate of 24.54 kg P_2O_5/ ha.a to replace straw removal, based on Canadian data (Ref. 21) adjusted pro rata to an average wheat straw yield of 3.5 t/ha.a with 1.394 t straw collected for fuel from 0.398ha.a/t bioethanol, and a total energy requirement for phosphate fertiliser of 15.8 MJ/kg P_2O_5 (Ref. 7).

(o) Potash fertiliser application rate of 123.8 kg K_2O/ha.a to replace straw removal, based on Canadian data (Ref. 21) adjusted pro rata to an average wheat straw yield of 3.5 t/ha.a with 1.394 t straw collected for fuel from 0.398ha.a/t bioethanol, and a total energy requirement for potash fertiliser of 9.3 MJ/ kg K_2O (Ref. 7).

(p) Diesel fuel consumption for baling of 215 MJ/ha.a and loading in the field of 128 MJ/ha.a, based on data for straw fuel recovery (Ref. 22) adjusted for collection of 1.394 t straw from 0.398 ha.a/t bioethanol, and a gross energy requirement of 1.110 MJ/MJ for diesel fuel in the UK in 1996 (Ref. 8).

(q) Primary energy input to manufacture of tractor for baling of 52 MJ/ha.a, Hesston baler of 312 MJ/ha.a and telescopic handler for loading in field of 41 MJ/ha.a, based on data for straw fuel recovery (Ref. 22) adjusted for collection of 1.394 t straw from 0.398 ha.a/t bioethanol.

(r) Primary energy input to manufacture of baling twine of 94.3 MJ/ha.a, based on data for straw fuel recovery (Ref. 22) adjusted for collection of 1.394 t straw from 0.398 ha.a/t bioethanol.

(s) Primary energy input to maintenance and repair of tractor for baling of 13.25 MJ/ha.a, of Hesston baler of 147 MJ/ha.a and of telescopic handler for loading in the field of 14.1MJ/ha.a, based on data for straw fuel recovery (Ref. 22) adjusted for collection of 1.394 t straw from 0.398 ha.a/t bioethanol.

(t) Land requirement of 0.398 ha.a/t bioethanol and partitioning, based on relative energy, with heat and electricity measured on an equivalent basis, to drying (13%), to milling, hydrolysis, fermentation and distillation (86.6%), and to dehydration (0.4%), and allocation between bioethanol and animal feed (84.4%), resulting in a total allocation to bioethanol of (99.6% x 84.4%)+ (0.4%) = 84.5%.

(u) Average round trip distance of 80 km (Ref. 10) 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. 14).

(v) Baled straw requirement of 1.38 t/t bioethanol and partitioning, based on relative energy, with heat and electricity measured on an equivalent basis, to drying (13%), to milling, hydrolysis, fermentation and distillation (86.6%), and to dehydration (0.4%), and allocation between bioethanol and animal feed (84.4%), resulting in a total allocation to bioethanol of (99.6% x 84.4%)+ (0.4%) = 84.5%.

(w) Diesel fuel consumption for baled straw handling in storage of 65.8 MJ/t of baled wheat straw (Ref. 22) and a gross energy requirement of 1.110 MJ/MJ for diesel fuel in the UK in 1996 (Ref. 13).

(x) Based on 2 tonnes of polyethylene sheeting used to protect each storage stack of 1,000 tonnes of baled wheat straw, with a life of 1 year and a direct energy requirement of 47 MJ/kg and a feedstock energy requirement of 46 MJ/kg for low density polyethylene (Ref. 22).

(y) Primary energy input for manufacture of telescopic handler of 21.0 MJ/t of baled wheat straw (Ref. 22).

(z) Primary energy input to maintenance and repair of telescopic handler of 7.2 MJ/t of baled wheat straw (Ref. 22).

(aa) Average round trip distance of 186 km (Ref. 12) 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. 14).

(bb) Harvested wheat grain requirement of 3.425 t/t of bioethanol and allocation of 84.4% to bioethanol.

(cc) Heat supplied by a straw-fired combined heat and power plant equivalent to 271 MJ/ t of harvested wheat grain, based on pro-rata diesel fuel consumption of 677 MJ/t of harvested wheat grain with a moisture content of 19% (Ref. 12) and a boiler efficiency of 80%. Assuming 50% of the harvested wheat grain (1.7125 t/t of bioethanol) requires artificial drying and 50% of the harvested wheat grain dries naturally on the farm to a moisture content of 14%.

(dd) Heat and electricity supplied by a straw-fired combined heat and power plant. Assuming that milling, hydrolysis, fermentation and distillation accounts for all the steam provided from the combined heat and power plant, at a rate of 25.0 t/hr, accounting for 25.0/44.5 = 56.2% of total steam consumption, or 69,450 MJ/hr, and electricity consumption of 7,612 MJ/hr from the combined heat and power plant, based pro-rata on the power requirement of all milling, hydrolysis, fermentation and distillation electrical equipment (1,903 kWh/hr) compared to the total power requirement of the bioethanol plant (4,500 kWh/hr), or 42.3% of the total electrical output (Ref. 12).

(ee) Total distillate (94.5% alcohol) output rate of 13.12 t/hr, based on an annual output rate of 105,800 t/a of distillate, or 100,000 t/a of bioethanol, and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 12).

(ff) Caustic soda (49% concentration) consumption rate of 4,427,136 kg/a (Ref. 12), or 41.8 kg/t of distillate, and an energy requirement of 20 MJ/kg for caustic soda (Ref. 7).

(gg) Diammonium phosphate (21% concentration) consumption rate of 2,921,103 kg/a (Ref. 12), or 27.6 kg/t of distillate, and an energy requirement of 2 MJ/kg for diammonium phosphate (Ref. 15).

(hh) Sulphuric acid (93% concentration) consumption rate of 2,911,104 kg/a (Ref. 12), or 27.5 kg/t of distillate, and an energy requirement of 2.4 ± 2.7 MJ/kg for sulphuric acid (Ref. 16).

(ii) Enzyme AMG consumption rate of 247,176 kg/a (Ref. 12), or 2.3 kg/t of distillate, and an energy requirement of 47 MJ/kg for enzyme AMG (Refs. 17 to 19).

(jj) Enzyme Alpha Amylase consumption rate of 137,007 kg/a (Ref. 12), or 1.3 kg/t of distillate, and an energy requirement of 33 MJ/kg for enzyme alpha amylase (Refs. 17 to 19).

(kk) Calcium chloride consumption rate of 90,317 kg/a (Ref. 12), or 0.9 kg/t of distillate, and an energy requirement of 7 MJ/kg for calcium chloride (Ref. 20).

(ll) Distillate (94.5% alcohol) requirement 1.058 t/t of bioethanol and allocation of 84.4% to bioethanol.

(mm) Assuming dehydration accounts for electricity consumption of 312 MJ/hr from the combined heat and power plant, based pro-rata on the power requirement of dehydration electrical equipment (78 kWh/hr) compared to the total power requirement of the bioethanol plant (4,500 kWh/hr), or 1.7% of the total electrical output supplied by the straw fired CHP plant (Ref. 12).

(nn) Total bioethanol output rate of 12.4 t/hr, based on an annual output rate of 100,000 t/a of bioethanol and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 12).

(oo) Surplus electricity for sale equal to 4,975 MJ/t of bioethanol which displaces average electricity supplies with a gross energy requirement of 3.083 MJ/ MJ for the UK in 1996 (Ref. 13) and assuming 84.4% contribution to bioethanol by price of co-products.

(pp) Primary energy input of 1,282,500 GJ for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £51.3 m (Ref. 12) and an energy intensity of 25 MJ/£ (Ref. 17), and assuming 84.4% contribution to bioethanol by price of co-products.

(qq) Straw-fired combined heat and power plant with a 32 MW rated heat output and a 22 MW rated electricity output and a load factor of 91% which has a straw fuel feed consumption of 124,066 t/a, providing a total heat supplies of 9,181 MJ/t of bioethanol (consisting of 783 MJ/ t of bioethanol for drying, 4,698 MJ/t of bioethanol for milling, hydrolysis, fermentation and distillation, and 25 MJ/t of bioethanol for dehydration with excess heat of 3,580 MJ/t of bioethanol) and total electricity supplies of 6,427 MJ/t of bioethanol (consisting of 515 MJ/t of bioethanol for milling, hydrolysis, fermentation and distillation, 25 MJ/t for dehydration, 912 MJ/t of bioethanol for the animal feed plant and 4,975 MJ/t of bioethanol of surplus for sale).

(rr) Primary energy input of 1,581,800 GJ for construction of a straw-fired combined heat and power plant with a 32 MW rated heat output and a 22 MW rated electricity output, based pro rata on data for a straw-fired combined heat and power plant with a 13.0 MW rated heat output and a 5.0 MW rated electricity output (Ref. 22), with a 25 year life.

(ss) Primary energy input of annual plant maintenance assumed to be 1.5% of primary energy input to plant construction (Ref. 12).

(tt) Ash sent for spreading as a fertiliser on fields at an average round trip distance of 80km (Ref.22) 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. 11).

(uu) Ash output of 5.5% of straw fuel feed (Ref. 22) and straw requirement of 1.242 t/t of bioethanol.

(vv) Average round trip distance of 450 km (Ref. 20) 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. 14).

References

1. "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.

2. Annual average ex-farm price of feed wheat, United Kingdom, 2000/02 from www.hgca.com/c-stats accessed 3 February 2003.

3. Private communication with D. Darby, British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication, based on an assumed derogation of fuel duty of 26 p/l and a delivered market price of 39 p/l for bioethanol, with G. Punter, British Sugar plc. Peterborough, United Kingdom, 28 January 2003.

5. "British Survey of Fertiliser Practice 1999", Fertiliser Manufacturers' Association.

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003.

7. "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

8. "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

9. "Pesticide Use Survey" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. "Farm Management Pocket Handbook" by J. Nix, Wye College, University of London, United Kingdom, 2002.

11. "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.

12. Private communication with A. Nixon, British Sugar plc., Peterborough, United Kingdom, 22 January 2003.

13. "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.

14. "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.

15. "Düngemittel – Energie- und Stoffstrombilanzen" (Fertilisers – Energy and Material Balance) by A. Patyk and G. A. Reinhardt, Vieweg Umweltwissenschaften, Braunschweig/Wiesbaden, Germany, 1997.

16 "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

17. "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.

18. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

19. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

20. "Interim Report on Energy-Use in Metallurgical and Non-Metallic Mineral Processing, Phase 5" Battelle Columbus Laboratories, PB-246-357, United States of America, 1975.

21. "Assessment of Net Emissions of Greenhouse Gases from Ethanol-Blended Gasolines in Canada: Lignocellulosic Feedstocks" R-2000-2, Levelton Engineering Ltd., Richmond, Canada, December 1998.

22. "Energy and Carbon Analysis of Using Straw as a Fuel" by J. F. Grant, R. Hetherington, R. E. Horne and N. D. Mortimer, Report ETSU B/M4/00487/01, Energy Technology Support Unit, Harwell, United Kingdom, 1995

Spreadsheet for Carbon Dioxide Outputs from Bioethanol Production from Wheat Using Straw as Fuel (Model 7)

Functional Unit: :	Bioethanol at point of distribution derived from wheat using natural gas-fired combined heat and power generation during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on average market prices, assuming 1.394 tonnes of wheat straw at £25/t (Ref. 1) and 3.425 tonnes of harvested wheat grain with 20% moisture content at £69/t (Ref. 2), giving a 87.1% allocation to bioethanol, and 1.141 tonnes of animal feed at £80/t (Ref. 3) and 1.000 tonnes of bioethanol at £494/t (Ref. 4), giving a 84.4% allocation to bioethanol.

Contribution	Per Unit	Carbon Dioxide Output (kg CO_2)						
		Direct		Indirect		Total		Notes
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	*ha.a*	-	-	*352*	*±51*	*352*	*±51*	(a)
- P Fertiliser	*ha.a*	-	-	*66*	*±10*	*66*	*±10*	(b, c)
- K Fertiliser	*ha.a*	-	-	*25*	*±4*	*25*	*±4*	(c, d)
- Pesticide	*ha.a*	-	-	*10*	*±1*	*10*	*±1*	(c, e)
- Herbicide	*ha.a*	-	-	-	-	-	-	(c, f)
- Insecticide	*ha.a*	-	-	*4*	*±1*	*4*	*±1*	(c, g)
- Fungicide	*ha.a*	-	-	*5*	*±1*	*5*	*±1*	(c, h)
- Seed	*ha.a*	-	-	*66*	*±10*	*66*	*±10*	(c, i)
- Diesel Fuel	*ha.a*	*377*	*±60*	*44*	*±20*	*421*	*±63*	(c, j)
Reference System:								
- Diesel Fuel	*ha.a*	*- 63*	*±10*	*- 7*	*±3*	*- 70*	*±11*	(c, k)
Sub-Totals	*ha.a*	*314*	*±61*	*565*	*±57*	*879*	*±83*	
	t be	**92**	**±18**	**165**	**±17**	**257**	**±25**	(l)
Straw Baling:								
- N Fertiliser	*ha.a*	-	-	*113*	*±16*	*113*	*±16*	(m)
- P Fertiliser	*ha.a*	-	-	*17*	*±3*	*17*	*±3*	(c, n)
- K Fertiliser	*ha.a*	-	-	*56*	*±8*	*56*	*±8*	(c, o)
- Diesel Fuel	*ha.a*	*23*	*±3*	*3*	-	*26*	*±3*	(c, p)
- Machinery	*ha.a*	-	-	*19*	*±3*	*19*	*±3*	(c, q)
- Twine	*ha.a*	-	-	*7*	*±1*	*7*	*±1*	(c, r)
- Maintenance	*ha.a*	-	-	*8*	*±1*	*8*	*±1*	(c, s)
Sub-Totals	*ha.a*	*23*	*±3*	223	*±18*	*246*	*±19*	
	t be	**8**	**±1**	**75**	**±6**	**83**	**±6**	(t)
Straw Transport:								
- Diesel Fuel	*t bws*	*4*	*±1*	*1*	-	*5*	*±1*	(u)
	t be	**5**	**±1**	**1**	**-**	**6**	**±1**	(v)
Straw Storage:								
- Diesel Fuel	*t bws*	*5*	*±1*	*1*	-	*6*	*±1*	(c,w)
- Sheeting	*t bws*	-	-	*12*	*±2*	*12*	*±2*	(c, x)
- Machinery	*t bws*	-	-	*1*	-	*1*	-	(c, y)
- Maintenance	*t bws*	-	-	-	-	-	-	(c, z)
Sub-Totals	*t bws*	*5*	*±1*	*14*	*±2*	*19*	*±2*	
	t be	**6**	**±1**	**16**	**±2**	**22**	**±2**	(v)
Wheat Transport:								
- Diesel Fuel	*t hwg*	*10*	*±1*	*3*	-	*13*	*±1*	(aa)
	t be	**30**	**±3**	**9**	**-**	**39**	**±3**	(bb)
Wheat Drying:	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(bb) (cc)
Milling, Hydrolysis, Fermentation and Distillation:								(dd) (ee)
- Caustic Soda	*t de*	-	-	*47*	*±7*	*47*	*±7*	(ff)
- Diam. Phosph.	*t de*	-	-	*2*	-	*2*	-	(gg)
- Sulphuric Acid	*t de*	-	-	*4*	*±4*	*4*	*±4*	(hh)
- Enzyme AMG	*t de*	-	-	*5*	*±1*	*5*	*±1*	(ii)
- Enzyme AA	*t de*	-	-	*2*	-	*2*	-	(jj)
- Calcium Chlor.	*t de*	-	-	*1*	-	*1*	-	(kk)
Sub-Totals	*t de*	-	-	*61*	*±8*	*61*	*±8*	
	t be	**-**	**-**	**54**	**±7**	**54**	**±7**	(ll)
Dehydration:	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(c)(mm)(nn)
Surplus Electricity	**t be**	**-630**	**-**	**-**	**-**	**-630**	**-**	(oo)
Plant Construction	**t be**	**-**	**-**	**55**	**±**	**55**	**±8**	(pp)-(rr)
Plant Maintenance	**t be**	**-**	**-**	**19**	**±**	**19**	**±3**	(ss)
Ash Disposal:	*t ash*	*4*	-	-	-	*4*	-	(tt) (uu)
	t be	**-**	**-**	**-**	**-**	**-**	**-**	
Distribution:								
- Diesel Fuel	**t be**	**25**	**±1**	**7**	**±1**	**32**	**±1**	(vv)
Totals	**t be**	**- 464**	**±18**	**401**	**±21**	**-63**	**±28**	

Biofuel Specifications

Density of bioethanol	= 0.79 kg/l
Net calorific value of bioethanol	= 26.72 MJ/kg
Gross calorific value of bioethanol	= 29.74 MJ/kg

Abbreviations

ha.a	= hectare year
t bws	= tonne of baled wheat straw
t hwg	= tonne of harvested wheat grain
t dwg	= tonne of dried wheat grain
t ash	= tonne of ash
t be	= tonne of bioethanol

Notes

(a) Nitrogen fertiliser application rate of 185 kg N/ha.a (Ref. 5) and a total carbon requirement for ammonium nitrate of 1.904 ± 0.275 kg CO_2/kg N (Ref. 6).

(b) Phosphate fertiliser application rates of 41 kg P/ha.a (Ref. 5), or 93.9 kg P_2O_5/ ha.a assuming 2.290 kg P_2O_5/kg P, and a total carbon requirement for phosphate fertiliser of 0.700 kg CO_2/kg P_2O_5 (Ref. 7).

(c) Assuming an error bar of ±15% based on similar analyses (Ref. 8).

(d) Potash fertiliser application rate of 46 kg K/ha.a (Ref. 5), or 55.4 kg K_2O/ha.a assuming 1.205 kg K_2O/kg K, and a total carbon requirement for potash fertiliser of 0.453 kg CO_2/ kg K_2O (Ref. 7).

(e) Pesticide application rate of 2.0 kg/ha.a (Ref. 9) and a total carbon requirement for general pesticides, herbicides and fungicides of 4.921 kg CO_2/kg (Ref. 7).

(f) Herbicide application rate of 0.1 kg/ha.a (Ref. 9) and a total carbon requirement for general pesticides, herbicides and fungicides of 4.921 kg CO_2/kg (Ref. 7).

(g) Insecticide application rate of 0.8 kg/ha.a (Ref. 9) and a total carbon requirement for general pesticides, herbicides and fungicides of 4.921 kg CO_2/kg (Ref. 7).

(h) Fungicide application rate of 1.0 kg/ha.a (Ref. 9) and a total carbon requirement for general pesticides, herbicides and fungicides of 4.921 kg CO_2/kg (Ref. 7).

(i) Sowing rate of 185 kg/ha.a (Ref. 10) and a total carbon requirement of 0.547 kg CO_2/kg of seed based on a ratio of 0.0405 kg CO_2/MJ for oilseed (Ref. 7).

(j) Diesel fuel consumption of 5,490 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides, insecticides and fungicides, harvesting, carting and loading (Ref. 11) 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. 12).

(k) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 7) 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. 12).

(l) Land requirement of 0.398 ha.a/t of bioethanol and allocation of 87.1% x 84.4% = 73.5% to bioethanol.

(m) Ammonium nitrate fertiliser application rate of 59.31 kg N /ha.a to replace straw removal, based on Canadian data (Ref. 21) adjusted pro rata to an average wheat straw yield of 3.5 t/ha.a (Ref. 12) with 1.394 t straw collected for fuel from 0.398ha.a/t bioethanol, and a total carbon requirement of 1.904±0.275 kg CO_2/MJ N for ammonium nitrate (Ref. 6).

(n) Phosphate fertiliser application rate of 24.54 kg P_2O_5/ ha.a to replace straw removal, based on Canadian data (Ref. 21) adjusted pro rata to an average wheat straw yield of 3.5 t/ha.a (Ref. 12) with 1.394 t straw collected for fuel from 0.398 ha.a/t bioethanol, and a total carbon requirement for phosphate fertiliser of 0.700 kg CO2/kg P_2O_5 (Ref. 7).

(o) Potash fertiliser application rate of 123.8 kg K_2O/ha.a to replace straw removal, based on Canadian data (Ref. 21) adjusted pro rata to an average wheat straw yield of 3.5 t/ha.a (Ref. 12) with 1.394 t straw collected for fuel from 0.398ha.a/t bioethanol, and a total carbon requirement for potash fertiliser of 0.453 kg CO2/ kg K_2O (Ref. 7).

(p) Diesel fuel consumption for baling of 232 MJ/ha.a and loading in the field of 138 MJ/ha.a, based on data for straw fuel recovery (Ref. 22) adjusted for collection of 1.394 t straw from 0.398 ha.a/t bioethanol, 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. 13).

(q) Carbon dioxide output from manufacture of tractor for baling of 2.4 kg CO_2/ha.a, Hesston baler of 14.4 kg CO_2/ha.a and telescopic handler for loading in field of 1.9 kg CO_2/ha.a, based on data for straw fuel recovery (Ref. 22) adjusted for collection of 1.394 t straw from 0.398 ha.a/t bioethanol.

(r) Carbon dioxide output from manufacture of baling twine of 7.01 kg CO_2/ha.a, based on data for straw fuel recovery (Ref. 22) adjusted for collection of 1.394 t straw from 0.398 ha.a/t bioethanol.

(s) Carbon dioxide output from maintenance and repair of tractor for baling of 0.61 kg CO_2/ha.a, of Hesston baler of 6.8 kg CO_2/ha.a and of telescopic handler for loading in the field of 0.65 kg CO_2/ha.a, based on data for straw fuel recovery (Ref. 22) adjusted for collection of 1.394 t straw from 0.398 ha.a/t bioethanol.

(t) Land requirement of 0.398 ha.a/t bioethanol and partitioning, based on relative energy, with heat and electricity measured on an equivalent basis, to drying (13%), to milling, hydrolysis, fermentation and distillation (86.6%), and to dehydration (0.4%), and allocation between bioethanol and animal feed (84.4%), resulting in a total allocation to bioethanol of (99.6% x 84.4%)+ (0.4%) = 84.5%.

(u) Average round trip distance of 80 km (Ref. 22) 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. 11).

(v) Baled straw requirement of 1.38 t/t bioethanol and partitioning, based on relative energy, with heat and electricity measured on an equivalent basis, to drying (13%), to milling, hydrolysis, fermentation and distillation (86.6%), and to dehydration (0.4%), and allocation between bioethanol and animal feed (84.4%), resulting in a total allocation to bioethanol of (99.6% x 84.4%)+ (0.4%) = 84.5%.

(w) Diesel fuel consumption for baled straw handling in storage of 65.8 MJ/t of baled wheat straw (Ref. 22), 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. 8).

(x) Based on 2 tonnes of polyethylene sheeting used to protect each storage stack of 1,000 tonnes of baled wheat straw, with a life of 1 year and a carbon requirement of 6.2 kg CO_2/kg for low density polyethylene (Ref. 22).

(y) Carbon dioxide output from manufacture of telescopic handler of 1.0 kg CO_2/t of baled wheat straw (Ref. 22).

(z) Carbon dioxide output from maintenance and repair of telescopic handler of 0.3 kg CO_2/t of baled wheat straw (Ref. 22).

(aa) Average round trip distance of 186 km (Ref. 11) 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. 13).

(bb) Harvested wheat grain requirement of 3.425 t/t of bioethanol and allocation of 84.4% to bioethanol.

(cc) Heat supplied by a straw-fired combined heat and power plant equivalent to 271 MJ/ t of harvested wheat grain, based on pro-rata diesel fuel consumption of 677 MJ/t of harvested wheat grain with a moisture content of 19% (Ref. 12) and a boiler efficiency of 80%. Assuming 50% of the harvested wheat grain (1.7125 t/t of bioethanol) requires artificial drying and 50% of the harvested wheat grain dries naturally on the farm to a moisture content of 14%.

(dd) Heat and electricity supplied by a straw-fired combined heat and power plant. Assuming that milling, hydrolysis, fermentation and distillation accounts for all the steam provided from the combined heat and power plant, at a rate of 25.0 t/hr, accounting for 25.0/44.5 = 56.2% of total steam consumption, or 69,450 MJ/hr, and electricity consumption of 7,612 MJ/hr from the combined heat and power plant, based pro-rata on the power requirement of all milling, hydrolysis, fermentation and distillation electrical equipment (1,903 kWh/hr) compared to the total power requirement of the bioethanol plant (4,500 kWh/hr), or 42.3% of the total electrical output (Ref. 12).

(ee) Total distillate (94.5% alcohol) output rate of 13.12 t/hr, based on an annual output rate of 105,800 t/a of distillate, or 100,000 t/a of bioethanol, and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 12).

(ff) Caustic soda (49% concentration) consumption rate of 4,427,136 kg/a (Ref. 11), or 41.8 kg/t of distillate, and a total carbon requirement of 1.120 kg CO_2/kg for caustic soda (Ref. 7).

(gg) Diammonium phosphate (21% concentration) consumption rate of 2,921,103 kg/a (Ref. 11), or 27.6 kg/t of distillate, and a total carbon requirement of 0.06 kg CO_2/kg for diammonium phosphate (Ref. 14).

(hh) Sulphuric acid (93% concentration) consumption rate of 2,911,104 kg/a (Ref. 11), or 27.5 kg/t of distillate, and a total carbon requirement of 0.13 ± 0.16 kg CO_2/ kg for sulphuric acid (Ref. 15).

(ii) Enzyme AMG consumption rate of 247,176 kg/a (Ref. 11), or 2.3 kg/t of distillate, and a total carbon requirement of 2.25 kg CO_2/ kg for enzyme AMG (Refs. 16 to 18).

(jj) Enzyme Alpha Amylase consumption rate of 137,007 kg/a (Ref. 11), or 1.3 kg/t of distillate, and a total carbon requirement of 1.6 kg CO_2/ kg for enzyme alpha amylase (Refs. 16 to 18).

(kk) Calcium chloride consumption rate of 90,317 kg/a (Ref. 11), or 0.9 kg/t of distillate, and a total carbon requirement of 0.6 kg CO_2/ kg for calcium chloride (Ref. 19).

(ll) Distillate (94.5% alcohol) requirement 1.058 t/t of bioethanol and allocation of 84.4% to bioethanol

(mm) Assuming dehydration accounts for electricity consumption of 312 MJ/hr from the combined heat and power plant, based pro-rata on the power requirement of dehydration electrical equipment (78 kWh/hr) compared to the total power requirement of the bioethanol plant (4,500 kWh/hr), or 1.7% of the total electrical output supplied by the straw fired CHP plant (Ref. 12).

(nn) Total bioethanol output rate of 12.4 t/hr, based on an annual output rate of 100,000 t/a of bioethanol and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 11).

(oo) Surplus electricity for sale equal to 4,975 MJ/t of bioethanol which displaces average electricity supplies with a carbon requirement of 0.15 kg CO_2/ MJ for the UK in 1996 (Ref. 12) and assuming 84.4% contribution to bioethanol by price of co-products.

(pp) Carbon dioxide output of 64,125 tonnes of CO_2 for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £51.3 m (Ref. 11) and a carbon intensity of 1.25 kg CO_2/£ (Ref. 16), and assuming 84.4% contribution to bioethanol by price of co-products.

(qq) Straw-fired combined heat and power plant with a 32 MW rated heat output and a 22 MW rated electricity output and a load factor of 91% which has a straw fuel feed consumption of 124,066 t/a, providing a total heat supplies of 9,181 MJ/t of bioethanol (consisting of 783 MJ/ t of bioethanol for drying, 4,698 MJ/t of bioethanol for milling, hydrolysis, fermentation and distillation, and 25 MJ/t of bioethanol for dehydration with excess heat of 3,580 MJ/t of bioethanol) and total electricity supplies of 6,427 MJ/t of bioethanol (consisting of 515 MJ/t of bioethanol for milling, hydrolysis, fermentation and distillation, 25 MJ/t for dehydration, 912 MJ/t of bioethanol for the animal feed plant and 4,975 MJ/t of bioethanol of surplus for sale).

(rr) Carbon dioxide output of 84,629 ± 12,694 tonnes CO_2 for construction of a straw-fired combined heat and power plant with a 32 MW rated heat output and a 22 MW rated electricity output, based pro rata on data for a straw-fired combined heat and power plant with a 13.0 MW rated heat output and a 5.0 MW rated electricity output (Ref. 22), with a 25 year life assuming 84.4% contribution to bioethanol by price of co-products.

(ss) Carbon dioxide output of annual plant maintenance assumed to be 1.5% of carbon dioxide output from plant construction (Ref. 11).

(tt) Ash sent for spreading as a fertiliser on fields at an average round trip distance of 80 km (Ref. 10) 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. 11).

(uu) Ash output of 5.5% of straw fuel feed (Ref. 10) and straw requirement of 1.242 t/t of bioethanol.

(vv) Average round trip distance of 450 km (Ref. 3) 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. 13).

References

1. "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.

2. Annual average ex-farm price of feed wheat, United Kingdom, 2000/02 from www.hgca.com/c-stats accessed 3 February 2003.

3. Private communication with D. Darby, British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication, based on an assumed derogation of fuel duty of 26 p/l and a delivered market price of 39 p/l for bioethanol, with G. Punter, British Sugar plc. Peterborough, United Kingdom, 28 January 2003.

5. "British Survey of Fertiliser Practice 1999", Fertiliser Manufacturers' Association.

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003.

7. "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

8. "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

9. "Pesticide Use Survey" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. "Farm Management Pocket Handbook" by J. Nix, Wye College, University of London, United Kingdom, 2002.

11. Private communication with A. Nixon, British Sugar plc., Peterborough, United Kingdom, 22 January 2003.

12. "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.

13. "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.

14. "Düngemittel – Energie- und Stoffstrombilanzen" (Fertilisers – Energy and Material Balance) by A. Patyk and G. A. Reinhardt, Vieweg Umweltwissenschaften, Braunschweig/Wiesbaden, Germany, 1997.

15. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

16. "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.

17. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

18. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

19. "Interim Report on Energy-Use in Metallurgical and Non-Metallic Mineral Processing, Phase 5" Battelle Columbus Laboratories, PB-246-357, United States of America, 1975.

20. "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.

21. "Assessment of Net Emissions of Greenhouse Gases from Ethanol-Blended Gasolines in Canada: Lignocellulosic Feedstocks" R-2000-2, Levelton Engineering Ltd., Richmond, Canada, December 1998.

22. "Energy and Carbon Analysis of Using Straw as a Fuel" by J. F. Grant, R. Hetherington, R. E. Horne and N. D. Mortimer, Report ETSU B/M4/00487/01, Energy Technology Support Unit, Harwell, United Kingdom, 1995

Spreadsheet for Methane Outputs from Bioethanol Production from Wheat Using Straw as Fuel (Model 7)

Functional Unit: :	Bioethanol at point of distribution derived from wheat using natural gas-fired combined heat and power generation during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on average market prices, assuming 1.394 tonnes of wheat straw at £25/t (Ref. 1) and 3.425 tonnes of harvested wheat grain with 20% moisture content at £69/t (Ref. 2), giving a 87.1% allocation to bioethanol, and 1.141 tonnes of animal feed at £80/t (Ref. 3) and 1.000 tonnes of bioethanol at £494/t (Ref. 4), giving a 84.4% allocation to bioethanol.

Contribution	Per Unit	Methane Output (kg CH_4)						Notes
		Direct		Indirect		Total		
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	*ha.a*	-	-	*0.666*	*±0.111*	*0.666*	*±0.111*	(a)
- P Fertiliser	*ha.a*	-	-	*0.002*	-	*0.002*	-	(b, c)
- K Fertiliser	*ha.a*	-	-	*0.001*	-	*0.001*	-	(c, d)
- Pesticide	*ha.a*	-	-	-	-	-	-	(c, e)
- Herbicide	*ha.a*	-	-	-	-	-	-	(c, f)
- Insecticide	*ha.a*	-	-	-	-	-	-	(c, g)
- Fungicide	*ha.a*	-	-	-	-	-	-	(c, h)
- Seed	*ha.a*	-	-	-	-	-	-	(c, i)
- Diesel Fuel	*ha.a*	*0.003*	-	*0.112*	*±0.017*	*0.115*	*±0.017*	(c, j)
Reference System:								
- Diesel Fuel	*ha.a*	*- 0.001*	-	*- 0.019*		*- 0.020*	*±0.003*	(c, k)
Sub-Totals	*ha.a*	*0.002*	-	*0.762*	*±0.112*	*0.764*	*±0.112*	
	t be	**0.001**	**-**	**0.223**	**±0.033**	**0.224**	**±0.033**	(l)
Straw Baling:								
- N Fertiliser	*ha.a*	-	-	*0.213*	*±0.036*	*0.213*	*±0.036*	(m)
- P Fertiliser	*ha.a*	-	-	*0.001*	-	*0.001*	-	(c, n)
- K Fertiliser	*ha.a*	-	-	*0.003*	-	*0.003*	-	(c, o)
- Diesel Fuel	*ha.a*	-	-	*0.007*	-	*0.007*	-	(c, p)
- Machinery	*ha.a*	-	-	-	-	-	-	(c, q)
- Twine	*ha.a*	-	-	-	-	-	-	(c, r)
- Maintenance	*ha.a*	-	-	-	-	-	-	(c, s)
Sub-Totals	*ha.a*	-	-	*0.224*	*±0.036*	*0.224*	*±0.036*	
	t be	-	**-**	**0.075**	**±0.012**	**0.075**	**±0.012**	(t)
Straw Transport:								
- Diesel Fuel	*t bws*	-	-	*0.001*	-	*0.001*	-	(u)
	t be	**-**	**-**	**0.001**	**-**	**0.001**	**-**	(v)
Straw Storage:								
- Diesel Fuel	*t bws*	-	-	*0.001*	-	*0.001*	-	(c,w)
- Sheeting	*t bws*	-	-	-	-	-	-	(c, x)
- Machinery	*t bws*	-	-	-	-	-	-	(c, y)
- Maintenance	*t bws*	-	-	-	-	-	-	(c, z)
Sub-Totals	*t bws*	-	-	*0.001*	-	*0.001*	-	
	t be	**-**	**-**	**0.001**	**-**	**0.001**	**-**	(v)
Wheat Transport:								
- Diesel Fuel	*t hwg*	-	-	*0.003*	-	*0.003*	-	(aa)
	t be	**-**	**-**	**0.009**	**-**	**0.009**	**-**	(bb)
Wheat Drying:	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(bb) (cc)
Milling, Hydrolysis, Fermentation and Distillation:								(dd) (ee)
- Caustic Soda	*t de*	-	-	*0.136*	*±0.020*	*0.136*	*±0.020*	(ff)
- Diam. Phosph.	*t de*	-	-	-	-	-	-	(gg)
- Sulphuric Acid	*t de*	-	-	*0.007*	*±0.008*	*0.007*	*±0.008*	(hh)
- Enzyme AMG	*t de*	-	-	-	-	-	-	(ii)
- Enzyme AA	*t de*	-	-	-	-	-	-	(jj)
- Calcium Chlor.	*t de*	-	-	-	-	-	-	(kk)
Sub-Totals	*t de*	-	-	*0.143*	*±0.022*	*0.143*	*0.022*	
	t be	**-**	**-**	**0.128**	**±0.019**	**0.128**	**±0.019**	(ll)
Dehydration:	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(c) (mm) (nn)
Direct Emissions	**t be**	**0.030**	**-**	**-**	**-**	**0.030**	**-**	(oo)
Surplus Electricity	**t be**	**-1.698**	**-**	**-**	**-**	**-1.698**	**-**	(pp)
Plant Construction	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(qq)-(ss)
Plant Maintenance	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(tt)
Ash Disposal	*t ash*	-	-	*0.001*	-	*0.001*	-	(uu)
	t be	**-**	**-**	**-**	**-**	**-**	**-**	(vv)
Distrib.: Diesel Fuel	**t be**	**-**	**-**	**0.008**	**-**	**0.008**	**-**	(ww)
Totals	**t be**	**-1.667**	**-**	**0.445**	**±0.040**	**-1.222**	**±0.040**	

Biofuel Specifications

Density of bioethanol	= 0.79 kg/l
Net calorific value of bioethanol	= 26.72 MJ/kg
Gross calorific value of bioethanol	= 29.74 MJ/kg

Abbreviations

ha.a	= hectare year
t bws	= tonne of baled wheat straw
t hwg	= tonne of harvested wheat grain
t dwg	= tonne of dried wheat grain
t ash	= tonne of ash
t be	= tonne of bioethanol

Notes

(a) Nitrogen fertiliser application rate of 185 N/ha.a (Ref. 5) 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 (Ref. 6).

(b) Phosphate fertiliser application rates of 41 kg P/ha.a (Ref. 5), or 93.9 kg P_2O_5/ ha.a assuming 2.290 kg P_2O_5/kg P, and a total methane requirement for phosphate fertiliser of 2.3×10^{-5} kg CH_4/kg P_2O_5 (Ref. 7).

(c) Assuming an error bar of ±15% based on similar analyses (Ref. 8).

(d) Potash fertiliser application rate of 46 kg K/ha.a (Ref. 5), or 55.4 kg K_2O/ha.a assuming 1.205 kg K_2O/kg K, and a total methane requirement for potash fertiliser of 2.1×10^{-5} kg CH_4/ kg K_2O (Ref. 7).

(e) Pesticide application rate of 2.0 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.8×10^{-4} kg CH_4/kg (Ref. 7).

(f) Herbicide application rate of 0.1 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.8×10^{-4} kg CH_4/kg (Ref. 7).

(g) Insecticide application rate of 0.8 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.8×10^{-4} kg CH_4/kg (Ref. 7).

(h) Fungicide application rate of 1.0 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.8×10^{-4} kg CH_4/kg (Ref. 7).

(i) Sowing rate of 185 kg/ha.a (Ref. 10) and a total methane requirement of 0 kg CH_4/kg of seed, assuming similarity with oilseed (Ref. 7).

(j) Diesel fuel consumption of 5,490 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides, insecticides and fungicides, harvesting, carting and loading (Ref. 11) 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. 12).

(k) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 7) 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. 12).

(l) Land requirement of 0.398 ha.a/t of bioethanol and allocation of 87.1% x 84.4% = 73.5% to bioethanol.

(m) Ammonium nitrate fertiliser application rate of 59.31 kg N /ha.a to replace straw removal, based on Canadian data (Ref. 21) adjusted pro rata to an average wheat straw yield of 3.5 t/ha.a (Ref. 12) with 1.394 t straw collected for fuel from 0.398ha.a/t bioethanol, and a total methane requirement of $3.6 \times 10^{-3} \pm 0.6 \times 10^{-3}$ kg CH_4/MJ N for ammonium nitrate (Ref. 6).

(n) Phosphate fertiliser application rate of 24.54 kg P_2O_5/ ha.a to replace straw removal, based on Canadian data (Ref. 21) adjusted pro rata to an average wheat straw yield of 3.5 t/ha.a (Ref. 12) with 1.394 t straw collected for fuel from 0.398 ha.a/t bioethanol, and a total methane requirement for phosphate fertiliser of 2.3×10^{-5} kg CH_4/kg P_2O_5 (Ref. 7).

(o) Potash fertiliser application rate of 123.8 kg K_2O/ha.a to replace straw removal, based on Canadian data (Ref. 21) adjusted pro rata to an average wheat straw yield of 3.5 t/ha.a (Ref. 12) with 1.394 t straw collected for fuel from 0.398ha.a/t bioethanol, and a total methane requirement for potash fertiliser of 2.1×10^{-5} kg CH_4/ kg K_2O (Ref. 7).

(p) Diesel fuel consumption for baling of 232 MJ/ha.a and loading in the field of 138 MJ/ha.a, based on data for straw fuel recovery (Ref. 22) adjusted for collection of 1.394 t straw from 0.398 ha.a/t bioethanol, 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. 12).

(q) Primary energy input to manufacture of tractor for baling of 52 MJ/ha.a, Hesston baler of 312 MJ/ha.a and telescopic handler for loading in field of 41 MJ/ha.a, based on data for straw fuel recovery (Ref. 22) adjusted for collection of 1.394 t straw from 0.398 ha.a/t bioethanol and an estimated total methane requirement of 1.192 x 10^{-7} kg CH_4/ MJ primary energy input to manufacturing (Ref. 18).

(r) Primary energy input to manufacture of baling twine of 94.3 MJ/ha.a, based on data for straw fuel recovery (Ref. 22) adjusted for collection of 1.394 t straw from 0.398 ha.a/t bioethanol and an estimated total methane requirement of 1.192 x 10^{-7} kg CH_4/ MJ primary energy input to manufacturing (Ref. 18).

(s) Primary energy input to maintenance and repair of tractor for baling of 13.25 MJ/ha.a, of Hesston baler of 147 MJ/ha.a and of telescopic handler for loading in the field of 14.1MJ/ha.a, based on data for straw fuel recovery (Ref. 22) adjusted for collection of 1.394 t straw from 0.398 ha.a/t bioethanol and an estimated total methane requirement of 1.192 x 10^{-7} kg CH_4/ MJ primary energy input to manufacturing (Ref. 18).

(t) Land requirement of 0.398 ha.a/t bioethanol and partitioning, based on relative energy, with heat and electricity measured on an equivalent basis, to drying (13%), to milling, hydrolysis, fermentation and distillation (86.6%), and to dehydration (0.4%), and allocation between bioethanol and animal feed (84.4%), resulting in a total allocation to bioethanol of (99.6% x 84.4%)+ (0.4%) = 84.5%.

(u) Average round trip distance of 80 km (Ref. 22) by bulk road carrier transport with a a direct methane requirement of 4.900 x 10^{-7} ± 2.000 x 10^{-8} kg CH_4/t-km, an indirect methane requirement of 1.672 x 10^{-5} ± 6.3 x 10^{-7} kg CH_4/t-km and a total methane requirement of 1.721 x 10^{-5} ± 6.5 x 10^{-7} kg CH_4/t-km (Ref. 13).

(v) Baled straw requirement of 1.38 t/t bioethanol and partitioning, based on relative energy, with heat and electricity measured on an equivalent basis, to drying (13%), to milling, hydrolysis, fermentation and distillation (86.6%), and to dehydration (0.4%), and allocation between bioethanol and animal feed (84.4%), resulting in a total allocation to bioethanol of (99.6% x 84.4%)+ (0.4%) = 84.5%.

(w) Diesel fuel consumption for baled straw handling in storage of 65.8 MJ/t of baled wheat straw (Ref. 22), and a direct methane requirement of 6.0 x 10^{-7} kg CH_4/ MJ, an indirect methane requirement of 2.04 x 10^{-5} kg CH_4/ MJ and a total methane requirement of 2.1 x 10^{-5} kg CH_4/ MJ for diesel fuel in the UK in 1996 (Ref. 12).

(x) Based on 2 tonnes of polyethylene sheeting used to protect each storage stack of 1,000 tonnes of baled wheat straw, with a life of 1 year and a direct energy requirement of 47 MJ/kg and a feedstock energy requirement of 46 MJ/kg for low density polyethylene (Ref. 22) and an estimated total methane requirement of 1.192 x 10^{-7} kg CH_4/ MJ primary energy input to manufacturing (Ref. 18).

(y) Primary energy input for manufacture of telescopic handler of 21.0 MJ/t of baled wheat straw (Ref. 22) and an estimated total methane requirement of 1.192 x 10^{-7} kg CH_4/ MJ primary energy input to manufacturing (Ref. 18).

(z) Primary energy input to maintenance and repair of telescopic handler of 7.2 MJ/t of baled wheat straw (Ref. 22) and an estimated total methane requirement of 1.192 x 10^{-7} kg CH_4/ MJ primary energy input to manufacturing (Ref. 18).

(aa) Average round trip distance of 186 km (Ref. 11) by bulk road carrier transport with a direct methane requirement of 4.900 x 10^{-7} ± 2.000 x 10^{-8} kg CH_4/t-km, an indirect methane requirement of 1.672 x 10^{-5} ± 6.3 x 10^{-7} kg CH_4/t-km and a total methane requirement of 1.721 x 10^{-5} ± 6.5 x 10^{-7} kg CH_4/t-km (Ref. 13).

(bb) Harvested wheat grain requirement of 3.425 t/t of bioethanol and allocation of 84.4% to bioethanol.

(cc) Heat supplied by a straw-fired combined heat and power plant equivalent to 271 MJ/ t of harvested wheat grain, based on pro-rata diesel fuel consumption of 677 MJ/t of harvested wheat grain with a moisture content of 19% (Ref. 12) and a boiler efficiency of 80%. Assuming 50% of the harvested wheat grain (1.7125 t/t of bioethanol) requires artificial drying and 50% of the harvested wheat grain dries naturally on the farm to a moisture content of 14%.

(dd) Heat and electricity supplied by a straw-fired combined heat and power plant. Assuming that milling, hydrolysis, fermentation and distillation accounts for all the steam provided from the combined heat and power plant, at a rate of 25.0 t/hr, accounting for 25.0/44.5 = 56.2% of total steam consumption, or 69,450 MJ/hr, and electricity consumption of 7,612 MJ/hr from the combined heat and power plant, based pro-rata on the power requirement of all milling, hydrolysis, fermentation and distillation electrical equipment (1,903 kWh/hr) compared to the total power requirement of the bioethanol plant (4,500 kWh/hr), or 42.3% of the total electrical output (Ref. 12).

(ee) Total distillate (94.5% alcohol) output rate of 13.12 t/hr, based on an annual output rate of 105,800 t/a of distillate, or 100,000 t/a of bioethanol, and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 12).

(ff) Caustic soda (49% concentration) consumption rate of 4,427,136 kg/a (Ref. 11), or 41.8 kg/t of distillate, and a total methane requirement of 3.25 x 10^{-3} kg CH_4/kg for caustic soda (Ref. 7).

(gg) Diammonium phosphate (21% concentration) consumption rate of 2,921,103 kg/a (Ref. 11), or 27.6 kg/t of distillate, and a total methane requirement of 2 x 10^{-6} kg CH_4/kg for diammonium phosphate (Ref. 14).

(hh) Sulphuric acid (93% concentration) consumption rate of 2,911,104 kg/a (Ref. 11), or 27.5 kg/t of distillate, and a total methane requirement of 2.7 x 10^{-4} ± 3.0 x 10^{-4} kg CH_4/ kg for sulphuric acid (Ref. 15).

(ii) Enzyme AMG consumption rate of 247,176 kg/a (Ref. 11), or 2.3 kg/t of distillate, and a total methane requirement of 6 x 10^{-6} kg CH_4/ kg for enzyme AMG (Refs. 16 to 18).

(jj) Enzyme Alpha Amylase consumption rate of 137,007 kg/a (Ref. 11), or 1.3 kg/t of distillate, and a total methane requirement of 4 x 10^{-6} kg CH_4/ kg for enzyme alpha amylase (Refs. 16 to 18).

(kk) Calcium chloride consumption rate of 90,317 kg/a (Ref. 11), or 0.9 kg/t of distillate, and a total methane requirement of 2 x 10^{-4} kg CH_4/ kg for calcium chloride (Ref. 19).

(ll) Distillate (94.5% alcohol) requirement 1.058 t/t of bioethanol and allocation of 84.4% to bioethanol

(mm) Assuming dehydration accounts for electricity consumption of 312 MJ/hr from the combined heat and power plant, based pro-rata on the power requirement of dehydration electrical equipment (78 kWh/hr) compared to the total power requirement of the bioethanol plant (4,500 kWh/hr), or 1.7% of the total electrical output supplied by the straw fired CHP plant (Ref. 12).

(nn) Total bioethanol output rate of 12.4 t/hr, based on an annual output rate of 100,000 t/a of bioethanol and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 11).

(oo) Direct methane emissions of 29 g CH_4/t of straw fuel feed from the combined heat and power plant (Ref. 23) and straw fuel feed requirement of 1.242 t/t bioethanol and with heat and electricity measured on an equivalent basis, to drying (13%), to milling, hydrolysis, fermentation and distillation (86.6%), and to dehydration (0.4%), and allocation between bioethanol and animal feed (84.4%), resulting in a total allocation to bioethanol of (99.6% x 84.4%)+ (0.4%) = 84.5%.

(pp) Surplus electricity for sale equal to 4,975 MJ/t of bioethanol which displaces average electricity supplies with a methane requirement of 4.034 x 10^{-4} kg CH_4/ MJ for the UK in 1996 (Ref. 12) and assuming 84.4% contribution to bioethanol by price of co-products.

(qq) Primary energy input of 1,282,500 GJ for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £51.3 m (Ref. 11) and an energy intensity of 25 MJ/£ (Ref. 16) , and an estimated total methane requirement of 1.192 x 10^{-7} kg CH_4/MJ primary energy input to construction (Ref. 18), assuming 84.4% contribution to bioethanol by price of co-products

(rr) Straw-fired combined heat and power plant with a 32 MW rated heat output and a 22 MW rated electricity output and a load factor of 91% which has a straw fuel feed consumption of 124,066 t/a, providing a total heat supplies of 9,181 MJ/t of bioethanol (consisting of 783 MJ/ t of bioethanol for drying, 4,698 MJ/t of bioethanol for milling, hydrolysis, fermentation and distillation, and 25 MJ/t of bioethanol for dehydration with excess heat of 3,580 MJ/t of bioethanol) and total electricity supplies of 6,427 MJ/t of bioethanol (consisting of 515 MJ/t of bioethanol for milling, hydrolysis, fermentation and distillation, 25 MJ/t for dehydration, 912 MJ/t of bioethanol for the animal feed plant and 4,975 MJ/t of bioethanol of surplus for sale).

(ss) Primary energy input of 1,581,800 GJ for construction of a straw-fired combined heat and power plant with a 32 MW rated heat output and a 22 MW rated electricity output, based pro rata on data for a straw-fired combined heat and power plant with a 13.0 MW rated heat output and a 5.0 MW rated electricity output (Ref. 22), with a 25 year life. and an estimated total methane requirement of 1.192 x 10^{-7} kg CH_4/MJ primary energy input to construction (Ref. 18), assuming 84.4% contribution to bioethanol by price of co-products

(tt) Methane output of annual plant maintenance assumed to be 1.5% of carbon dioxide output from plant construction (Ref. 11).

(uu) Ash sent for spreading as a fertiliser on fields at an average round trip distance of 80 km (Ref. 10) by bulk road carrier transport with a direct methane requirement of 4.900 x 10^{-7} ± 2.000 x 10^{-8} kg CH_4/t-km, an indirect methane requirement of 1.672 x 10^{-5} ± 6.3 x 10^{-7} kg CH_4/t-km and a total methane requirement of 1.721 x 10^{-5} ± 6.5 x 10^{-7} kg CH_4/t-km (Ref. 12).

(vv) Ash output of 5.5% of straw fuel feed (Ref. 10) and straw requirement of 1.242 t/t of bioethanol.

(ww) Average round trip distance of 450 km (Ref. 3) by bulk road carrier transport with a direct methane requirement of 4.900 x 10^{-7} ± 2.000 x 10^{-8} kg CH_4/t-km, an indirect methane requirement of 1.672 x 10^{-5} ± 6.3 x 10^{-7} kg CH_4/t-km and a total methane requirement of 1.721 x 10^{-5} ± 6.5 x 10^{-7} kg CH_4/t-km (Ref. 13).

References

1. "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.

2. Annual average ex-farm price of feed wheat, United Kingdom, 2000/02 from www.hgca.com/c-stats accessed 3 February 2003.

3. Private communication with D. Darby, British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication, based on an assumed derogation of fuel duty of 26 p/l and a delivered market price of 39 p/l for bioethanol, with G. Punter, British Sugar plc. Peterborough, United Kingdom, 28 January 2003.

5. "British Survey of Fertiliser Practice 1999", Fertiliser Manufacturers' Association.

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003.

7. "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

8. "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

9. "Pesticide Use Survey" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. "Farm Management Pocket Handbook" by J. Nix, Wye College, University of London, United Kingdom, 2002.

11. Private communication with A. Nixon, British Sugar plc., Peterborough, United Kingdom, 22 January 2003.

12. "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.

13. "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.

14. "Düngemittel – Energie- und Stoffstrombilanzen" (Fertilisers – Energy and Material Balance) by A. Patyk and G. A. Reinhardt, Vieweg Umweltwissenschaften, Braunschweig/Wiesbaden, Germany, 1997.

15. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

16. "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.

17. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

18. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

19. "Interim Report on Energy-Use in Metallurgical and Non-Metallic Mineral Processing, Phase 5" Battelle Columbus Laboratories, PB-246-357, United States of America, 1975.

20. "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.

21. "Assessment of Net Emissions of Greenhouse Gases from Ethanol-Blended Gasolines in Canada: Lignocellulosic Feedstocks" R-2000-2, Levelton Engineering Ltd., Richmond, Canada, December 1998.

22. "Energy and Carbon Analysis of Using Straw as a Fuel" by J. F. Grant, R. Hetherington, R. E. Horne and N. D. Mortimer, Report ETSU B/M4/00487/01, Energy Technology Support Unit, Harwell, United Kingdom, 1995

23. Private communication with G. Jungmeier, Joanneum Research, Austria, 15 January 2003.

<u>Spreadsheet for Nitrous Oxide Outputs from Bioethanol Production from Wheat Using Straw as Fuel</u> (Model 7)

Functional Unit: :	Bioethanol at point of distribution derived from wheat
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on average market prices, assuming 1.394 tonnes of wheat straw at £25/t (Ref. 1) and 3.425 tonnes of harvested wheat grain with 20% moisture content at £69/t (Ref. 2), giving a 87.1% allocation to bioethanol, and 1.141 tonnes of animal feed at £80/t (Ref. 3) and 1.000 tonnes of bioethanol at £494/t (Ref. 4), giving a 84.4% allocation to bioethanol.

Contribution	Per Unit	Nitrous Oxide Output (kg N_2O)						
		Direct		Indirect		Total		Notes
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	*ha.a*	*0.666*	*±0.100*	*2.720*	*±0.408*	*3.386*	*±0.420*	(a, b)
- P Fertiliser	*ha.a*	-	-	*0.004*	*±0.001*	*0.004*	*±0.001*	(b, c)
- K Fertiliser	*ha.a*	-	-	*0.001*	-	*0.001*	-	(b, d)
- Pesticide	*ha.a*	-	-	*0.003*	-	*0.003*	-	(b, e)
- Herbicide	*ha.a*	-	-	-	-	-	-	(b, f)
- Insecticide	*ha.a*	-	-	*0.001*	-	*0.001*	-	(b, g)
- Fungicide	*ha.a*	-	-	*0.002*	-	*0.002*	-	(b, h)
- Seed	*ha.a*	-	-	*0.185*	*±0.028*	*0.185*	*±0.028*	(b, i)
- Diesel Fuel	*ha.a*	*0.003*	-	-	-	*0.003*	-	(b, j)
Reference System:								
- Diesel Fuel	*ha.a*	*- 0.001*	-	-		*- 0.001*	-	(b, k)
Sub-Totals	*ha.a*	*0.668*	*±0.100*	*2.916*	*±0.409*	*3.584*	*±0.421*	
	t be	**0.195**	**±0.029**	**0.853**	**±0.120**	**1.048**	**±0.123**	(l)
Straw Baling:								
- N Fertiliser	*ha.a*	*0.213*	*±0.033*	*0.872*	*±0.131*	*1.085*	*±0.135*	(m)
- P Fertiliser	*ha.a*	-	-	-	-	-	-	(c, n)
- K Fertiliser	*ha.a*	-	-	-	-	-	-	(c, o)
- Diesel Fuel	*ha.a*	-	-	-	-	-	-	(c, p)
- Machinery	*ha.a*	-	-	-	-	-	-	(c, q)
- Twine	*ha.a*	-	-	-	-	-	-	(c, r)
- Maintenance	*ha.a*	-	-	-	-	-	-	(c, s)
Sub-Totals	*ha.a*	*0.213*	*±0.033*	*0.872*	*±0.125*	*1.085*	*±0.135*	
	t be	**0.072**	**±0.011**	**0.293**	**±0.044**	**0.365**	**±0.045**	(t)
Straw Transport:								
- Diesel Fuel	*t bws*	-	-	-	-	-	-	(u)
	t be	**-**	**-**	**-**	**-**	**-**	**-**	(v)
Straw Storage:								
- Diesel Fuel	*t bws*	-	-	-	-	-	-	(c,w)
- Sheeting	*t bws*	-	-	-	-	-	-	(c, x)
- Machinery	*t bws*	-	-	-	-	-	-	(c, y)
- Maintenance	*t bws*	-	-	-	-	-	-	(c, z)
Sub-Totals	*t bws*	-	-	-	-	-	-	
	t be	**-**	**-**	**-**	**-**	**-**	**-**	(v)
Wheat Transport:	*t hwg*	-	-	-	-	-	-	(aa)
	t be	**-**	**-**	**-**	**-**	**-**	**-**	(bb)
Wheat Drying:	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(bb) (cc)
Milling, Hydrolysis, Fermentation and Distillation:								(dd) (ee)
- Caustic Soda	*t de*	-	-	-	-	-	-	(ff)
- Diam. Phosph.	*t de*	-	-	-	-	-	-	(gg)
- Sulphuric Acid	*t de*	-	-	-	-	-	-	(hh)
- Enzyme AMG	*t de*	-	-	-	-	-	-	(ii)
- Enzyme AA	*t de*	-	-	-	-	-	-	(jj)
- Calcium Chlor.	*t de*	-	-	-	-	-	-	(kk)
Sub-Totals	*t de*	-	-	-	-	-	-	
	t be	**-**	**-**	**-**	**-**	**-**	**-**	(ll)
Dehydration:	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(c) (mm) (nn)
Direct Emissions	**t be**	**0.077**	**-**	**-**	**-**	**0.077**	**-**	(oo)
Surplus Electricity	**t be**	**- 0.023**	**-**	**-**	**-**	**- 0.023**	**-**	(pp)
Plant Construction	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(qq)-(ss)
Plant Maintenance	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(tt)
Ash Disposal								(uu)
	t be							(vv)
Distribution:								
- Diesel Fuel	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(ww)
Totals	**t be**	**0.321**	**±0.031**	**1.146**	**±0.128**	**1.467**	**±0.131**	

Biofuel Specifications

Density of bioethanol	= 0.79 kg/l
Net calorific value of bioethanol	= 26.72 MJ/kg
Gross calorific value of bioethanol	= 29.74 MJ/kg

Abbreviations

ha.a	= hectare year
t bws	= tonne of baled wheat straw
t hwg	= tonne of harvested wheat grain
t dwg	= tonne of dried wheat grain
t ash	= tonne of ash
t be	= tonne of bioethanol

Notes

(a) Nitrogen fertiliser application rate of 185 N/ha.a (Ref. 5) and a direct nitrous oxide requirement of 0.0036 kg N_2O/kg N (Ref. 5), an indirect nitrous oxide requirement of 0.0147 kg N_2O/kg N (Ref. 6) and a total nitrous oxide requirement for ammonium nitrate of 0.0183 kg N_2O/kg N (Ref. 6).

(b) Assuming an error bar of ±15% based on similar analyses (Ref. 7).

(c) Phosphate fertiliser application rates of 41 kg P/ha.a (Ref. 5), or 93.9 kg P_2O_5/ ha.a assuming 2.290 kg P_2O_5/kg P, and a total nitrous oxide requirement for phosphate fertiliser of 4.2×10^{-5} kg N_2O/kg P_2O_5 (Ref. 8).

(d) Potash fertiliser application rate of 46 kg K/ha.a (Ref. 5), or 55.4 kg K_2O/ha.a assuming 1.205 kg K_2O/kg K, and a total nitrous oxide requirement for potash fertiliser of 9.4×10^{-6} kg N_2O/ kg K_2O (Ref. 6).

(e) Pesticide application rate of 2.0 kg/ha.a (Ref. 9) and a total nitrous oxide requirement for general pesticides, herbicides and fungicides of 1.51×10^{-3} kg N_2O/kg (Ref. 8).

(f) Herbicide application rate of 0.1 kg/ha.a (Ref. 9) and a total nitrous oxide requirement for general pesticides, herbicides and fungicides of 1.51×10^{-3} kg N_2O/kg (Ref. 8).

(g) Insecticide application rate of 0.8 kg/ha.a (Ref. 9) and a total nitrous oxide requirement for general pesticides, herbicides and fungicides of 1.51×10^{-3} kg N_2O/kg (Ref. 8).

(h) Fungicide application rate of 1.0 kg/ha.a (Ref. 9) and a total nitrous oxide requirement for general pesticides, herbicides and fungicides of 1.51×10^{-3} kg N_2O/kg (Ref. 8).

(i) Sowing rate of 185 kg/ha.a (Ref. 10) and a total nitrous oxide requirement of 0.001 kg N_2O/kg of seed assuming similarity with oilseed (Ref. 8).

(j) Diesel fuel consumption of 5,490 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides, insecticides and fungicides, harvesting, carting and loading (Ref. 11) and a direct nitrous oxide requirement of 5.64×10^{-7} kg N_2O/MJ, an indirect nitrous oxide requirement of 2.60×10^{-8} kg N_2O/MJ and a total nitrous oxide requirement of 5.90×10^{-7} kg N_2O/MJ for diesel fuel in the UK in 1996 (Ref. 12).

(k) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 8) and a direct nitrous oxide requirement of 5.64×10^{-7} kg N_2O/MJ, an indirect nitrous oxide requirement of 2.60×10^{-8} kg N_2O/MJ and a total nitrous oxide requirement of 5.90×10^{-7} kg N_2O/MJ for diesel fuel in the UK in 1996 (Ref. 12).

(l) Land requirement of 0.398 ha.a/t of bioethanol and allocation of 87.1% x 84.4% = 73.5% to bioethanol.

(m) Ammonium nitrate fertiliser application rate of 59.31 kg N /ha.a to replace straw removal, based on Canadian data (Ref. 21) adjusted pro rata to an average wheat straw yield of 3.5 t/ha.a (Ref. 12) with 1.394 t straw collected for fuel from 0.398ha.a/t bioethanol, and a direct nitrous oxide requirement of 0.0036 kg N_2O/kg N (Ref. 5), an indirect nitrous oxide requirement of 0.0147 kg N_2O/kg N (Ref. 6) and a total nitrous oxide requirement for ammonium nitrate of 0.0183 kg N_2O/kg N (Ref. 6).

(n) Phosphate fertiliser application rate of 24.54 kg P_2O_5/ ha.a to replace straw removal, based on Canadian data (Ref. 21) adjusted pro rata to an average wheat straw yield of 3.5 t/ha.a (Ref. 12) with 1.394 t straw collected for fuel from 0.398 ha.a/t bioethanol, and a total nitrous oxide requirement for phosphate fertiliser of 4.2×10^{-5} kg N_2O/kg P_2O_5 (Ref. 7).

(o) Potash fertiliser application rate of 123.8 kg K_2O/ha.a to replace straw removal, based on Canadian data (Ref. 21) adjusted pro rata to an average wheat straw yield of 3.5 t/ha.a (Ref. 12) with 1.394 t straw collected for fuel from 0.398ha.a/t bioethanol, and a total nitrous oxide requirement for potash fertiliser of 9.4×10^{-6} kg N_2O/ kg K_2O (Ref. 7).

(p) Diesel fuel consumption for baling of 232 MJ/ha.a and loading in the field of 138 MJ/ha.a, based on data for straw fuel recovery (Ref. 22) adjusted for collection of 1.394 t straw from 0.398 ha.a/t bioethanol, and a a direct nitrous oxide requirement of 5.64×10^{-7} kg N_2O/MJ, an indirect nitrous oxide requirement of 2.60×10^{-8} kg N_2O/MJ and a total nitrous oxide requirement of 5.90×10^{-7} kg N_2O/MJ for diesel fuel in the UK in 1996 (Ref. 12).

(q) Primary energy input to manufacture of tractor for baling of 52 MJ/ha.a, Hesston baler of 312 MJ/ha.a and telescopic handler for loading in field of 41 MJ/ha.a, based on data for straw fuel recovery (Ref. 22) adjusted for collection of 1.394 t straw from 0.398 ha.a/t bioethanol and an estimated total nitrous oxide requirement of 1.866×10^{-9} kg N_2O/ MJ primary energy input to manufacturing (Ref. 18).

(r) Primary energy input to manufacture of baling twine of 94.3 MJ/ha.a, based on data for straw fuel recovery (Ref. 22) adjusted for collection of 1.394 t straw from 0.398 ha.a/t bioethanol and an estimated total nitrous oxide requirement of 1.866×10^{-9} kg N_2O/ MJ primary energy input to manufacturing (Ref. 18).

(s) Primary energy input to maintenance and repair of tractor for baling of 13.25 MJ/ha.a, of Hesston baler of 147 MJ/ha.a and of telescopic handler for loading in the field of 14.1MJ/ha.a, based on data for straw fuel recovery (Ref. 22) adjusted for collection of 1.394 t straw from 0.398 ha.a/t bioethanol and an estimated total total nitrous oxide requirement of 1.866×10^{-9} kg N_2O/ MJ primary energy input to manufacturing (Ref. 18).

(t) Land requirement of 0.398 ha.a/t bioethanol and partitioning, based on relative energy, with heat and electricity measured on an equivalent basis, to drying (13%), to milling, hydrolysis, fermentation and distillation (86.6%), and to dehydration (0.4%), and allocation between bioethanol and animal feed (84.4%), resulting in a total allocation to bioethanol of (99.6% x 84.4%)+ (0.4%) = 84.5%.

(u) Average round trip distance of 80 km (Ref. 22) by bulk road carrier transport with a direct nitrous oxide requirement of $4.6 \times 10^{-7} \pm 1.7 \times 10^{-8}$ kg N_2O/t-km, an indirect nitrous oxide requirement of $2.1 \times 10^{-8} \pm 8 \times 10^{-10}$ kg N_2O/t-km and a total nitrous oxide requirement of $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8}$ kg N_2O/t-km (Ref. 13).

(v) Baled straw requirement of 1.38 t/t bioethanol and partitioning, based on relative energy, with heat and electricity measured on an equivalent basis, to drying (13%), to milling, hydrolysis, fermentation and distillation (86.6%), and to dehydration (0.4%), and allocation between bioethanol and animal feed (84.4%), resulting in a total allocation to bioethanol of (99.6% x 84.4%)+ (0.4%) = 84.5%.

(w) Diesel fuel consumption for baled straw handling in storage of 65.8 MJ/t of baled wheat straw (Ref. 22), and a a direct nitrous oxide requirement of 5.64×10^{-7} kg N_2O/MJ, an indirect nitrous oxide requirement of 2.60×10^{-8} kg N_2O/MJ and a total nitrous oxide requirement of 5.90×10^{-7} kg N_2O/MJ for diesel fuel in the UK in 1996 (Ref. 12).

(x) Based on 2 tonnes of polyethylene sheeting used to protect each storage stack of 1,000 tonnes of baled wheat straw, with a life of 1 year and a direct energy requirement of 47 MJ/kg and a feedstock energy requirement of 46 MJ/kg for low density polyethylene (Ref. 22) and an estimated total total nitrous oxide requirement of 1.866×10^{-9} kg N_2O/ MJ primary energy input to manufacturing (Ref. 18).

(y) Primary energy input for manufacture of telescopic handler of 21.0 MJ/t of baled wheat straw (Ref. 22) and an estimated total total nitrous oxide requirement of 1.866×10^{-9} kg N_2O/ MJ primary energy input to manufacturing (Ref. 18).

(z) Primary energy input to maintenance and repair of telescopic handler of 7.2 MJ/t of baled wheat straw (Ref. 22) and an estimated total total nitrous oxide requirement of 1.866×10^{-9} kg N_2O/ MJ primary energy input to manufacturing (Ref. 18).

(aa) Average round trip distance of 186 km (Ref. 11) by bulk road carrier transport with a direct nitrous oxide requirement of $4.6 \times 10^{-7} \pm 1.7 \times 10^{-8}$ kg N_2O/t-km, an indirect nitrous oxide requirement of $2.1 \times 10^{-8} \pm 8 \times 10^{-10}$ kg N_2O/t-km and a total nitrous oxide requirement of $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8}$ kg N_2O/t-km (Ref. 13).

(bb) Harvested wheat grain requirement of 3.425 t/t of bioethanol and allocation of 84.4% to bioethanol.

(cc) Heat supplied by a straw-fired combined heat and power plant equivalent to 271 MJ/ t of harvested wheat grain, based on pro-rata diesel fuel consumption of 677 MJ/t of harvested wheat grain with a moisture content of 19% (Ref. 12) and a boiler efficiency of 80%. Assuming 50% of the harvested wheat grain (1.7125 t/t of bioethanol) requires artificial drying and 50% of the harvested wheat grain dries naturally on the farm to a moisture content of 14%.

(dd) Heat and electricity supplied by a straw-fired combined heat and power plant. Assuming that milling, hydrolysis, fermentation and distillation accounts for all the steam provided from the combined heat and power plant, at a rate of 25.0 t/hr, accounting for 25.0/44.5 = 56.2% of total steam consumption, or 69,450 MJ/hr, and electricity consumption of 7,612 MJ/hr from the combined heat and power plant, based pro-rata on the power requirement of all milling, hydrolysis, fermentation and distillation electrical equipment (1,903 kWh/hr) compared to the total power requirement of the bioethanol plant (4,500 kWh/hr), or 42.3% of the total electrical output (Ref. 12).

(ee) Total distillate (94.5% alcohol) output rate of 13.12 t/hr, based on an annual output rate of 105,800 t/a of distillate, or 100,000 t/a of bioethanol, and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 12).

(ff) Caustic soda (49% concentration) consumption rate of 4,427,136 kg/a (Ref. 11), or 41.8 kg/t of distillate, and a total nitrous oxide requirement of 0 kg N_2O /kg for caustic soda (Ref. 7).

(gg) Diammonium phosphate (21% concentration) consumption rate of 2,921,103 kg/a (Ref. 11), or 27.6 kg/t of distillate, and a total nitrous oxide requirement of 2 x 10^{-6} kg N_2O/kg for diammonium phosphate (Ref. 14).

(hh) Sulphuric acid (93% concentration) consumption rate of 2,911,104 kg/a (Ref. 11), or 27.5 kg/t of distillate, and a total nitrous oxide requirement of 2 x 10^{-7} ± 3 x 10^{-7} kg N_2O/ kg for sulphuric acid (Ref. 15).

(ii) Enzyme AMG consumption rate of 247,176 kg/a (Ref. 11), or 2.3 kg/t of distillate, and a total nitrous oxide requirement of 9 x 10^{-8} kg N_2O/ kg for enzyme AMG (Refs. 16 to 18).

(jj) Enzyme Alpha Amylase consumption rate of 137,007 kg/a (Ref. 11), or 1.3 kg/t of distillate, and a total nitrous oxide requirement of 6 x 10^{-8} kg N_2O/ kg for enzyme alpha amylase (Refs. 16 to 18).

(kk) Calcium chloride consumption rate of 90,317 kg/a (Ref. 11), or 0.9 kg/t of distillate, and a total nitrous oxide requirement of 4 x 10^{-7} kg N_2O/ kg for (Ref. 19).

(ll) Distillate (94.5% alcohol) requirement 1.058 t/t of bioethanol and allocation of 84.4% to bioethanol

(mm) Assuming dehydration accounts for electricity consumption of 312 MJ/hr from the combined heat and power plant, based pro-rata on the power requirement of dehydration electrical equipment (78 kWh/hr) compared to the total power requirement of the bioethanol plant (4,500 kWh/hr), or 1.7% of the total electrical output supplied by the straw fired CHP plant (Ref. 12).

(nn) Total bioethanol output rate of 12.4 t/hr, based on an annual output rate of 100,000 t/a of bioethanol and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 11).

(oo) Direct nitrous oxide emissions of 73 g N_2O/t of straw fuel feed from the combined heat and power plant (Ref. 23) and straw fuel feed requirement of 1.242 t/t bioethanol and with heat and electricity measured on an equivalent basis, to drying (13%), to milling, hydrolysis, fermentation and distillation (86.6%), and to dehydration (0.4%), and allocation between bioethanol and animal feed (84.4%), resulting in a total allocation to bioethanol of (99.6% x 84.4%)+ (0.4%) = 84.5%.

(pp) Surplus electricity for sale equal to 4,975 MJ/t of bioethanol which displaces average electricity supplies with a nitrous oxide requirement of 5.577 x 10^{-6} kg N_2O/ MJ for the UK in 1996 (Ref. 12) and assuming 84.4% contribution to bioethanol by price of co-products.

(qq) Primary energy input of 1,282,500 GJ for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £51.3 m (Ref. 11) and an energy intensity of 25 MJ/£ (Ref. 16) , and an estimated total nitrous oxide requirement of 1.866 x 10^{-9} kg N_2O /MJ primary energy input to construction (Ref. 18), assuming 84.4% contribution to bioethanol by price of co-products

(rr) Straw-fired combined heat and power plant with a 32 MW rated heat output and a 22 MW rated electricity output and a load factor of 91% which has a straw fuel feed consumption of 124,066 t/a, providing a total heat supplies of 9,181 MJ/t of bioethanol (consisting of 783 MJ/ t of bioethanol for drying, 4,698 MJ/t of bioethanol for milling, hydrolysis, fermentation and distillation, and 25 MJ/t of bioethanol for dehydration with excess heat of 3,580 MJ/t of bioethanol) and total electricity supplies of 6,427 MJ/t of bioethanol (consisting of 515 MJ/t of bioethanol for milling, hydrolysis, fermentation and distillation, 25 MJ/t for dehydration, 912 MJ/t of bioethanol for the animal feed plant and 4,975 MJ/t of bioethanol of surplus for sale).

(ss) Primary energy input of 1,581,800 GJ for construction of a straw-fired combined heat and power plant with a 32 MW rated heat output and a 22 MW rated electricity output, based pro rata on data for a straw-fired combined heat and power plant with a 13.0 MW rated heat output and a 5.0 MW rated electricity output (Ref. 22), with 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. 18), assuming 84.4% contribution to bioethanol by price of co-products

(tt) Nitrous oxide output of annual plant maintenance assumed to be 1.5% of carbon dioxide output from plant construction (Ref. 11).

(uu) Ash sent for spreading as a fertiliser on fields at an average round trip distance of 80 km (Ref. 10) 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 methane requirement of 4.8 x 10^{-7} ± 1.8 x 10^{-8} kg N_2O/t-km (Ref. 12).

(vv) Ash output of 5.5% of straw fuel feed (Ref. 10) and straw requirement of 1.242 t/t of bioethanol.

(ww) Average round trip distance of 450 km (Ref. 20) by bulk road carrier transport with a direct nitrous oxide requirement of $4.6 \times 10^{-7} \pm 1.7 \times 10^{-8}$ kg N_2O/t-km, an indirect nitrous oxide requirement of $2.1 \times 10^{-8} \pm 8 \times 10^{-10}$ kg N_2O/t-km and a total nitrous oxide requirement of $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8}$ kg N_2O/t-km (Ref. 13).

References

1. "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.

2. Annual average ex-farm price of feed wheat, United Kingdom, 2000/02 from www.hgca.com/c-stats accessed 3 February 2003.

3. Private communication with D. Darby, British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication, based on an assumed derogation of fuel duty of 26 p/l and a delivered market price of 39 p/l for bioethanol, with G. Punter, British Sugar plc. Peterborough, United Kingdom, 28 January 2003.

5. "British Survey of Fertiliser Practice 1999", Fertiliser Manufacturers' Association.

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003.

7. "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

8. "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

9. "Pesticide Use Survey" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. "Farm Management Pocket Handbook" by J. Nix, Wye College, University of London, United Kingdom, 2002.

11. Private communication with A. Nixon, British Sugar plc., Peterborough, United Kingdom, 22 January 2003.

12. "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.

13. "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.

14. "Düngemittel – Energie- und Stoffstrombilanzen" (Fertilisers – Energy and Material Balance) by A. Patyk and G. A. Reinhardt, Vieweg Umweltwissenschaften, Braunschweig/Wiesbaden, Germany, 1997.

15. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

16. "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.

17. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

18. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

19. "Interim Report on Energy-Use in Metallurgical and Non-Metallic Mineral Processing, Phase 5" Battelle Columbus Laboratories, PB-246-357, United States of America, 1975.

20. "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.

21. "Assessment of Net Emissions of Greenhouse Gases from Ethanol-Blended Gasolines in Canada: Lignocellulosic Feedstocks" R-2000-2, Levelton Engineering Ltd., Richmond, Canada, December 1998.

22. "Energy and Carbon Analysis of Using Straw as a Fuel" by J. F. Grant, R. Hetherington, R. E. Horne and N. D. Mortimer, Report ETSU B/M4/00487/01, Energy Technology Support Unit, Harwell, United Kingdom, 1995

23. Private communication with G. Jungmeier, Joanneum Research, Austria, 15 January 2003.

Greenhouse Gas Outputs from Bioethanol Production from Wheat Using Straw as Fuel (Model 7)

Functional Unit: :	Bioethanol at point of distribution derived from wheat
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on average market prices, assuming 1.394 tonnes of wheat straw at £25/t (Ref. 1) and 3.425 tonnes of harvested wheat grain with 20% moisture content at £69/t (Ref. 2), giving a 87.1% allocation to bioethanol, and 1.141 tonnes of animal feed at £80/t (Ref. 3) and 1.000 tonnes of bioethanol at £494/t (Ref. 4), giving a 84.4% allocation to bioethanol.

Contribution	Per Unit	Total Greenhouse Gas Output (kg eq CO_2)						
		Direct		Indirect		Total		Notes
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	ha.a	213	±32	1,239	±140	1,452	±144	(a)
- P Fertiliser	ha.a	-	-	67	±10	67	±10	(a)
- K Fertiliser	ha.a	-	-	25	±4	25	±4	(a)
- Pesticide	ha.a	-	-	11	±1	11	±1	(a)
- Herbicide	ha.a	-	-	-	-	-	-	(a)
- Insecticide	ha.a	-	-	4	±1	4	±1	(a)
- Fungicide	ha.a	-	-	6	±1	6	±1	(a)
- Seed	ha.a	-	-	125	±13	125	±13	(a)
- Diesel Fuel	ha.a	378	±60	47	±20	425	±63	(a)
Reference System:								
- Diesel Fuel	ha.a	- 63	±10	- 7	±3	- 70	±11	(a)
Sub-Totals	ha.a	528	±68	1,517	±142	2,045	±158	
	t be	**154**	**±20**	**444**	**±42**	**598**	**±46**	(b)
Straw Baling:								
- N Fertiliser	ha.a	68	±11	397	±45	465	±46	(a)
- P Fertiliser	ha.a	-	-	17	±3	17	±3	(a)
- K Fertiliser	ha.a	-	-	56	±8	56	±8	(a)
- Diesel Fuel	ha.a	23	±3	3	-	26	-	(a)
- Machinery	ha.a	-	-	19	±3	19	±3	(a)
- Twine	ha.a	-	-	7	±1	7	±1	(a)
- Maintenance	ha.a	-	-	8	±1	8	±1	(a)
Sub-Totals	ha.a	89	±11	507	±46	596	±47	
	t be	**30**	**±4**	**170**	**±15**	**200**	**±16**	(c)
Straw Transport:								
- Diesel Fuel	t bws	4	-	1	-	5	-	(a)
	t be	**5**	**-**	**1**	**-**	**6**	**-**	(d)
Straw Storage:								
- Diesel Fuel	t bws	5	±1	1	-	6	±1	(a)
- Sheeting	t bws	-	-	12	±2	12	±2	(a)
- Machinery	t bws	-	-	1	-	1	-	(a)
- Maintenance	t bws	-	-	-	-	-	-	(a)
Sub-Totals	t bws	5	±1	14	±2	19	±2	
	t be	**6**	**±1**	**16**	**±2**	**22**	**±2**	(d)
Wheat Transport:								
- Diesel Fuel	t hwg	10	±1	3	-	13	±1	(a)
	t be	**30**	**±3**	**9**	**-**	**39**	**±3**	(e)
Milling, Hydrolysis, Fermentation and Distillation:								
- Caustic Soda	t de	-	-	50	±7	50	±7	(a)
- Diam. Phosph.	t de	-	-	2	-	2	-	(a)
- Sulphuric Acid	t de	-	-	4	±4	4	±4	(a)
- Enzyme AMG	t de	-	-	5	±1	5	±1	(a)
- Enzyme AA	t de	-	-	2	-	2	-	(a)
- Calcium Chlor.	t de	-	-	1	-	1	-	(a)
Sub-Totals	t de	-	-	64	±8	64	±8	
	t be	**-**	**-**	**57**	**±7**	**57**	**±7**	(e)
Dehydration:	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	-
Direct Emissions	**t be**	**25**	**-**	**-**	**-**	**25**		(a)
Surplus Electricity	**t be**	**-679**	**-**	**-**	**-**	**-679**		(a)
Plant Construction	**t be**	**-**	**-**	**55**	±8	**55**	±8	(a)
Plant Maintenance	**t be**	**-**	**-**	**19**	±3	**19**	±3	(a)
Ash Disposal	t ash	4	-	-	-	4	**-**	
	t be	-	-	-	-	-	**-**	(g)
Distribution:								
- Diesel Fuel	**t be**	**25**	±1	**7**	±1	**32**	±1	(a)
Totals	**t be**	**-404**	±21	**778**	±43	**374**	±49	

Biofuel Specifications

Density of bioethanol	= 0.79 kg/l
Net calorific value of bioethanol	= 26.72 MJ/kg
Gross calorific value of bioethanol	= 29.74 MJ/kg

Abbreviations

ha.a	= hectare year
t bws	= tonne of baled wheat straw
t hwg	= tonne of harvested wheat grain
t dwg	= tonne of dried wheat grain
t ash	= tonne of ash
t be	= tonne of bioethanol

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 0.398 ha.a/t of bioethanol and allocation of 87.1% x 84.4% = 73.5% to bioethanol.

(c) Land requirement of 0.398 ha.a/t bioethanol and partitioning, based on relative energy, with heat and electricity measured on an equivalent basis, to drying (13%), to milling, hydrolysis, fermentation and distillation (86.6%), and to dehydration (0.4%), and allocation between bioethanol and animal feed (84.4%), resulting in a total allocation to bioethanol of (99.6% x 84.4%)+ (0.4%) = 84.5%.

(d) Baled straw requirement of 1.38t/t bioethanol and partitioning, based on relative energy, with heat and electricity measured on an equivalent basis, to drying (13%), to milling, hydrolysis, fermentation and distillation (86.6%), and to dehydration (0.4%), and allocation between bioethanol and animal feed (84.4%), resulting in a total allocation to bioethanol of (99.6% x 84.4%)+ (0.4%) = 84.5%..

(e) Harvested wheat grain requirement of 3.425t/t bioethanol and allocation of 84.4% to bioethanol.

(f) Distillate (94.5% alcohol) requirement 1.058 t/t of bioethanol and allocation of 84.4% to bioethanol.

(g) Ash output of 5.5% of straw fuel feed and straw requirement of 1.242 t/t of bioethanol.

References

1. "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.

2. Annual average ex-farm price of feed wheat, United Kingdom, 2000/02 from www.hgca.com/c-stats accessed 3 February 2003.

3. Private communication with D. Darby, British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication, based on an assumed derogation of fuel duty of 26 p/l and a delivered market price of 39 p/l for bioethanol, with G. Punter, British Sugar plc. Peterborough, United Kingdom, 28 January 2003.

APPENDIX E: Model 2

Spreadsheet for Primary Energy Inputs to Bioethanol Production from Sugar Beet using a Natural Gas-fired Boiler and Grid Electricity (Model 2)

Functional Unit:	Bioethanol at point of distribution derived from sugar beet using natural gas-fired boiler and grid electricity during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on a market price for 13.296 tonnes of sugar beet on the farm of £22.00/t (Ref. 1) and an effective price for 1.507 tonnes of sugar beet tops (dry matter) of £10.0/t, based on an average market price of £2.00/t (wet basis) with a 80% moisture content (Ref. 2), substitution of 0.669 tonnes of soil from washing by soil from main sources, substitution of 0.049 tonnes of stones from washing by stones from quarrying, an effective average price for 14.560 tonnes of thin juice (15% solids and 88% sugar purity) of £16.2/t, derived from a price for thick juice (67% solids and 92% sugar purity) of £72.48/t (Ref. 3), and an effective average price for 25.996 tonnes of pulp (97% moisture content) of £2.56/t, derived from an average market price for animal feed pellets (15% moisture content) of £72.50/t (Ref. 2), substitution of 0.566 tonnes of LimeX by agricultural lime, and an assumed price for bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solids and 66.5% sugar purity) of £122.15/t, based on the price of thick juice (Ref. 4).

Contribution	Per Unit	Primary Energy Input (MJ)								Notes
		Direct		Indirect		Feedstock		Total		
		Value	Range	Value	Range	Value	Range	Value	Range	
Cult. and Harvest:										
- N Fertiliser	*ha.a*	-	-	*1,443*	*±577*	*2,739*	*±109*	*4,182*	*±587*	(a)
- P Fertiliser	*ha.a*	-	-	*1,375*	*±206*	-	-	*1,375*	*±206*	(b, c)
- K Fertiliser	*ha.a*	-	-	*1,165*	*±175*	-	-	*1,165*	*±175*	(c, d)
- Pesticides	*ha.a*	-	-	*795*	*±119*	-	-	*795*	*±119*	(c, e)
- Herbicide	*ha.a*	-	-	*110*	*±16*	-	-	*110*	*±16*	(c, f)
- Insecticide	*ha.a*	-	-	*66*	*±10*	-	-	*66*	*±10*	(c, g)
- Seed	*ha.a*	-	-	*135*	*±20*	-	-	*135*	*±20*	(c, h)
- Diesel Fuel	*ha.a*	*8,870*	*±1,402*	*976*	*±465*	-	-	*9,846*	*±1,477*	(c, i)
Reference System:										
- Diesel Fuel	*ha.a*	*- 922*	*±146*	*- 101*	*±48*	-	-	*- 1,023*	*±154*	(c, j)
Sub-Totals	*ha.a*	*7,948*	*±1,410*	*5,964*	*±800*	*2,739*	*±109*	*16,651*	*±1,624*	
	t be	**1,289**	**±229**	**967**	**±130**	**444**	**±18**	**2,700**	**±263**	(k)
Transport:										
- Diesel Fuel	*t ssb*	*77*	*±3*	*27*	*±3*	-	-	*104*	*±4*	(l)
	t be	**684**	**±27**	**240**	**±27**	**-**	**-**	**924**	**±36**	(m)
Washing, Shredding and Diffusion:										
- Natural Gas	*t csb*	*312*	*±47*	*34*	*±5*	-	-	*346*	*±52*	(c, n-p)
- Electricity	*t csb*	*81*	*±12*	*168*	*±25*			*249*	*±28*	(c, n-p)
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	-	-	(q)
- Gypsum	*t csb*	-	-	*1*	-	-	-	*1*	-	(c, r)
- Hydrochlor. Acid	*t csb*	-	-	*1*	-	-	-	*1*	-	(s)
- Formaldehyde	*t csb*	-	-	-	-	-	-	-	-	(c, t)
- Biocide	*t csb*	-	-	-	-	-	-	-	-	(c, u)
- Foam Oil	*t csb*	-	-	-	-	-	-	-	-	(v)
Credits:										
- Soil	*t csb*	-	-	*- 4*	*± 1*	-	-	*- 4*	*± 1*	(c, w)
- Stones	*t csb*	-	-	-	-	-	-	-	-	(c, x)
Sub-Totals	*t csb*	*399*	*±49*	*200*	*±26*	-	-	*599*	*±59*	
	t be	**3,353**	**±408**	**1,680**	**±214**	**-**	**-**	**5,033**	**±495**	(y)
Purification, Concentration, Fermentation, Distillation and Dehydration:										
- Natural Gas	*t csb*	*868*	*±130*	*96*	*±46*	-	-	*964*	*±138*	(c, n, p,z)
- Electricity	*t csb*	*60*	*±9*	*125*	*±19*			*185*	*±21*	(c, n, p,z)
- Sulphur	*t csb*	-	-	*1*	-	-	-	*1*	-	(aa)
- Soda	*t csb*	-	-	*1*	-	-	-	*1*	-	(bb)
- Anti-Scalant	*t csb*	-	-	*1*	-	-	-	*1*	-	(cc)
- EDTA	*t csb*	-	-	-	-	-	-	-	-	(dd)
- Limestone	*t csb*	-	-	*13*	*±2*	-	-	*13*	*±2*	(ee)
- Coke	*t csb*	*51*	*±9*	*16*	*±5*	-	-	*67*	*±10*	(c, ff)
- Anti-Foam	*t csb*	-	-	*6*	*±1*	-	-	*6*	*±1*	(c, gg)
- Sulphuric Acid	*t csb*	-	-	*1*	*±1*	-	-	*1*	*±1*	(hh)
Credit:										
- LimeX	*t csb*	-	-	*- 94*	*±14*	-	-	*- 94*	*±14*	(c, ii)
Sub-Totals	*t csb*	*979*	*±131*	*166*	*±52*	-	-	*1,145*	*±141*	
	t be	**10,553**	**±1,408**	**1,789**	**±560**	**-**	**-**	**12,342**	**±1,519**	(jj)
Plant Construction	**t be**	**-**	**-**	**475**	**±71**	**-**	**-**	**475**	**±71**	(kk)
Plant Maintenance	**t be**	**-**	**-**	**142**	**±21**	**-**	**-**	**142**	**±21**	(ll)
Distribution	**t be**	**369**	**±14**	**129**	**±16**	**-**	**-**	**498**	**±21**	(mm)
Totals	**t be**	**16,248**	**±2,201**	**5,422**	**±619**	**444**	**±18**	**22,114**	**±2,286**	

Biofuel Specifications

Density of bioethanol	= 0.79 kg/l
Net calorific value of bioethanol	= 26.72 MJ/kg
Gross calorific value of bioethanol	= 29.74 MJ/kg

Abbreviations

ha.a	= hectare year
t ssb	= tonne of soiled sugar beet
t csb	= tonne of clean sugar beet
t be	= tonne of bioethanol

Notes

(a) Nitrogen fertiliser application rate of 103.0 kg N/ha.a (Ref. 5) 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 nitrogen fertiliser (Ref. 6).

(b) Phosphate fertiliser application rates of 38.0 kg P/ha.a (Ref. 5), or 87.0 kg P_2O_5/ ha.a assuming 2.290 kg P_2O_5/kg P, and a total energy requirement for phosphate fertiliser of 15.8 MJ/kg P_2O_5 (Ref. 7).

(c) Assuming an error bar of ±15% based on similar analyses (Ref. 8).

(d) Potash fertiliser application rate of 104.0 kg K/ha.a (Ref. 5), or 125.3 kg K_2O/ha.a assuming 1.205 kg K_2O/kg K, and a total energy requirement for potash fertiliser of 9.3 MJ/ kg K_2O (Ref. 7).

(e) Pesticide application rate of 2.90 kg/ha.a (Ref. 9) and a total energy requirement for general pesticides, herbicides and fungicides of 274.1 MJ/kg (Ref. 7).

(f) Herbicide application rate of 0.40 kg/ha.a (Ref. 9) and a total energy requirement for general pesticides, herbicides and fungicides of 274.1 MJ/kg (Ref. 7).

(g) Insecticide application rate of 0.24 kg/ha.a (Ref. 9) and a total energy requirement for general pesticides, herbicides and fungicides of 274.1 MJ/kg (Ref. 7).

(h) Sowing rate of 3.8 kg/ha.a, consisting of 1.2 kg/ha.a of seed and 2.6 kg/ha.a pelletising material (Ref. 10), and a total energy requirement of 35.5 MJ/kg of seed (Ref. 7).

(i) Diesel fuel consumption of 8,870 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides and insecticides, and harvesting (Ref. 2) and a gross energy requirement of 1.110 MJ/MJ for diesel fuel in the UK in 1996 (Ref. 11).

(j) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 7) and a gross energy requirement of 1.110 MJ/MJ for diesel fuel in the UK in 1996 (Ref. 11).

(k) Land requirement of 0.255 ha.a/t of bioethanol, partitioning between13.296 t of sugar beet at farm with a price of £22/t (Ref. 1) and 1.507 t sugar beet tops (dry matter) with an effective price of £10.00/t, based on an average market price of £2.00/t (wet basis) 80% moisture content (Ref. 2), and partitioning between 14.560 t of thin juice with an effective price of £16.2/t and an effective average price for 25.996 t of pulp with a moisture content of 97% of £2.56/t, derived from an average price for animal feed pellets with a moisture content of 15% of £72.50/t (Ref. 2), and an assumed price of bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solid and 66.5% sugar purity), based on the price of thick juice, giving an allocation of 95.1% x 78.0% x 85.7% = 63.6% to bioethanol.

(l) Average round trip distance of 94 km (Ref. 2) 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. 12).

(m) Soiled sugar beet requirement of 13.296 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(n) Steam production with a natural gas-fired boiler with an overall efficiency of 80% (Ref. 1) and a gross energy requirement of 1.110 MJ/MJ for natural gas in the UK in 1996 (Ref. 11), and electricity obtained from the grid with a gross energy requirement of 3.083 MJ/MJ for the UK in 1996 (Ref. 12).

(o) Steam consumption rate for washing, shredding and diffusion of 14 t/hr, assumed to be 50% of total steam requirements of sugar plant (Ref. 2), equivalent to 1.11 x 14 x 2,778 MJ/t steam /0.8 MJ/hr = 53,963 MJ/hr of natural gas, and an electricity consumption rate for washing, shredding and diffusion of 3.5 MW (Ref. 2) with a gross energy requirement of 3.083 MJ/MJ for average electricity generation from the grid the UK in 1996 (Ref. 12).

(p) Total clean sugar beet input of 1,257,774 t/a and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 2), giving a clean sugar beet input rate of 156 t/hr.

(q) Sulphuric acid (93% concentration) consumption rate of 0.18 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 2.4 ± 2.7 MJ/kg for sulphuric acid (Ref. 13).

(r) Gypsum (calcium sulphate) consumption rate of 1.06 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 1 MJ/kg for gypsum (Ref. 13).

(s) Hydrochloric acid (100% concentration) consumption rate of 0.025 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 40 ± 3 MJ/kg for hydrochloric acid (Ref. 13).

(t) Formaldehyde consumption rate of 0.15 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 3 MJ/kg for formaldehyde (Refs. 2 and 14 to 16).

(u) Biocide consumption rate of 0.024 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 3 MJ/kg for biocide (Refs. 2 and 14 to 16).

(v) Foam oil consumption rate of 0.03 kg/t of clean sugar beet (Ref. 2) and, assuming foam oil is similar to refined rapeseed oil, an energy requirement of 11 ± 1 MJ/kg of refined rapeseed oil (Ref. 17).

(w) Soil recovery rate of 5.32% of clean sugar beet (Ref. 2), or 53.2 kg/t of clean sugar beet, and, assuming soil production is similar to sand extraction, an energy requirement of 0.08 MJ/kg for sand (Ref. 18).

(x) Stone recovery rate of 0.39% of clean sugar beet (Ref. 2), or 3.9 kg/t of clean sugar beet, and, assuming stone production is similar to sand extraction, an energy requirement of 0.08 MJ/kg for sand (Ref. 18).

(y) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(z) Steam consumption rate for purification of 1 t/hr and for fermentation, distillation and dehydration of 38 t/hr (Ref. 2), resulting in a total steam consumption rate of 39 t/hr or equivalent to 1.11 x 39 x 2,778 MJ/t steam /0.8 = 150,325 MJ/hr of natural gas, and an electricity consumption rate for diffusion of 1.4 MW and for fermentation, distillation and dehydration of 1.2 MW (Ref. 2) with a gross energy requirement of 3.083 MJ/MJ for average electricity generation from the grid the UK in 1996 (Ref. 12).

(aa) Sulphur (as SO_2) consumption rate of 0.13 kg/t of clean sugar beet and an energy requirement of 11 ± 3 MJ/kg for sulphur (Ref. 13).

(bb) Soda (sodium carbonate) consumption rate of 0.05 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 29 ± 8 MJ/kg for soda (Ref. 13).

(cc) Anti-scalant consumption rate of 0.04 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 32 MJ/kg for anti-scalant (Refs. 2 and 14 to 16).

(dd) EDTA consumption rate of 0.055 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 8 MJ/kg for EDTA (Refs. 2 and 14 to 16).

(ee) Limestone consumption rate of 2.3% of clean sugar beet (Ref. 2), or 23 kg/t of clean sugar beet, and an energy requirement of 0.58 MJ/kg for limestone (Ref. 18).

(ff) Coke consumption rate of 0.18% of clean sugar beet (Ref. 2), or 1.8 kg/t of clean sugar beet, and a gross energy requirement of 1.316 x 28.1 = 37 MJ/kg for coke in the UK in 1996 (Ref. 11).

(gg) Anti-foam consumption rate of 253,344 kg/a (Ref. 2), or 0.20 kg/t of clean sugar beet, and, assuming similarity with anti-scalant, an energy requirement of 32 MJ/kg of anti-foam (Refs. 2 and 14 to 16).

(hh) Sulphuric acid (93% concentration) consumption rate of 380,016 kg/a, or 0.30 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 2.4 ± 2.7 MJ/kg for sulphuric acid (Ref. 13).

(ii) LimeX production rate of 45 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 2.1 MJ/kg for lime (Ref. 7).

(jj) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 85.7% to bioethanol.

(kk) Primary energy input of 950,000 GJ for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £38.0 m (Ref. 2) and an energy intensity of 25 MJ/£ (Ref. 14).

(ll) Primary energy input of annual plant maintenance assumed to be 1.5% of primary energy input to plant construction (Ref. 2).

(mm) Average round trip distance of 450 km (Ref. 19) 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. 11).

References

1. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 28 April 2003.

2. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 2 May 2003.

3. Private communication with D. Darby of British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication with G. Punter of British Sugar plc., Peterborough, United Kingdom, 8 May 2003.

5. "British Sugar Field Crop Survey 2001"

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Report No. 20/1, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003, for the Department for the Environment, Food and Rural Affairs, www.defra.

7. "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.

8. "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.

9. "Pesticide Use Survey Reports" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. British Sugar Internal Survey 2001

11. "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.

12. "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.

13. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

14. "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.

15. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

16. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

17. "Carbon and Energy Balances for a Range of Biofuel Options" by M. A. Elsayed, R. Matthews and N. D. Mortimer, B/B6/00784/REP, Energy Technology Support Unit, Harwell, United Kingdom, March 2003, www.shu.ac.uk/rru/projects/biofuels/biofuels.html.

18. "Handbook of Industrial Energy Analysis" by I. Boustead and G. Hancock, Ellis Horwood, Chichester, United Kingdom, 1979.

19. "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.

Spreadsheet for Carbon Dioxide Outputs from Bioethanol Production from Sugar Beet using a Natural Gas-fired Boiler and Grid Electricity (Model 2)

Functional Unit:	Bioethanol at point of distribution derived from sugar beet using natural gas-fired boiler and grid electricity during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on a market price for 13.296 tonnes of sugar beet on the farm of £22.00/t (Ref. 1) and an effective price for 1.507 tonnes of sugar beet tops (dry matter) of £10.0/t, based on an average market price of £2.00/t (wet basis) with a 80% moisture content (Ref. 2), substitution of 0.669 tonnes of soil from washing by soil from main sources, substitution of 0.049 tonnes of stones from washing by stones from quarrying, an effective average price for 14.560 tonnes of thin juice (15% solids and 88% sugar purity) of £16.2/t, derived from a price for thick juice (67% solids and 92% sugar purity) of £72.48/t (Ref. 3), and an effective average price for 25.996 tonnes of pulp (97% moisture content) of £2.56/t, derived from an average market price for animal feed pellets (15% moisture content) of £72.50/t (Ref. 2), substitution of 0.566 tonnes of LimeX by agricultural lime, and an assumed price for bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solids and 66.5% sugar purity) of £122.15/t, based on the price of thick juice (Ref. 4).

Contribution	Per Unit	Carbon Dioxide Output (kg CO_2)						Notes
		Direct		Indirect		Total		
		Value	Range	Value	Range	Value	Range	
Cult. and Harvest.:								
- N Fertiliser	*ha.a*	-	-	*196*	*±28*	*196*	*±28*	(a)
- P Fertiliser	*ha.a*	-	-	*61*	*±9*	*61*	*±9*	(b, c)
- K Fertiliser	*ha.a*	-	-	*57*	*±9*	*57*	*±9*	(c, d)
- Pesticides	*ha.a*	-	-	*14*	*±2*	*14*	*±2*	(c, e)
- Herbicide	*ha.a*	-	-	*2*	-	*2*	-	(c, f)
- Insecticide	*ha.a*	-	-	*1*	-	*1*	-	(c, g)
- Seed	*ha.a*	-	-	*7*	*±1*	*7*	*±1*	(c, h)
- Diesel Fuel	*ha.a*	*608*	*±96*	*72*	*±33*	*680*	*±102*	(c, i)
Reference System:								
- Diesel Fuel	*ha.a*	*- 63*	*±10*	*- 7*	*±3*	*- 70*	*±10*	(c, j)
Sub-Totals	*ha.a*	*545*	*±97*	*403*	*±45*	*948*	*±107*	
	t be	**88**	**±16**	**65**	**±7**	**153**	**±17**	(k)
Transport:								
- Diesel Fuel	*t ssb*	*5*	-	*2*	-	*7*	-	(l)
	t be	**44**	**-**	**18**	**-**	**62**	**-**	(m)
Washing, Shredding and Diffusion:								
- Natural Gas	*t csb*	*16*	*±2*	*1*	-	*17*	*±2*	(c, n - p)
- Electricity	*t csb*	-	-	*12*	*±2*	*12*	*±2*	(c, n - p)
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	(q)
- Gypsum	*t csb*	-	-	-	-	-	-	(c, r)
- Hydrochloric Acid	*t csb*	-	-	-	-	-	-	(s)
- Formaldehyde	*t csb*	-	-	-	-	-	-	(c, t)
- Biocide	*t csb*	-	-	-	-	-	-	(c, u)
- Foam Oil	*t csb*	-	-	-	-	-	-	(v)
Credits:								
- Soil	*t csb*	-	-	-	-	-	-	(c, w)
- Stones	*t csb*	-	-	-	-	-	-	(c, x)
Sub-Totals	*t csb*	*16*	*±2*	*13*	*±2*	*29*	*±3*	
	t be	**134**	**±19**	**109**	**±19**	**243**	**±26**	(y)
Purification, Concentration, Fermentation, Distillation and Dehydration:								
- Natural Gas	*t csb*	*45*	*±7*	*1*	*±1*	*46*	*±7*	(c, n,p, z)
- Electricity	*t csb*	-	-	*9*	*±1*	*9*	*±1*	
- Sulphur	*t csb*	-	-	-	-	-	-	(aa)
- Soda	*t csb*	-	-	-	-	-	-	(bb)
- Anti-Scalant	*t csb*	-	-	-	-	-	-	(cc)
- EDTA	*t csb*	-	-	-	-	-	-	(dd)
- Limestone	*t csb*	-	-	-	-	-	-	(ee)
- Coke	*t csb*	*5*	*±1*	*1*	-	*6*	*±1*	(c, ff)
- Anti-Foam	*t csb*	-	-	-	-	-	-	(c, gg)
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	(hh)
Credit:								
- LimeX	*t csb*	-	-	*- 8*	*±1*	*- 8*	*±1*	(c, ii)
Sub-Totals	*t csb*	*50*	*±7*	*3*	*±2*	*53*	*±7*	
	t be	**539**	**±75**	**32**	**±22**	**571**	**±78**	(jj)
Plant Construction	**t be**	**-**	**-**	**24**	**±4**	**24**	**±4**	(kk)
Plant Maintenance	**t be**	**-**	**-**	**7**	**±1**	**7**	**±1**	(ll)
Distribution	**t be**	**25**	**±1**	**7**	**±1**	**32**	**±1**	(mm)
Totals	**t be**	**830**	**±79**	**262**	**±30**	**1,092**	**±85**	

Biofuel Specifications

Density of bioethanol	= 0.79 kg/l
Net calorific value of bioethanol	= 26.72 MJ/kg
Gross calorific value of bioethanol	= 29.74 MJ/kg

Abbreviations

ha.a	= hectare year
t csb	= tonne of clean sugar beet
t ssb	= tonne of soiled sugar beet
t be	= tonne of bioethanol

Notes

(a) Nitrogen fertiliser application rate of 103.0 kg N/ha.a (Ref. 4) and a total carbon requirement for ammonium nitrate of 1.904 ± 0.275 kg CO_2/kg N (Ref. 6).

(b) Phosphate fertiliser application rates of 38.0 kg P/ha.a (Ref. 5), or 87.0 kg P_2O_5/ ha.a assuming 2.290 kg P_2O_5/kg P, and a total carbon requirement for phosphate fertiliser of 0.700 kg CO_2/kg P_2O_5 (Ref. 7).

(c) Assuming an error bar of ±15% based on similar analyses (Ref. 8).

(d) Potash fertiliser application rate of 104.0 kg K/ha.a (Ref. 5), or 125.3 kg K_2O/ha.a assuming 1.205 kg K_2O/kg K, and a total carbon requirement for potash fertiliser of 0.453 kg CO_2/ kg K_2O (Ref. 7).

(e) Pesticide application rate of 2.90 kg/ha.a (Ref. 9) and a total carbon requirement for general pesticides, herbicides and fungicides of 4.921 kg CO_2/kg (Ref. 7).

(f) Herbicide application rate of 0.40 kg/ha.a (Ref. 9) and a total carbon requirement for general pesticides, herbicides and fungicides of 4.921 kg CO_2/kg (Ref. 7).

(g) Insecticide application rate of 0.24 kg/ha.a (Ref. 9) and a total carbon requirement for general pesticides, herbicides and fungicides of 4.921 kg CO_2/kg (Ref. 7).

(h) Sowing rate of 3.8 kg/ha.a, consisting of 1.2 kg/ha.a of seed and 2.6 kg/ha.a pelletising material (Ref. 10), and a total carbon requirement of 1.775 kg CO_2 /kg of seed (Ref. 7).

(i) Diesel fuel consumption of 8,870 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides and insecticides, and harvesting (Ref. 2) 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. 11).

(j) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 7) 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. 11).

(k) Land requirement of 0.255 ha.a/t of bioethanol, partitioning between13.296 t of sugar beet at farm with a price of £22/t (Ref. 1) and 1.507 t sugar beet tops (dry matter) with an effective price of £10.00/t, based on an average market price of £2.00/t (wet basis) 80% moisture content (Ref. 2), and partitioning between 14.560 t of thin juice with an effective price of £16.2/t and an effective average price for 25.996 t of pulp with a moisture content of 97% of £2.56/t, derived from an average price for animal feed pellets with a moisture content of 15% of £72.50/t (Ref. 2), and an assumed price of bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solid and 66.5% sugar purity), based on the price of thick juice, giving an allocation of 95.1% x 78.0% x 85.7% = 63.6% to bioethanol.

(l) Average round trip distance of 94 km (Ref. 2) 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. 12).

(m) Soiled sugar beet requirement of 13.296 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(n) Steam production with a natural gas-fired boiler with an overall efficiency of 80% (Ref. 1) 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. 11), and electricity obtained from the grid with an indirect carbon requirement of 0.150 kg CO_2/MJ in the UK in 1996 (Ref. 11).

(o) Steam consumption rate for washing, shredding and diffusion of 14 t/hr, assumed to be 50% of total steam requirements of sugar plant (Ref. 2), equivalent to 14 x 2,778 MJ/t steam /0.8 MJ/hr = 48,615 MJ/hr of natural gas, and an electricity consumption rate for washing, shredding and diffusion of 3.5 MW (Ref. 2).

(p) Total clean sugar beet input of 1,257,774 t/a and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 2), giving a clean sugar beet input rate of 156 t/hr.

(q) Sulphuric acid (93% concentration) consumption rate of 0.18 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 0.13 ± 0.16 kg CO_2/kg for sulphuric acid (Ref. 13).

(r) Gypsum (calcium sulphate) consumption rate of 1.06 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 0.08 kg CO_2/kg for gypsum (Ref. 13).

(s) Hydrochloric acid (100% concentration) consumption rate of 0.025 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 0.15 kg CO_2/kg for hydrochloric acid (Ref. 13).

(t) Formaldehyde consumption rate of 0.15 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 2.1×10^{-5} kg CO_2/kg for formaldehyde (Refs. 2 and 14 to 16).

(u) Biocide consumption rate of 0.024 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 0.12 kg CO_2/kg for biocide (Refs. 2 and 14 to 16).

(v) Foam oil consumption rate of 0.03 kg/t of clean sugar beet (Ref. 2) and, assuming foam oil is similar to refined rapeseed oil, a carbon requirement of 0.59 ± 0.04 kg CO_2/kg of refined rapeseed oil (Ref. 17).

(w) Soil recovery rate of 5.32% of clean sugar beet (Ref. 2), or 53.2 kg/t of clean sugar beet, and, assuming soil production is similar to sand extraction, a carbon requirement of 5.7×10^{-3} kg CO_2/kg for sand (Ref. 18).

(x) Stone recovery rate of 0.39% of clean sugar beet (Ref. 2), or 3.9 kg/t of clean sugar beet, and, assuming stone production is similar to sand extraction, a carbon requirement of 5.7×10^{-3} kg CO_2/kg for sand (Ref. 18).

(y) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(z) Steam consumption rate for purification of 1 t/hr and for fermentation, distillation and dehydration of 38 t/hr (Ref. 2), resulting in a total steam consumption rate of 39 t/hr or equivalent to 39 x 2,778 MJ/t steam /0.8 = 135,428 MJ/hr of natural gas, and an electricity consumption rate for diffusion of 1.4 MW and for fermentation, distillation and dehydration of 1.2 MW (Ref. 2).

(aa) Sulphur (as SO_2) consumption rate of 0.13 kg/t of clean sugar beet and a carbon requirement of 0.89 ± 0.24 kg CO_2/kg for sulphur (Ref. 13).

(bb) Soda (sodium carbonate) consumption rate of 0.05 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 2.13 ± 0.64 kg CO_2/kg for soda (Ref. 13).

(cc) Anti-scalant consumption rate of 0.04 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 1.52 kg CO_2/kg for anti-scalant (Refs. 2 and 14 to 16).

(dd) EDTA consumption rate of 0.055 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 0.40 kg CO_2/kg for EDTA (Refs. 2 and 14 to 16).

(ee) Limestone consumption rate of 2.3% of clean sugar beet (Ref. 2), or 23 kg/t of clean sugar beet, and a carbon requirement of 0.02 kg CO_2/kg for limestone (Ref. 18).

(ff) Coke consumption rate of 0.18% of clean sugar beet (Ref. 2), or 1.8 kg/t of clean sugar beet, and a direct carbon requirement of 0.104 x 28.1 = 2.92 kg CO_2/kg and an indirect carbon requirement of 0.37 kg CO_2/kg for coke in the UK in 1996 (Ref. 11).

(gg) Anti-foam consumption rate of 253,344 kg/a (Ref. 2), or 0.20 kg/t of clean sugar beet, and, assuming similarity with anti-scalant, a carbon requirement of 1.52 kg CO_2/kg of anti-foam (Refs. 2 and 14 to 16).

(hh) Sulphuric acid (93% concentration) consumption rate of 380,016 kg/a, or 0.30 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 0.13 ± 016 kg CO_2/kg for sulphuric acid (Ref. 13).

(ii) LimeX production rate of 45 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 0.18 kg CO_2/kg for lime (Ref. 6), excluding carbon dioxide from calcination which is not accounted for in the bioethanol plant.

(jj) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 85.7% to bioethanol.

(kk) Carbon dioxide output of 47,500 tonnes of CO_2 for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £38.0 m (Ref. 2) and a carbon intensity of 1.25 kg CO_2/£ (Ref. 14).

(ll) Carbon dioxide output of annual plant maintenance assumed to be 1.5% of carbon dioxide output of plant construction (Ref. 2).

(mm) Average round trip distance of 450 km (Ref. 19) 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. 11).

References

1. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 28 April 2003.

2. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 2 May 2003.

3. Private communication with D. Darby of British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication with G. Punter of British Sugar plc., Peterborough, United Kingdom, 8 May 2003.

5. "British Sugar Field Crop Survey 2001"

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Report No. 20/1, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003, for the Department for the Environment, Food and Rural Affairs, www.defra.

7. "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.

8. "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.

9. "Pesticide Use Survey Reports" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. British Sugar Internal Survey 2001

11. "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.

12. "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.

13. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

14. "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.

15. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

16. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

17. "Carbon and Energy Balances for a Range of Biofuel Options" by M. A. Elsayed, R. Matthews and N. D. Mortimer, B/B6/00784/REP, Energy Technology Support Unit, Harwell, United Kingdom, March 2003, www.shu.ac.uk/rru/projects/biofuels/biofuels.html.

18. "Handbook of Industrial Energy Analysis" by I. Boustead and G. Hancock, Ellis Horwood, Chichester, United Kingdom, 1979.

19. "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.

<u>Spreadsheet for Methane Outputs from Bioethanol Production from Sugar Beet using a Natural Gas-fired Boiler and Grid Electricity</u> (Model 2)

Functional Unit:	Bioethanol at point of distribution derived from sugar beet using natural gas-fired boiler and grid electricity during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on a market price for 13.296 tonnes of sugar beet on the farm of £22.00/t (Ref. 1) and an effective price for 1.507 tonnes of sugar beet tops (dry matter) of £10.0/t, based on an average market price of £2.00/t (wet basis) with a 80% moisture content (Ref. 2), substitution of 0.669 tonnes of soil from washing by soil from main sources, substitution of 0.049 tonnes of stones from washing by stones from quarrying, an effective average price for 14.560 tonnes of thin juice (15% solids and 88% sugar purity) of £16.2/t, derived from a price for thick juice (67% solids and 92% sugar purity) of £72.48/t (Ref. 3), and an effective average price for 25.996 tonnes of pulp (97% moisture content) of £2.56/t, derived from an average market price for animal feed pellets (15% moisture content) of £72.50/t (Ref. 2), substitution of 0.566 tonnes of LimeX by agricultural lime, and an assumed price for bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solids and 66.5% sugar purity) of £122.15/t, based on the price of thick juice (Ref. 4).

Contribution	Per Unit	Methane Output (kg CH_4)						Notes
		Direct		Indirect		Total		
		Value	Range	Value	Range	Value	Range	
Cult. and Harvest.:								
- N Fertiliser	*ha.a*	-	-	*0.371*	*±0.062*	*0.371*	*±0.062*	(a)
- P Fertiliser	*ha.a*	-	-	*0.002*	-	*0.002*	-	(b, c)
- K Fertiliser	*ha.a*	-	-	*0.003*	-	*0.003*	-	(c, d)
- Pesticides	*ha.a*	-	-	*0.001*	-	*0.001*	-	(c, e)
- Herbicide	*ha.a*	-	-	-	-	-	-	(c, f)
- Insecticide	*ha.a*	-	-	-	-	-	-	(c, g)
- Seed	*ha.a*	-	-	*0.008*	*±0.001*	*0.008*	*±0.001*	(c, h)
- Diesel Fuel	*ha.a*	*0.005*	*±0.005*	*0.181*	*±0.027*	*0.186*	*±0.028*	(c, i)
Reference System:								
- Diesel Fuel	*ha.a*	*- 0.001*	*±0.001*	*- 0.019*	*±0.003*	*- 0.020*	*±0.003*	(c, j)
Sub-Totals	*ha.a*	*0.004*	*±0.005*	*0.547*	*±0.068*	*0.551*	*±0.068*	
	t be	**0.001**	**±0.001**	**0.088**	**±0.011**	**0.089**	**±0.011**	(k)
Transport:								
- Diesel Fuel	*t ssb*	-	-	*0.002*	-	*0.002*	-	(l)
	t be	**-**	**-**	**0.018**	**-**	**0.018**	**-**	(m)
Washing, Shredding and Diffusion:								
- Natural Gas	*t csb*	*0.001*	*±0.001*	*0.034*	*±0.005*	*0.035*	*±0.005*	(c, n - p)
- Electricity	*t csb*	-	-	*0.033*	*±0.005*	*0.033*	*±0.005*	(c, n - p)
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	(q)
- Gypsum	*t csb*	-	-	-	-	-	-	(c, r)
- Hydrochloric Acid	*t csb*	-	-	-	-	-	-	(s)
- Formaldehyde	*t csb*	-	-	-	-	-	-	(c, t)
- Biocide	*t csb*	-	-	-	-	-	-	(c, u)
- Foam Oil	*t csb*	-	-	-	-	-	-	(v)
Credits:								
- Soil	*t csb*	-	-	-	-	-	-	(c, w)
- Stones	*t csb*	-	-	-	-	-	-	(c, x)
Sub-Totals	*t csb*	*0.001*	*±0.001*	*0.067*	*±0.007*	*0.068*	*±0.007*	
	t be	**0.008**	**±0.008**	**0.563**	**±0.051**	**0.571**	**±0.051**	(y)
Purification, Concentration, Fermentation, Distillation and Dehydration:								
- Natural Gas	*t csb*	*0.003*	*±0.001*	*0.094*	*±0.014*	*0.097*	*±0.014*	(c,n,p,z)
- Electricity	*t csb*	-	-	*0.024*	*±0.004*	*0.024*	*±0.004*	(c,n,p,z
- Sulphur	*t csb*	-	-	-	-	-	-	(aa)
- Soda	*t csb*	-	-	-	-	-	-	(bb)
- Anti-Scalant	*t csb*	-	-	-	-	-	-	(cc)
- EDTA	*t csb*	-	-	-	-	-	-	(dd)
- Limestone	*t csb*	-	-	-	-	-	-	(ee)
- Coke	*t csb*	-	-	-	-	-	-	(c, ff)
- Anti-Foam	*t csb*	-	-	-	-	-	-	(c, gg)
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	(hh)
Credit:								
- LimeX	*t csb*	-	-	-	-	-	-	(c, ii)
Sub-Totals	*t csb*	*0.003*	*±0.001*	*0.118*	*±0.015*	*0.121*	*±0.015*	
	t be	**0.032**	**±0.011**	**1.272**	**±0.162**	**1.304**	**±0.165**	(jj)
Plant Construction	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(kk)
Plant Maintenance	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(ll)
Distribution	**t be**	**-**	**-**	**0.008**	**-**	**0.008**	**-**	(mm)
Totals	**t be**	**0.041**	**±0.033**	**1.949**	**±0.171**	**1.990**	**±0.173**	

Biofuel Specifications

Density of bioethanol	= 0.79 kg/l
Net calorific value of bioethanol	= 26.72 MJ/kg
Gross calorific value of bioethanol	= 29.74 MJ/kg

Abbreviations

ha.a	= hectare year
t csb	= tonne of clean sugar beet
t ssb	= tonne of soiled sugar beet
t be	= tonne of bioethanol

Notes

(a) Nitrogen fertiliser application rate of 103.0 kg N/ha.a (Ref. 5) 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 (Ref. 6).

(b) Phosphate fertiliser application rates of 38.0 kg P/ha.a (Ref. 5), or 87.0 kg P_2O_5/ ha.a assuming 2.290 kg P_2O_5/kg P, and a total methane requirement for phosphate fertiliser of 2.3×10^{-5} kg CH_4/kg P_2O_5 (Ref. 7).

(c) Assuming an error bar of ±15% based on similar analyses (Ref. 8).

(d) Potash fertiliser application rate of 104.0 kg K/ha.a (Ref. 5), or 125.3 kg K_2O/ha.a assuming 1.205 kg K_2O/kg K, and a total methane requirement for potash fertiliser of 2.1×10^{-5} kg CH_4/ kg K_2O (Ref. 7).

(e) Pesticide application rate of 2.90 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.8×10^{-4} kg CH_4/kg (Ref. 7).

(f) Herbicide application rate of 0.40 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.8×10^{-4} kg CH_4/kg (Ref. 7).

(g) Insecticide application rate of 0.24 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.8×10^{-4} kg CH_4/kg (Ref. 7).

(h) Sowing rate of 3.8 kg/ha.a, consisting of 1.2 kg/ha.a of seed and 2.6 kg/ha.a pelletising material (Ref. 10), and a total methane requirement of 0.002 kg CH_4 /kg of seed (Ref. 7).

(i) Diesel fuel consumption of 8,870 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides and insecticides, and harvesting (Ref. 2) 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. 11).

(j) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 7) 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. 11).

(k) Land requirement of 0.255 ha.a/t of bioethanol, partitioning between13.296 t of sugar beet at farm with a price of £22/t (Ref. 1) and 1.507 t sugar beet tops (dry matter) with an effective price of £10.00/t, based on an average market price of £2.00/t (wet basis) 80% moisture content (Ref. 2), and partitioning between 14.560 t of thin juice with an effective price of £16.2/t and an effective average price for 25.996 t of pulp with a moisture content of 97% of £2.56/t, derived from an average price for animal feed pellets with a moisture content of 15% of £72.50/t (Ref. 2), and an assumed price of bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solid and 66.5% sugar purity), based on the price of thick juice, giving an allocation of 95.1% x 78.0% x 85.7% = 63.6% to bioethanol.

(l) Average round trip distance of 94 km (Ref. 2) 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. 12).

(m) Soiled sugar beet requirement of 13.296 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(n) Steam production with a natural gas-fired boiler with an overall efficiency of 80% (Ref. 1), and a direct methane requirement of 3.7×10^{-6} kg CH_4/MJ, an indirect methane requirement of 1.1×10^{-4} kg CH_4/MJ and a total methane requirement of 1.1×10^{-4} kg CH_4/MJ for natural gas in the UK in 1996 (Ref. 11), and electricity obtained from the grid with an indirect methane requirement of 4.043×10^{-4} kg CH_4/MJ in the UK in 1996 (Ref. 11).

(o) Steam consumption rate for washing, shredding and diffusion of 14 t/hr, assumed to be 50% of total steam requirements of sugar plant (Ref. 2), equivalent to 14 x 2,778 MJ/t steam /0.8 MJ/hr = 48,615 MJ/hr of natural gas, and an electricity consumption rate for washing, shredding and diffusion of 3.5 MW (Ref. 2).

(p) Total clean sugar beet input of 1,257,774 t/a and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 2), giving a clean sugar beet input rate of 156 t/hr.

(q) Sulphuric acid (93% concentration) consumption rate of 0.18 kg/t of clean sugar beet (Ref. 2) and a methane requirement of $2.7 \times 10^{-4} \pm 3.0 \times 10^{-4}$ kg CH_4/kg for sulphuric acid (Ref. 13).

(r) Gypsum (calcium sulphate) consumption rate of 1.06 kg/t of clean sugar beet (Ref. 2) and a methane requirement of 2.1×10^{-5} kg CH_4/kg for gypsum (Ref. 13).

(s) Hydrochloric acid (100% concentration) consumption rate of 0.025 kg/t of clean sugar beet (Ref. 2) and a methane requirement of 0.01 ± 0.001 kg CH_4/kg for hydrochloric acid (Ref. 13).

(t) Formaldehyde consumption rate of 0.15 kg/t of clean sugar beet (Ref. 2) and a methane requirement of 4.0×10^{-7} kg CH_4/kg for formaldehyde (Refs. 2 and 14 to 16).

(u) Biocide consumption rate of 0.024 kg/t of clean sugar beet (Ref. 2) and a methane requirement of 3.0×10^{-7} kg CH_4/kg for biocide (Refs. 2 and 14 to 16).

(v) Foam oil consumption rate of 0.03 kg/t of clean sugar beet (Ref. 2) and, assuming foam oil is similar to refined rapeseed oil, a methane requirement of $7.7 \times 10^{-4} \pm 7.0 \times 10^{-5}$ kg CH_4/kg of refined rapeseed oil (Ref. 17).

(w) Soil recovery rate of 5.32% of clean sugar beet (Ref. 2), or 53.2 kg/t of clean sugar beet, and, assuming soil production is similar to sand extraction, a methane requirement of 1.6×10^{-6} kg CH_4/kg for sand (Ref. 18).

(x) Stone recovery rate of 0.39% of clean sugar beet (Ref. 2), or 3.9 kg/t of clean sugar beet, and, assuming stone production is similar to sand extraction, a methane requirement of 1.6×10^{-6} kg CH_4/kg for sand (Ref. 18).

(y) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(z) Steam consumption rate for purification of 1 t/hr and for fermentation, distillation and dehydration of 38 t/hr (Ref. 2), resulting in a total steam consumption rate of 39 t/hr or equivalent to 39 x 2,778 MJ/t steam /0.8 = 135,428 MJ/hr of natural gas, and an electricity consumption rate for diffusion of 1.4 MW and for fermentation, distillation and dehydration of 1.2 MW (Ref. 2).

(aa) Sulphur (as SO_2) consumption rate of 0.13 kg/t of clean sugar beet and a methane requirement of $2.5 \times 10^{-5} \pm 7.0 \times 10^{-6}$ kg CH_4/kg for sulphur (Ref. 13).

(bb) Soda (sodium carbonate) consumption rate of 0.05 kg/t of clean sugar beet (Ref. 2) and a methane requirement of $7.2 \times 10^{-4} \pm 2.0 \times 10^{-5}$ kg CH_4/kg for soda (Ref. 13).

(cc) Anti-scalant consumption rate of 0.04 kg/t of clean sugar beet (Ref. 2) and a methane requirement of 4.0×10^{-6} kg CH_4/kg for anti-scalant (Refs. 2 and 14 to 16).

(dd) EDTA consumption rate of 0.055 kg/t of clean sugar beet (Ref. 2) and a methane requirement of 1.0×10^{-6} kg CH_4/kg for EDTA (Refs. 2 and 14 to 16).

(ee) Limestone consumption rate of 2.3% of clean sugar beet (Ref. 2), or 23 kg/t of clean sugar beet, and a methane requirement of 2.1×10^{-5} kg CH_4/kg for limestone (Ref. 18).

(ff) Coke consumption rate of 0.18% of clean sugar beet (Ref. 2), or 1.8 kg/t of clean sugar beet, and a direct methane requirement of $9.5 \times 10^{-6} \times 28.1 = 2.7 \times 10^{-4}$ kg CH_4/kg and an indirect methane requirement of 9.2×10^{-3} kg CH_4/kg for coke in the UK in 1996 (Ref. 11).

(gg) Anti-foam consumption rate of 253,344 kg/a (Ref. 2), or 0.20 kg/t of clean sugar beet, and, assuming similarity with anti-scalant, a methane requirement of 4.0×10^{-6} kg CH_4/kg of anti-foam (Refs. 2 and 14 to 16).

(hh) Sulphuric acid (93% concentration) consumption rate of 380,016 kg/a, or 0.30 kg/t of clean sugar beet (Ref. 2) and a methane requirement of $2.7 \times 10^{-4} \pm 3.0 \times 10^{-4}$ kg CH_4/kg for sulphuric acid (Ref. 13).

(ii) LimeX production rate of 45 kg/t of clean sugar beet (Ref. 2) and a methane requirement 3.9×10^{-6} kg CH_4/kg for lime (Ref. 7).

(jj) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 85.7% to bioethanol.

(kk) Primary energy input of 950,000 GJ for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £38.0 m (Ref. 2) and an estimated total methane requirement of 1.192×10^{-7} kg CH_4/MJ of primary energy input to plant construction (Ref. 16).

(ll) Primary energy input of annual plant maintenance assumed to be 1.5% of primary energy input to plant construction (Ref. 2).

(mm) Average round trip distance of 450 km (Ref. 19) by bulk road carrier transport with a direct methane requirement of 4.900 x 10^{-7} ± 2.000 x 10^{-8} kg CH_4/t-km, an indirect methane requirement of 1.672 x 10^{-5} ± 6.3 x 10^{-7} kg CH_4/t-km and a total methane requirement of 1.721 x 10^{-5} ± 6.5 x 10^{-7} kg CH_4/t-km (Ref. 11).

References

1. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 28 April 2003.

2. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 2 May 2003.

3. Private communication with D. Darby of British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication with G. Punter of British Sugar plc., Peterborough, United Kingdom, 8 May 2003.

5. "British Sugar Field Crop Survey 2001"

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Report No. 20/1, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003, for the Department for the Environment, Food and Rural Affairs, www.defra.

7. "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.

8. "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.

9. "Pesticide Use Survey Reports" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. British Sugar Internal Survey 2001

11. "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.

12. "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.

13. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

14. "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.

15. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

16. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

17. "Carbon and Energy Balances for a Range of Biofuel Options" by M. A. Elsayed, R. Matthews and N. D. Mortimer, B/B6/00784/REP, Energy Technology Support Unit, Harwell, United Kingdom, March 2003, www.shu.ac.uk/rru/projects/biofuels/biofuels.html.

18. "Handbook of Industrial Energy Analysis" by I. Boustead and G. Hancock, Ellis Horwood, Chichester, United Kingdom, 1979.

19. "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.

Spreadsheet for Nitrous Oxide Outputs from Bioethanol Production from Sugar Beet using a Natural Gas-fired Boiler and Grid Electricity (Model 2)

Functional Unit:	Bioethanol at point of distribution derived from sugar beet using natural gas-fired boiler and grid electricity during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on a market price for 13.296 tonnes of sugar beet on the farm of £22.00/t (Ref. 1) and an effective price for 1.507 tonnes of sugar beet tops (dry matter) of £10.0/t, based on an average market price of £2.00/t (wet basis) with a 80% moisture content (Ref. 2), substitution of 0.669 tonnes of soil from washing by soil from main sources, substitution of 0.049 tonnes of stones from washing by stones from quarrying, an effective average price for 14.560 tonnes of thin juice (15% solids and 88% sugar purity) of £16.2/t, derived from a price for thick juice (67% solids and 92% sugar purity) of £72.48/t (Ref. 3), and an effective average price for 25.996 tonnes of pulp (97% moisture content) of £2.56/t, derived from an average market price for animal feed pellets (15% moisture content) of £72.50/t (Ref. 2), substitution of 0.566 tonnes of LimeX by agricultural lime, and an assumed price for bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solids and 66.5% sugar purity) of £122.15/t, based on the price of thick juice (Ref. 4).

Contribution	Per Unit	Nitrous Oxide Output (kg N_2O)						Notes
		Direct		Indirect		Total		
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	*ha.a*	*0.371*	*±0.125*	*1.514*	*±0.253*	*1.885*	*±0.283*	(a)
- P Fertiliser	*ha.a*	-	-	*0.004*	*±0.001*	*0.004*	*±0.001*	(b, c)
- K Fertiliser	*ha.a*	-	-	*0.001*	-	*0.001*	-	(c, d)
- Pesticides	*ha.a*	-	-	*0.004*	*±0.001*	*0.004*	*±0.001*	(c, e)
- Herbicide	*ha.a*	-	-	*0.001*	-	*0.001*	-	(c, f)
- Insecticide	*ha.a*	-	-	-	-	-	-	(c, g)
- Seed	*ha.a*	-	-	*0.004*	*±0.001*	*0.004*	*±0.001*	(c, h)
- Diesel Fuel	*ha.a*	*0.005*	*±0.001*	-	-	*0.005*	*±0.001*	(c, i)
Reference System:								
- Diesel Fuel	*ha.a*	*- 0.001*	-	-	-	*- 0.001*	-	(c, j)
Sub-Totals	*ha.a*	*0.375*	*±0.125*	*1.528*	*±0.253*	*1.903*	*±0.283*	
	t be	**0.061**	**±0.020**	**0.248**	**±0.041**	**0.309**	**±0.046**	(k)
Transport:								
- Diesel Fuel	*t ssb*	-	-	-	-	-	-	(l)
	t be	**-**	**-**	**-**	**-**	**-**	**-**	(m)
Washing, Shredding and Diffusion:								
- Natural Gas	*t csb*	-	-	-	-	-	-	(c, n - p)
- Electricity	*t csb*	-	-	*0.001*	-	*0.001*	-	(c, n - p)
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	(q)
- Gypsum	*t csb*	-	-	-	-	-	-	(c, r)
- Hydrochloric Acid	*t csb*	-	-	-	-	-	-	(s)
- Formaldehyde	*t csb*	-	-	-	-	-	-	(c, t)
- Biocide	*t csb*	-	-	-	-	-	-	(c, u)
- Foam Oil	*t csb*	-	-	-	-	-	-	(v)
Credits:								
- Soil	*t csb*	-	-	-	-	-	-	(c, w)
- Stones	*t csb*	-	-	-	-	-	-	(c, x)
Sub-Totals	*t csb*	-	-	*0.001*	-	*0.001*	-	
	t be	**-**	**-**	**0.008**	**-**	**0.008**	**-**	(y)
Purification, Concentration, Fermentation, Distillation and Dehydration:								
- Natural Gas	*t csb*	-	-	-	-	-	-	(c,n,p, z)
- Electricity	*t csb*	-	-	-	-	-	-	(aa)
- Sulphur	*t csb*	-	-	-	-	-	-	(bb)
- Soda	*t csb*	-	-	-	-	-	-	(cc)
- Anti-Scalant	*t csb*	-	-	-	-	-	-	(dd)
- EDTA	*t csb*	-	-	-	-	-	-	(ee)
- Limestone	*t csb*	-	-	-	-	-	-	(c, ff)
- Coke	*t csb*	-	-	-	-	-	-	(c, gg)
- Anti-Foam	*t csb*	-	-	-	-	-	-	(hh)
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	
Credit:								
- LimeX	*t csb*	-	-	*- 0.001*	-	*- 0.001*	-	(c, ii)
Sub-Totals	*t csb*	-	-	*- 0.001*	-	*- 0.001*	-	
	t be	**-**	**-**	**- 0.011**	**-**	**- 0.011**	**-**	(jj)
Plant Construction	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(kk)
Plant Maintenance	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(ll)
Distribution	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(mm)
Totals	**t be**	**0.061**	**±0.020**	**0.245**	**±0.041**	**0.306**	**±0.046**	

Biofuel Specifications

Density of bioethanol	= 0.79 kg/l
Net calorific value of bioethanol	= 26.72 MJ/kg
Gross calorific value of bioethanol	= 29.74 MJ/kg

Abbreviations

ha.a	= hectare year
t csb	= tonne of clean sugar beet
t ssb	= tonne of soiled sugar beet
t be	= tonne of bioethanol

Notes

(a) Nitrogen fertiliser application rate of 103.0 kg N/ha.a (Ref. 5) and a direct nitrous oxide requirement of 0.0036 kg N_2O/kg N (Ref. 5), an indirect nitrous oxide requirement of 0.0147 kg N_2O/kg N (Ref. 7) and a total nitrous oxide requirement for ammonium nitrate of 0.0183 kg N_2O/kg N (Ref. 6).

(b) Assuming an error bar of ±15% based on similar analyses (Ref. 8).

(c) Phosphate fertiliser application rates of 38.0 kg P/ha.a (Ref. 5), or 87.0 kg P_2O_5/ ha.a and a total nitrous oxide requirement for phosphate fertiliser of 4.2 x 10^{-5} kg N_2O/kg P_2O_5 (Ref. 7).

(d) Potash fertiliser application rate of 104.0 kg K/ha.a (Ref. 5), or 125.3 kg K_2O/ha.a and a total nitrous oxide requirement for potash fertiliser of 9.4 x 10^{-6} kg N_2O/ kg K_2O (Ref. 7).

(e) Pesticide application rate of 2.90 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.51 x 10^{-3} kg N_2O/kg (Ref. 7).

(f) Herbicide application rate of 0.40 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.51 x 10^{-3} kg N_2O/kg (Ref. 7).

(g) Insecticide application rate of 0.24 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.51 x 10^{-3} kg N_2O/kg (Ref. 7).

(h) Sowing rate of 3.8 kg/ha.a, consisting of 1.2 kg/ha.a of seed and 2.6 kg/ha.a pelletising material (Ref. 10), and a total methane requirement of 0.001 kg N_2O /kg of seed (Ref. 7).

(i) Diesel fuel consumption of 8,870 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides and insecticides, and harvesting (Ref. 2) 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. 11).

(j) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 7) 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. 11).

(k) Land requirement of 0.255 ha.a/t of bioethanol, partitioning between13.296 t of sugar beet at farm with a price of £22/t (Ref. 1) and 1.507 t sugar beet tops (dry matter) with an effective price of £10.00/t, based on an average market price of £2.00/t (wet basis) 80% moisture content (Ref. 2), and partitioning between 14.560 t of thin juice with an effective price of £16.2/t and an effective average price for 25.996 t of pulp with a moisture content of 97% of £2.56/t, derived from an average price for animal feed pellets with a moisture content of 15% of £72.50/t (Ref. 2), and an assumed price of bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solid and 66.5% sugar purity), based on the price of thick juice, giving an allocation of 95.1% x 78.0% x 85.7% = 63.6% to bioethanol.

(l) Average round trip distance of 94 km (Ref. 2) 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. 12).

(m) Soiled sugar beet requirement of 13.296 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(n) Steam production with a natural gas-fired boiler with an overall efficiency of 80% (Ref. 1), and a direct nitrous oxide 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. 11), and electricity obtained from the grid with an indirect nitrous oxide requirement of 5.577 x 10^{-6} kg N_2O/MJ in the UK in 1996 (Ref. 11).

(o) Steam consumption rate for washing, shredding and diffusion of 14 t/hr, assumed to be 50% of total steam requirements of sugar plant (Ref. 2), equivalent to 14 x 2,778 MJ/t steam /0.8 MJ/hr = 48,615 MJ/hr of natural gas, and an electricity consumption rate for washing, shredding and diffusion of 3.5 MW (Ref. 2).

(p) Total clean sugar beet input of 1,257,774 t/a and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 2), giving a clean sugar beet input rate of 156 t/hr.

(q) Sulphuric acid (93% concentration) consumption rate of 0.18 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of $2.7 \times 10^{-7} \pm 3.0 \times 10^{-7}$ kg N_2O/kg for sulphuric acid (Ref. 13).

(r) Gypsum (calcium sulphate) consumption rate of 1.06 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of 5.9×10^{-7} kg N_2O/kg for gypsum (Ref. 13).

(s) Hydrochloric acid (100% concentration) consumption rate of 0.025 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of 3.0×10^{-4} kg N_2O/kg for hydrochloric acid (Ref. 13)

(t) Formaldehyde consumption rate of 0.15 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of 6.0×10^{-9} kg N_2O/kg for formaldehyde (Refs. 2 and 14 to 16).

(u) Biocide consumption rate of 0.024 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of 5.0×10^{-9} kg N_2O/kg for biocide (Refs. 2 and 14 to 16).

(v) Foam oil consumption rate of 0.03 kg/t of clean sugar beet (Ref. 2) and, assuming foam oil is similar to refined rapeseed oil, a nitrous oxide requirement of $1.79 \times 10^{-3} \pm 2.20 \times 10^{-4}$ kg N_2O/kg of refined rapeseed oil (Ref. 17).

(w) Soil recovery rate of 5.32% of clean sugar beet (Ref. 2), or 53.2 kg/t of clean sugar beet, and, assuming soil production is similar to sand extraction, a nitrous oxide requirement of 4.2×10^{-8} kg N_2O/kg for sand (Ref. 18).

(x) Stone recovery rate of 0.39% of clean sugar beet (Ref. 2), or 3.9 kg/t of clean sugar beet, and, assuming stone production is similar to sand extraction, a nitrous oxide requirement of 4.2×10^{-8} kg N_2O/kg for sand (Ref. 18).

(y) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(z) Steam consumption rate for purification of 1 t/hr and for fermentation, distillation and dehydration of 38 t/hr (Ref. 2), resulting in a total steam consumption rate of 39 t/hr or equivalent to 39 x 2,778 MJ/t steam /0.8 = 135,428 MJ/hr of natural gas, and an electricity consumption rate for diffusion of 1.4 MW and for fermentation, distillation and dehydration of 1.2 MW (Ref. 2).

(aa) Sulphur (as SO_2) consumption rate of 0.13 kg/t of clean sugar beet and a nitrous oxide requirement of $6.6 \times 10^{-6} \pm 1.8 \times 10^{-6}$ kg N_2O/kg for sulphur (Ref. 13).

(bb) Soda (sodium carbonate) consumption rate of 0.05 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of $1.8 \times 10^{-5} \pm 0.5 \times 10^{-6}$ kg N_2O/kg for soda (Ref. 13).

(cc) Anti-scalant consumption rate of 0.04 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of 6.0×10^{-8} kg N_2O/kg for anti-scalant (Refs. 2 and 14 to 16).

(dd) EDTA consumption rate of 0.055 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of 2.0×10^{-8} kg N_2O/kg for EDTA (Refs. 2 and 14 to 16).

(ee) Limestone consumption rate of 2.3% of clean sugar beet (Ref. 2), or 23 kg/t of clean sugar beet, and a nitrous oxide requirement of 3.5×10^{-7} kg N_2O/kg for limestone (Ref. 18).

(ff) Coke consumption rate of 0.18% of clean sugar beet (Ref. 2), or 1.8 kg/t of clean sugar beet, and a direct nitrous oxide requirement of $4.0 \times 10^{-9} \times 28.1 = 1.1 \times 10^{-7}$ kg N_2O/kg and an indirect nitrous oxide requirement of 1.3×10^{-6} kg N_2O/kg for coke in the UK in 1996 (Ref. 11).

(gg) Anti-foam consumption rate of 253,344 kg/a (Ref. 2), or 0.20 kg/t of clean sugar beet, and, assuming similarity with anti-scalant, a nitrous oxide requirement of 6.0×10^{-8} kg N_2O/kg of anti-foam (Refs. 2 and 14 to 16).

(hh) Sulphuric acid (93% concentration) consumption rate of 380,016 kg/a, or 0.30 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of $2.0 \times 10^{-7} \pm 3.0 \times 10^{-7}$ kg N_2O/kg for sulphuric acid (Ref. 13).

(ii) LimeX production rate of 45 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement 1.6×10^{-5} kg N_2O/kg for lime (Ref. 7).

(jj) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 85.7% to bioethanol.

(kk) Primary energy input of 950,000 GJ for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £38.0 m (Ref. 2) and an estimated total nitrous oxide requirement of 1.866×10^{-9} kg N_2O/MJ of primary energy input to plant construction (Ref. 16).

(ll) Nitrous oxide output of annual plant maintenance assumed to be 1.5% of primary energy input to plant construction (Ref. 2).

(mm) Average round trip distance of 450 km (Ref. 19) by bulk road carrier transport with a direct nitrous oxide requirement of $4.6 \times 10^{-7} \pm 1.7 \times 10^{-8}$ kg N_2O/t-km, an indirect nitrous oxide requirement of $2.1 \times 10^{-8} \pm 8 \times 10^{-10}$ kg N_2O/t-km and a total nitrous oxide requirement of $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8}$ kg N_2O/t-km (Ref. 11).

References

1. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 28 April 2003.

2. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 2 May 2003.

3. Private communication with D. Darby of British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication with G. Punter of British Sugar plc., Peterborough, United Kingdom, 8 May 2003.

5. "British Sugar Field Crop Survey 2001"

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Report No. 20/1, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003, for the Department for the Environment, Food and Rural Affairs, www.defra.

7. "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.

8. "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.

9. "Pesticide Use Survey Reports" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. British Sugar Internal Survey 2001

11. "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.

12. "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.

13. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

14. "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.

15. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

16. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

17. "Carbon and Energy Balances for a Range of Biofuel Options" by M. A. Elsayed, R. Matthews and N. D. Mortimer, B/B6/00784/REP, Energy Technology Support Unit, Harwell, United Kingdom, March 2003, www.shu.ac.uk/rru/projects/biofuels/biofuels.html.

18. "Handbook of Industrial Energy Analysis" by I. Boustead and G. Hancock, Ellis Horwood, Chichester, United Kingdom, 1979.

19. "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.

Spreadsheet for Total Greenhouse Gas Outputs from Bioethanol Production from Sugar Beet using a Natural Gas-fired Boiler and Grid Electricity (Model 2)

Functional Unit:	Bioethanol at point of distribution derived from sugar beet using natural gas-fired boiler and grid electricity during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on a market price for 13.296 tonnes of sugar beet on the farm of £22.00/t (Ref. 1) and an effective price for 1.507 tonnes of sugar beet tops (dry matter) of £10.0/t, based on an average market price of £2.00/t (wet basis) with a 80% moisture content (Ref. 2), substitution of 0.669 tonnes of soil from washing by soil from main sources, substitution of 0.049 tonnes of stones from washing by stones from quarrying, an effective average price for 14.560 tonnes of thin juice (15% solids and 88% sugar purity) of £16.2/t, derived from a price for thick juice (67% solids and 92% sugar purity) of £72.48/t (Ref. 3), and an effective average price for 25.996 tonnes of pulp (97% moisture content) of £2.56/t, derived from an average market price for animal feed pellets (15% moisture content) of £72.50/t (Ref. 2), substitution of 0.566 tonnes of LimeX by agricultural lime, and an assumed price for bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solids and 66.5% sugar purity) of £122.15/t, based on the price of thick juice (Ref. 4).

Contribution	Per Unit	Total Greenhouse Gas Output (kg eq CO_2)						Notes
		Direct		Indirect		Total		
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:	*ha.a*	*119*	*±40*	*690*	*±86*	*809*	*±95*	(a)
- N Fertiliser	*ha.a*	-	-	*62*	*±9*	*62*	*±9*	(a)
- P Fertiliser	*ha.a*	-	-	*57*	*±9*	*57*	*±9*	(a)
- K Fertiliser	*ha.a*	-	-	*15*	*±2*	*15*	*±2*	(a)
- Pesticides	*ha.a*	-	-	*2*	-	*2*	-	(a)
- Herbicide	*ha.a*	-	-	*1*	-	*1*	-	(a)
- Insecticide	*ha.a*	-	-	*8*	*±1*	*8*	*±1*	(a)
- Seed	*ha.a*	*610*	*±96*	*76*	*±33*	*686*	*±102*	(a)
- Diesel Fuel Reference System:	*ha.a*	*- 63*	*±10*	*- 7*	*±3*	*- 70*	*±10*	(a)
- Diesel Fuel								
Sub-Totals	*ha.a*	*666*	*±104*	*904*	*±93*	*1,570*	*±140*	
	t be	**108**	**±17**	**147**	**±15**	**255**	**±23**	(b)
Transport:								
- Diesel Fuel	*t ssb*	*5*	-	*2*	-	*7*	-	(a)
	t be	**44**	**-**	**18**	**-**	**62**	**-**	(c)
Washing, Shredding and Diffusion:								
- Natural Gas	*t csb*	*16*	*±2*	*2*	*±1*	*18*	*±2*	(a)
- Electricity	*t csb*	-	-	*13*	*±2*	*13*	*±2*	(a)
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	(a)
- Gypsum	*t csb*	-	-	-	-	-	-	(a)
- Hydrochloric Acid	*t csb*	-	-	-	-	-	-	(a)
- Formaldehyde	*t csb*	-	-	-	-	-	-	(a)
- Biocide	*t csb*	-	-	-	-	-	-	(a)
- Foam Oil	*t csb*	-	-	-	-	-	-	(a)
Credits:								
- Soil	*t csb*	-	-	-	-	-	-	(a)
- Stones	*t csb*	-	-	-	-	-	-	(a)
Sub-Totals	*t csb*	*16*	*±2*	*15*	*±2*	*22*	*±3*	
	t be	**134**	**±19**	**126**	**±19**	**260**	**±26**	(d)
Purification, Concentration, Fermentation, Distillation and Dehydration:								
- Natural Gas	*t csb*	*45*	*±7*	*3*	*±1*	*48*	*±7*	(a)
- Electricity	*t csb*	-	-	*10*	*±1*	*10*	*±1*	(a)
- Sulphur	*t csb*	-	-	-	-	-	-	(a)
- Soda	*t csb*	-	-	-	-	-	-	(a)
- Anti-Scalant	*t csb*	-	-	-	-	-	-	(a)
- EDTA	*t csb*	-	-	-	-	-	-	(a)
- Limestone	*t csb*	-	-	-	-	-	-	(a)
- Coke	*t csb*	*5*	*±1*	*1*	-	*6*	*±1*	(a)
- Anti-Foam	*t csb*	-	-	-	-	-	-	(a)
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	(a)
Credit:								
- LimeX	*t csb*	-	-	*- 8*	*±1*	*- 8*	*±1*	(a)
Sub-Totals	*t csb*	*50*	*±7*	*6*	*±2*	*56*	*±7*	
	t be	**539**	**±75**	**64**	**±21**	**603**	**±78**	(e)
Plant Construction	**t be**	**-**	**-**	**24**	**±4**	**24**	**±4**	(a)
Plant Maintenance	**t be**	**-**	**-**	**7**	**±1**	**7**	**±1**	(a)
Distribution	**t be**	**25**	**±1**	**7**	**±1**	**32**	**±1**	(a)
Totals	**t be**	**850**	**±81**	**393**	**±27**	**1,243**	**±85**	

Biofuel Specifications

Density of bioethanol	= 0.79 kg/l
Net calorific value of bioethanol	= 26.72 MJ/kg
Gross calorific value of bioethanol	= 29.74 MJ/kg

Abbreviations

ha.a	= hectare year
t csb	= tonne of clean sugar beet
t ssb	= tonne of soiled sugar beet
t be	= tonne of bioethanol

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 0.255 ha.a/t of bioethanol, partitioning between13.296 t of sugar beet at farm with a price of £22/t (Ref. 1) and 1.507 t sugar beet tops (dry matter) with an effective price of £10.00/t, based on an average market price of £2.00/t (wet basis) 80% moisture content (Ref. 2), and partitioning between 14.560 t of thin juice with an effective price of £16.2/t and an effective average price for 25.996 t of pulp with a moisture content of 97% of £2.56/t, derived from an average price for animal feed pellets with a moisture content of 15% of £72.50/t (Ref. 2), and an assumed price of bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solid and 66.5% sugar purity), based on the price of thick juice, giving an allocation of 95.1% x 78.0% x 85.7% = 63.6% to bioethanol.

(c) Soiled sugar beet requirement of 13.296 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(d) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(e) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 85.7% to bioethanol.

APPENDIX F: Model 4a

Spreadsheet for Primary Energy Inputs to Bioethanol Production from Sugar Beet using a Natural Gas-fired Combined Heat and Power Plant with a Steam Turbine (Model 4a)

Functional Unit:	Bioethanol at point of distribution derived from sugar beet using natural gas-fired combined heat and power with a steam turbine during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on a market price for 13.296 tonnes of sugar beet on the farm of £22.00/t (Ref. 1) and an effective price for 1.507 tonnes of sugar beet tops (dry matter) of £10.0/t, based on an average market price of £2.00/t (wet basis) with a 80% moisture content (Ref. 2), substitution of 0.669 tonnes of soil from washing by soil from main sources, substitution of 0.049 tonnes of stones from washing by stones from quarrying, an effective average price for 14.560 tonnes of thin juice (15% solids and 88% sugar purity) of £16.2/t, derived from a price for thick juice (67% solids and 92% sugar purity) of £72.48/t (Ref. 3), and an effective average price for 25.996 tonnes of pulp (97% moisture content) of £2.56/t, derived from an average market price for animal feed pellets (15% moisture content) of £72.50/t (Ref. 2), substitution of 0.566 tonnes of LimeX by agricultural lime, and an assumed price for bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solids and 66.5% sugar purity) of £122.15/t, based on the price of thick juice (Ref. 4).

Contribution	Per Unit	Primary Energy Input (MJ)								
		Direct		Indirect		Feedstock		Total		Notes
		Value	Range	Value	Range	Value	Range	Value	Range	
Cult. and Harvest:										
- N Fertiliser	*ha.a*	-	-	*1,443*	*±577*	*2,739*	*±109*	*4,182*	*±587*	(a)
- P Fertiliser	*ha.a*	-	-	*1,375*	*±206*	-	-	*1,375*	*±206*	(b, c)
- K Fertiliser	*ha.a*	-	-	*1,165*	*±175*	-	-	*1,165*	*±175*	(c, d)
- Pesticides	*ha.a*	-	-	*795*	*±119*	-	-	*795*	*±119*	(c, e)
- Herbicide	*ha.a*	-	-	*110*	*±16*	-	-	*110*	*±16*	(c, f)
- Insecticide	*ha.a*	-	-	*66*	*±10*	-	-	*66*	*±10*	(c, g)
- Seed	*ha.a*	-	-	*135*	*±20*	-	-	*135*	*±20*	(c, h)
- Diesel Fuel	*ha.a*	*8,870*	*±1,402*	*976*	*±465*	-	-	*9,846*	*±1,477*	(c, i)
Reference System:										
- Diesel Fuel	*ha.a*	*- 922*	*±146*	*- 101*	*±48*	-	-	*- 1,023*	*±154*	(c, j)
Sub-Totals	*ha.a*	*7,948*	*±1,410*	*5,964*	*±800*	*2,739*	*±109*	*16,651*	*±1,624*	
	t be	**1,289**	**±229**	**967**	**±130**	**444**	**±18**	**2,700**	**±263**	(k)
Transport:										
- Diesel Fuel	*t ssb*	*77*	*±3*	*27*	*±3*	-	-	*104*	*±4*	(l)
	t be	**684**	**±27**	**240**	**±27**	**-**	**-**	**924**	**±36**	(m)
Washing, Shredding and Diffusion:										
- Natural Gas	*t csb*	*386*	*±61*	*42*	*±20*	-	-	*428*	*±64*	(c, n-p)
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	-	-	(q)
- Gypsum	*t csb*	-	-	*1*	-	-	-	*1*	-	(c, r)
- Hydrochlor. Acid	*t csb*	-	-	*1*	-	-	-	*1*	-	(s)
- Formaldehyde	*t csb*	-	-	-	-	-	-	-	-	(c, t)
- Biocide	*t csb*	-	-	-	-	-	-	-	-	(c, u)
- Foam Oil	*t csb*	-	-	-	-	-	-	-	-	(v)
Credits:										
- Soil	*t csb*	-	-	*- 4*	*± 1*	-	-	*- 4*	*± 1*	(c, w)
- Stones	*t csb*	-	-	-	-	-	-	-	-	(c, x)
Sub-Totals	*t csb*	*386*	*±61*	*40*	*±20*	-	-	*426*	*±64*	
	t be	**3,243**	**±513**	**336**	**±168**	**-**	**-**	**3,579**	**±538**	(y)
Purification, Concentration, Fermentation, Distillation and Dehydration:										
- Natural Gas	*t csb*	*878*	*±139*	*97*	*±46*	-	-	*975*	*±146*	(c, n, p,z)
- Sulphur	*t csb*	-	-	*1*	-	-	-	*1*	-	(aa)
- Soda	*t csb*	-	-	*1*	-	-	-	*1*	-	(bb)
- Anti-Scalant	*t csb*	-	-	*1*	-	-	-	*1*	-	(cc)
- EDTA	*t csb*	-	-	-	-	-	-	-	-	(dd)
- Limestone	*t csb*	-	-	*13*	*±2*	-	-	*13*	*±2*	(ee)
- Coke	*t csb*	*51*	*±9*	*16*	*±5*	-	-	*67*	*±10*	(c, ff)
- Anti-Foam	*t csb*	-	-	*6*	*±1*	-	-	*6*	*±1*	(c, gg)
- Sulphuric Acid	*t csb*	-	-	*1*	*±1*	-	-	*1*	*±1*	(hh)
Credit:										
- Electricity	*t csb*	*- 32*	*±7*	*- 29*	*±6*	-	-	*- 61*	*±9*	(c, ii)
- LimeX	*t csb*	-	-	*- 94*	*±14*	-	-	*- 94*	*±14*	(c, jj)
Sub-Totals	*t csb*	*897*	*±139*	*13*	*±49*	-	-	*910*	*±147*	
	t be	**9,669**	**±1,503**	**140**	**±526**	**-**	**-**	**9,809**	**±1,592**	(kk)
Plant Construction	**t be**	**-**	**-**	**475**	**±71**	**-**	**-**	**475**	**±71**	(ll)
Plant Maintenance	**t be**	**-**	**-**	**142**	**±21**	**-**	**-**	**142**	**±21**	(mm)
Distribution	**t be**	**369**	**±14**	**129**	**±16**	**-**	**-**	**498**	**±21**	(nn)
Totals	**t be**	**15,254**	**±1,605**	**2,429**	**±573**	**444**	**±18**	**18,127**	**±1,704**	

Biofuel Specifications

Density of bioethanol	= 0.79 kg/l
Net calorific value of bioethanol	= 26.72 MJ/kg
Gross calorific value of bioethanol	= 29.74 MJ/kg

Abbreviations

ha.a	= hectare year
t ssb	= tonne of soiled sugar beet
t csb	= tonne of clean sugar beet
t be	= tonne of bioethanol

Notes

(a) Nitrogen fertiliser application rate of 103.0 kg N/ha.a (Ref. 5) 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 nitrogen fertiliser (Ref. 6).

(b) Phosphate fertiliser application rates of 38.0 kg P/ha.a (Ref. 5), or 87.0 kg P_2O_5/ ha.a assuming 2.290 kg P_2O_5/kg P, and a total energy requirement for phosphate fertiliser of 15.8 MJ/kg P_2O_5 (Ref. 7).

(c) Assuming an error bar of ±15% based on similar analyses (Ref. 8).

(d) Potash fertiliser application rate of 104.0 kg K/ha.a (Ref. 5), or 125.3 kg K_2O/ha.a assuming 1.205 kg K_2O/kg K, and a total energy requirement for potash fertiliser of 9.3 MJ/ kg K_2O (Ref. 7).

(e) Pesticide application rate of 2.90 kg/ha.a (Ref. 9) and a total energy requirement for general pesticides, herbicides and fungicides of 274.1 MJ/kg (Ref. 7).

(f) Herbicide application rate of 0.40 kg/ha.a (Ref. 9) and a total energy requirement for general pesticides, herbicides and fungicides of 274.1 MJ/kg (Ref. 7).

(g) Insecticide application rate of 0.24 kg/ha.a (Ref. 9) and a total energy requirement for general pesticides, herbicides and fungicides of 274.1 MJ/kg (Ref. 7).

(h) Sowing rate of 3.8 kg/ha.a, consisting of 1.2 kg/ha.a of seed and 2.6 kg/ha.a pelletising material (Ref. 10), and a total energy requirement of 35.5 MJ/kg of seed (Ref. 7).

(i) Diesel fuel consumption of 8,870 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides and insecticides, and harvesting (Ref. 2) and a gross energy requirement of 1.110 MJ/MJ for diesel fuel in the UK in 1996 (Ref. 11).

(j) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 7) and a gross energy requirement of 1.110 MJ/MJ for diesel fuel in the UK in 1996 (Ref. 11).

(k) Land requirement of 0.255 ha.a/t of bioethanol, partitioning between13.296 t of sugar beet at farm with a price of £22/t (Ref. 1) and 1.507 t sugar beet tops (dry matter) with an effective price of £10.00/t, based on an average market price of £2.00/t (wet basis) 80% moisture content (Ref. 2), and partitioning between 14.560 t of thin juice with an effective price of £16.2/t and an effective average price for 25.996 t of pulp with a moisture content of 97% of £2.56/t, derived from an average price for animal feed pellets with a moisture content of 15% of £72.50/t (Ref. 2), and an assumed price of bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solid and 66.5% sugar purity), based on the price of thick juice, giving an allocation of 95.1% x 78.0% x 85.7% = 63.6% to bioethanol.

(l) Average round trip distance of 94 km (Ref. 2) 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. 12).

(m) Soiled sugar beet requirement of 13.296 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(n) Natural gas-fired combined heat and power plant based on a steam turbine with an overall efficiency of 84%, consuming 248,427 MJ/hr of natural gas to provide 67 t/hr or 181,578 MJ/hr of steam (matched to bioethanol plant requirements) and 7.5 MW (6.1 MW for bioethanol plant and 1.4 MW surplus) of electricity equal to 7,500 kWh/hr or 27,000 MJ/hr (Ref. 2), resulting in 0.109 MJ of electricity and 0.731 MJ of steam from each MJ of natural gas, or a natural gas consumption rate of 1.190 MJ/MJ of energy output in the form of electricity or steam, and a gross energy requirement of 1.110 MJ/MJ for natural gas in the UK in 1996 (Ref. 11).

(o) Steam consumption rate for washing, shredding and diffusion of 14 t/hr, assumed to be 50% of total steam requirements of sugar plant (Ref. 2), equivalent to 1.190 x 181,578 x 14/67 = 45,151 MJ/hr of natural gas,

and an electricity consumption rate for washing, shredding and diffusion of 3.5 MW (Ref. 2), equivalent to 1.190 x 27,000 x 3.5/7.5 = 14,994 MJ/hr of natural gas, resulting in a total natural gas consumption rate of 60,145 MJ/hr.

(p) Total clean sugar beet input of 1,257,774 t/a and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 2), giving a clean sugar beet input rate of 156 t/hr.

(q) Sulphuric acid (93% concentration) consumption rate of 0.18 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 2.4 $\pm$ 2.7 MJ/kg for sulphuric acid (Ref. 13).

(r) Gypsum (calcium sulphate) consumption rate of 1.06 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 1 MJ/kg for gypsum (Ref. 13).

(s) Hydrochloric acid (100% concentration) consumption rate of 0.025 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 40 $\pm$ 3 MJ/kg for hydrochloric acid (Ref. 13).

(t) Formaldehyde consumption rate of 0.15 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 3 MJ/kg for formaldehyde (Refs. 2 and 14 to 16).

(u) Biocide consumption rate of 0.024 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 3 MJ/kg for biocide (Refs. 2 and 14 to 16).

(v) Foam oil consumption rate of 0.03 kg/t of clean sugar beet (Ref. 2) and, assuming foam oil is similar to refined rapeseed oil, an energy requirement of 11 $\pm$ 1 MJ/kg of refined rapeseed oil (Ref. 17).

(w) Soil recovery rate of 5.32% of clean sugar beet (Ref. 2), or 53.2 kg/t of clean sugar beet, and, assuming soil production is similar to sand extraction, an energy requirement of 0.08 MJ/kg for sand (Ref. 18).

(x) Stone recovery rate of 0.39% of clean sugar beet (Ref. 2), or 3.9 kg/t of clean sugar beet, and, assuming stone production is similar to sand extraction, an energy requirement of 0.08 MJ/kg for sand (Ref. 18).

(y) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(z) Steam consumption rate for purification of 1 t/hr and for fermentation, distillation and dehydration of 38 t/hr (Ref. 2), resulting in a total steam consumption rate of 39 t/hr or equivalent to 1.190 x 181,578 x 39/67 = 125,777 MJ/hr of natural gas, and an electricity consumption rate for diffusion of 1.4 MW and for fermentation, distillation and dehydration of 1.2 MW (Ref. 2), equivalent to 1.190 x 27,000 x 2.6/7.5 = 11,138 MJ/hr of natural gas, resulting in a total natural gas consumption rate for diffusion of 136,915 MJ/hr.

(aa) Sulphur (as SO_2) consumption rate of 0.13 kg/t of clean sugar beet and an energy requirement of 11 $\pm$ 3 MJ/kg for sulphur (Ref. 13).

(bb) Soda (sodium carbonate) consumption rate of 0.05 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 29 $\pm$ 8 MJ/kg for soda (Ref. 13).

(cc) Anti-scalant consumption rate of 0.04 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 32 MJ/kg for anti-scalant (Refs. 2 and 14 to 16).

(dd) EDTA consumption rate of 0.055 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 8 MJ/kg for EDTA (Refs. 2 and 14 to 16).

(ee) Limestone consumption rate of 2.3% of clean sugar beet (Ref. 2), or 23 kg/t of clean sugar beet, and an energy requirement of 0.58 MJ/kg for limestone (Ref. 18).

(ff) Coke consumption rate of 0.18% of clean sugar beet (Ref. 2), or 1.8 kg/t of clean sugar beet, and a gross energy requirement of 1.316 x 28.1 = 37 MJ/kg for coke in the UK in 1996 (Ref. 11).

(gg) Anti-foam consumption rate of 253,344 kg/a (Ref. 2), or 0.20 kg/t of clean sugar beet, and, assuming similarity with anti-scalant, an energy requirement of 32 MJ/kg of anti-foam (Refs. 2 and 14 to 16).

(hh) Sulphuric acid (93% concentration) consumption rate of 380,016 kg/a, or 0.30 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 2.4 $\pm$ 2.7 MJ/kg for sulphuric acid (Ref. 13).

(ii) Surplus electricity of 1.4 MW for 8,064 hr/a resulting in 11,289,600 kWh/a or 40,642,560 MJ/a of electricity exported for sale, equivalent to 32 MJ/t of clean sugar beet, and an energy requirement of 3.083 MJ/MJ for displaced grid electricity supplies in the UK in 1996 (Ref. 11) less the energy requirement of 1.190 MJ/MJ for electricity generated from the gas-fired combined heat and power plant.

(jj) LimeX production rate of 45 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 2.1 MJ/kg for lime (Ref. 7).

(kk) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 85.7% to bioethanol.

(ll) Primary energy input of 950,000 GJ for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £38.0 m (Ref. 2) and an energy intensity of 25 MJ/£ (Ref. 14).

(mm) Primary energy input of annual plant maintenance assumed to be 1.5% of primary energy input to plant construction (Ref. 2).

(nn) Average round trip distance of 450 km (Ref. 19) 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. 11).

References

1. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 28 April 2003.

2. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 2 May 2003.

3. Private communication with D. Darby of British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication with G. Punter of British Sugar plc., Peterborough, United Kingdom, 8 May 2003.

5. "British Sugar Field Crop Survey 2001"

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Report No. 20/1, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003, for the Department for the Environment, Food and Rural Affairs, www.defra.

7. "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.

8. "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.

9. "Pesticide Use Survey Reports" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. British Sugar Internal Survey 2001

11. "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.

12. "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.

13. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

14. "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.

15. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

16. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

17. "Carbon and Energy Balances for a Range of Biofuel Options" by M. A. Elsayed, R. Matthews and N. D. Mortimer, B/B6/00784/REP, Energy Technology Support Unit, Harwell, United Kingdom, March 2003, www.shu.ac.uk/rru/projects/biofuels/biofuels.html.

18. "Handbook of Industrial Energy Analysis" by I. Boustead and G. Hancock, Ellis Horwood, Chichester, United Kingdom, 1979.

19. "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.

Spreadsheet for Carbon Dioxide Outputs from Bioethanol Production from Sugar Beet using a Natural Gas-fired Combined Heat and Power Plant with a Steam Turbine (Model 4a)

Functional Unit:	Bioethanol at point of distribution derived from sugar beet using natural gas-fired combined heat and power with a steam turbine during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on a market price for 13.296 tonnes of sugar beet on the farm of £22.00/t (Ref. 1) and an effective price for 1.507 tonnes of sugar beet tops (dry matter) of £10.0/t, based on an average market price of £2.00/t (wet basis) with a 80% moisture content (Ref. 2), substitution of 0.669 tonnes of soil from washing by soil from main sources, substitution of 0.049 tonnes of stones from washing by stones from quarrying, an effective average price for 14.560 tonnes of thin juice (15% solids and 88% sugar purity) of £16.2/t, derived from a price for thick juice (67% solids and 92% sugar purity) of £72.48/t (Ref. 3), and an effective average price for 25.996 tonnes of pulp (97% moisture content) of £2.56/t, derived from an average market price for animal feed pellets (15% moisture content) of £72.50/t (Ref. 2), substitution of 0.566 tonnes of LimeX by agricultural lime, and an assumed price for bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solids and 66.5% sugar purity) of £122.15/t, based on the price of thick juice (Ref. 4).

Contribution	Per Unit	Carbon Dioxide Output (kg CO_2)						Notes
		Direct		Indirect		Total		
		Value	Range	Value	Range	Value	Range	
Cult. and Harvest.:								
- N Fertiliser	*ha.a*	-	-	*196*	*±28*	*196*	*±28*	(a)
- P Fertiliser	*ha.a*	-	-	*61*	*±9*	*61*	*±9*	(b, c)
- K Fertiliser	*ha.a*	-	-	*57*	*±9*	*57*	*±9*	(c, d)
- Pesticides	*ha.a*	-	-	*14*	*±2*	*14*	*±2*	(c, e)
- Herbicide	*ha.a*	-	-	*2*	-	*2*	-	(c, f)
- Insecticide	*ha.a*	-	-	*1*	-	*1*	-	(c, g)
- Seed	*ha.a*	-	-	*7*	*±1*	*7*	*±1*	(c, h)
- Diesel Fuel	*ha.a*	*608*	*±96*	*72*	*±33*	*680*	*±102*	(c, i)
Reference System:								
- Diesel Fuel	*ha.a*	*- 63*	*±10*	*- 7*	*±3*	*- 70*	*±10*	(c, j)
Sub-Totals	*ha.a*	*545*	*±97*	*403*	*±45*	*948*	*±107*	
	t be	**88**	**±16**	**65**	**±7**	**153**	**±17**	(k)
Transport:								
- Diesel Fuel	*t ssb*	*5*	-	*2*	-	*7*	-	(l)
	t be	**44**	**-**	**18**	**-**	**62**	**-**	(m)
Washing, Shredding and Diffusion:								
- Natural Gas	*t csb*	*20*	*±3*	*1*	*±1*	*21*	*±3*	(c, n - p)
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	(q)
- Gypsum	*t csb*	-	-	-	-	-	-	(c, r)
- Hydrochloric Acid	*t csb*	-	-	-	-	-	-	(s)
- Formaldehyde	*t csb*	-	-	-	-	-	-	(c, t)
- Biocide	*t csb*	-	-	-	-	-	-	(c, u)
- Foam Oil	*t csb*	-	-	-	-	-	-	(v)
Credits:								
- Soil	*t csb*	-	-	-	-	-	-	(c, w)
- Stones	*t csb*	-	-	-	-	-	-	(c, x)
Sub-Totals	*t csb*	*20*	*±3*	*1*	*±1*	*21*	*±3*	
	t be	**168**	**±25**	**8**	**±8**	**176**	**±26**	(y)
Purification, Concentration, Fermentation, Distillation and Dehydration:								
- Natural Gas	*t csb*	*46*	*±7*	*1*	*±1*	*47*	*±7*	(c, n,p, z)
- Sulphur	*t csb*	-	-	-	-	-	-	(aa)
- Soda	*t csb*	-	-	-	-	-	-	(bb)
- Anti-Scalant	*t csb*	-	-	-	-	-	-	(cc)
- EDTA	*t csb*	-	-	-	-	-	-	(dd)
- Limestone	*t csb*	-	-	-	-	-	-	(ee)
- Coke	*t csb*	*5*	*±1*	*1*	-	*6*	*±1*	(c, ff)
- Anti-Foam	*t csb*	-	-	-	-	-	-	(c, gg)
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	(hh)
Credit:								
- Electricity	*t csb*	-	-	*- 3*	-	*- 3*	-	(c, ii)
- LimeX	*t csb*	-	-	*- 8*	*±1*	*- 8*	*±1*	(c, jj)
Sub-Totals	*t csb*	*51*	*±7*	*- 9*	*±1*	*42*	*±7*	
	t be	**550**	**±75**	**- 97**	**±11**	**453**	**±78**	(kk)
Plant Construction	**t be**	**-**	**-**	**24**	**±4**	**24**	**±4**	(ll)
Plant Maintenance	**t be**	**-**	**-**	**7**	**±1**	**7**	**±1**	(mm)
Distribution	**t be**	**25**	**±1**	**7**	**±1**	**32**	**±1**	(nn)
Totals	**t be**	**875**	**±81**	**32**	**±16**	**907**	**±84**	

Biofuel Specifications

Density of bioethanol	= 0.79 kg/l
Net calorific value of bioethanol	= 26.72 MJ/kg
Gross calorific value of bioethanol	= 29.74 MJ/kg

Abbreviations

ha.a	= hectare year
t csb	= tonne of clean sugar beet
t ssb	= tonne of soiled sugar beet
t be	= tonne of bioethanol

Notes

(a) Nitrogen fertiliser application rate of 103.0 kg N/ha.a (Ref. 4) and a total carbon requirement for ammonium nitrate of 1.904 ± 0.275 kg CO_2/kg N (Ref. 6).

(b) Phosphate fertiliser application rates of 38.0 kg P/ha.a (Ref. 5), or 87.0 kg P_2O_5/ ha.a assuming 2.290 kg P_2O_5/kg P, and a total carbon requirement for phosphate fertiliser of 0.700 kg CO_2/kg P_2O_5 (Ref. 7).

(c) Assuming an error bar of ±15% based on similar analyses (Ref. 8).

(d) Potash fertiliser application rate of 104.0 kg K/ha.a (Ref. 5), or 125.3 kg K_2O/ha.a assuming 1.205 kg K_2O/kg K, and a total carbon requirement for potash fertiliser of 0.453 kg CO_2/ kg K_2O (Ref. 7).

(e) Pesticide application rate of 2.90 kg/ha.a (Ref. 9) and a total carbon requirement for general pesticides, herbicides and fungicides of 4.921 kg CO_2/kg (Ref. 7).

(f) Herbicide application rate of 0.40 kg/ha.a (Ref. 9) and a total carbon requirement for general pesticides, herbicides and fungicides of 4.921 kg CO_2/kg (Ref. 7).

(g) Insecticide application rate of 0.24 kg/ha.a (Ref. 9) and a total carbon requirement for general pesticides, herbicides and fungicides of 4.921 kg CO_2/kg (Ref. 7).

(h) Sowing rate of 3.8 kg/ha.a, consisting of 1.2 kg/ha.a of seed and 2.6 kg/ha.a pelletising material (Ref. 10), and a total carbon requirement of 1.775 kg CO_2 /kg of seed (Ref. 7).

(i) Diesel fuel consumption of 8,870 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides and insecticides, and harvesting (Ref. 2) 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. 11).

(j) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 7) 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. 11).

(k) Land requirement of 0.255 ha.a/t of bioethanol, partitioning between13.296 t of sugar beet at farm with a price of £22/t (Ref. 1) and 1.507 t sugar beet tops (dry matter) with an effective price of £10.00/t, based on an average market price of £2.00/t (wet basis) 80% moisture content (Ref. 2), and partitioning between 14.560 t of thin juice with an effective price of £16.2/t and an effective average price for 25.996 t of pulp with a moisture content of 97% of £2.56/t, derived from an average price for animal feed pellets with a moisture content of 15% of £72.50/t (Ref. 2), and an assumed price of bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solid and 66.5% sugar purity), based on the price of thick juice, giving an allocation of 95.1% x 78.0% x 85.7% = 63.6% to bioethanol.

(l) Average round trip distance of 94 km (Ref. 2) 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. 12).

(m) Soiled sugar beet requirement of 13.296 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(n) Natural gas-fired combined heat and power plant based on a steam turbine with an overall efficiency of 84%, consuming 248,427 MJ/hr of natural gas to provide 67 t/hr or 181,578 MJ/hr of steam (matched to bioethanol plant requirements) and 7.5 MW (6.1 MW for bioethanol plant and 1.4 MW surplus) of electricity equal to 7,500 kWh/hr or 27,000 MJ/hr (Ref. 2), resulting in 0.109 MJ of electricity and 0.731 MJ of steam from each MJ of natural gas, or a natural gas consumption rate of 1.190 MJ/MJ of energy output in the form of electricity or 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. 11).

(o) Steam consumption rate for washing, shredding and diffusion of 14 t/hr, assumed to be 50% of total steam requirements of sugar plant (Ref. 2), equivalent to 1.190 x 181,578 x 14/67 = 45,151 MJ/hr of natural gas, and an electricity consumption rate for washing, shredding and diffusion of 3.5 MW (Ref. 2), equivalent to 1.190 x 27,000 x 3.5/7.5 = 14,994 MJ/hr of natural gas, resulting in a total natural gas consumption rate of 60,145 MJ/hr.

(p) Total clean sugar beet input of 1,257,774 t/a and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 2), giving a clean sugar beet input rate of 156 t/hr.

(q) Sulphuric acid (93% concentration) consumption rate of 0.18 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 0.13 $\pm$ 0.16 kg CO_2/kg for sulphuric acid (Ref. 13).

(r) Gypsum (calcium sulphate) consumption rate of 1.06 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 0.08 kg CO_2/kg for gypsum (Ref. 13).

(s) Hydrochloric acid (100% concentration) consumption rate of 0.025 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 0.15 kg CO_2/kg for hydrochloric acid (Ref. 13).

(t) Formaldehyde consumption rate of 0.15 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 2.1 x 10^{-5} kg CO_2/kg for formaldehyde (Refs. 2 and 14 to 16).

(u) Biocide consumption rate of 0.024 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 0.12 kg CO_2/kg for biocide (Refs. 2 and 14 to 16).

(v) Foam oil consumption rate of 0.03 kg/t of clean sugar beet (Ref. 2) and, assuming foam oil is similar to refined rapeseed oil, a carbon requirement of 0.59 $\pm$ 0.04 kg CO_2/kg of refined rapeseed oil (Ref. 17).

(w) Soil recovery rate of 5.32% of clean sugar beet (Ref. 2), or 53.2 kg/t of clean sugar beet, and, assuming soil production is similar to sand extraction, a carbon requirement of 5.7 x 10^{-3} kg CO_2/kg for sand (Ref. 18).

(x) Stone recovery rate of 0.39% of clean sugar beet (Ref. 2), or 3.9 kg/t of clean sugar beet, and, assuming stone production is similar to sand extraction, a carbon requirement of 5.7 x 10^{-3} kg CO_2/kg for sand (Ref. 18).

(y) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(z) Steam consumption rate for purification of 1 t/hr and for fermentation, distillation and dehydration of 38 t/hr (Ref. 2), resulting in a total steam consumption rate of 39 t/hr or equivalent to 1.190 x 181,578 x 39/67 = 125,777 MJ/hr of natural gas, and an electricity consumption rate for diffusion of 1.4 MW and for fermentation, distillation and dehydration of 1.2 MW (Ref. 2), equivalent to 1.190 x 27,000 x 2.6/7.5 = 11,138 MJ/hr of natural gas, resulting in a total natural gas consumption rate for diffusion of 136,915 MJ/hr.

(aa) Sulphur (as SO_2) consumption rate of 0.13 kg/t of clean sugar beet and a carbon requirement of 0.89 $\pm$ 0.24 kg CO_2/kg for sulphur (Ref. 13).

(bb) Soda (sodium carbonate) consumption rate of 0.05 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 2.13 $\pm$ 0.64 kg CO_2/kg for soda (Ref. 13).

(cc) Anti-scalant consumption rate of 0.04 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 1.52 kg CO_2/kg for anti-scalant (Refs. 2 and 14 to 16).

(dd) EDTA consumption rate of 0.055 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 0.40 kg CO_2/kg for EDTA (Refs. 2 and 14 to 16).

(ee) Limestone consumption rate of 2.3% of clean sugar beet (Ref. 2), or 23 kg/t of clean sugar beet, and a carbon requirement of 0.02 kg CO_2/kg for limestone (Ref. 18).

(ff) Coke consumption rate of 0.18% of clean sugar beet (Ref. 2), or 1.8 kg/t of clean sugar beet, and a direct carbon requirement of 0.104 x 28.1 = 2.92 kg CO_2/kg and an indirect carbon requirement of 0.37 kg CO_2/kg for coke in the UK in 1996 (Ref. 11).

(gg) Anti-foam consumption rate of 253,344 kg/a (Ref. 2), or 0.20 kg/t of clean sugar beet, and, assuming similarity with anti-scalant, a carbon requirement of 1.52 kg CO_2/kg of anti-foam (Refs. 2 and 14 to 16).

(hh) Sulphuric acid (93% concentration) consumption rate of 380,016 kg/a, or 0.30 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 0.13 $\pm$ 016 kg CO_2/kg for sulphuric acid (Ref. 13).

(ii) Surplus electricity of 1.4 MW for 8,064 hr/a resulting in 11,289,600 kWh/a or 40,642,560 MJ/a of electricity exported for sale, equivalent to 32 MJ/t of clean sugar beet, and a carbon requirement of 0.15 kg CO_2/MJ for displaced grid electricity supplies in the UK in 1996 (Ref. 11), less 1.190 x 32 of natural gas used to produce the surplus amount with 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. 11).

(jj) LimeX production rate of 45 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 0.18 kg CO_2/kg for lime (Ref. 6), excluding carbon dioxide from calcination which is not accounted for in the bioethanol plant.

(kk) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 85.7% to bioethanol.

(ll) Carbon dioxide output of 47,500 tonnes of CO_2 for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £38.0 m (Ref. 2) and a carbon intensity of 1.25 kg CO_2/£ (Ref. 14).

(mm) Carbon dioxide output of annual plant maintenance assumed to be 1.5% of carbon dioxide output of plant construction (Ref. 2).

(nn) Average round trip distance of 450 km (Ref. 19) 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. 11).

References

1. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 28 April 2003.

2. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 2 May 2003.

3. Private communication with D. Darby of British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication with G. Punter of British Sugar plc., Peterborough, United Kingdom, 8 May 2003.

5. "British Sugar Field Crop Survey 2001"

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Report No. 20/1, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003, for the Department for the Environment, Food and Rural Affairs, www.defra.

7. "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.

8. "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.

9. "Pesticide Use Survey Reports" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. British Sugar Internal Survey 2001

11. "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.

12. "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.

13. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

14. "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.

15. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

16. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

17. "Carbon and Energy Balances for a Range of Biofuel Options" by M. A. Elsayed, R. Matthews and N. D. Mortimer, B/B6/00784/REP, Energy Technology Support Unit, Harwell, United Kingdom, March 2003, www.shu.ac.uk/rru/projects/biofuels/biofuels.html.

18. "Handbook of Industrial Energy Analysis" by I. Boustead and G. Hancock, Ellis Horwood, Chichester, United Kingdom, 1979.

19. "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.

Spreadsheet for Methane Outputs from Bioethanol Production from Sugar Beet using a Natural Gas-fired Combined Heat and Power Plant with a Steam Turbine (Model 4a)

Functional Unit:	Bioethanol at point of distribution derived from sugar beet using natural gas-fired combined heat and power with a steam turbine during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on a market price for 13.296 tonnes of sugar beet on the farm of £22.00/t (Ref. 1) and an effective price for 1.507 tonnes of sugar beet tops (dry matter) of £10.0/t, based on an average market price of £2.00/t (wet basis) with a 80% moisture content (Ref. 2), substitution of 0.669 tonnes of soil from washing by soil from main sources, substitution of 0.049 tonnes of stones from washing by stones from quarrying, an effective average price for 14.560 tonnes of thin juice (15% solids and 88% sugar purity) of £16.2/t, derived from a price for thick juice (67% solids and 92% sugar purity) of £72.48/t (Ref. 3), and an effective average price for 25.996 tonnes of pulp (97% moisture content) of £2.56/t, derived from an average market price for animal feed pellets (15% moisture content) of £72.50/t (Ref. 2), substitution of 0.566 tonnes of LimeX by agricultural lime, and an assumed price for bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solids and 66.5% sugar purity) of £122.15/t, based on the price of thick juice (Ref. 4).

Contribution	Per Unit	Methane Output (kg CH_4)						Notes
		Direct		Indirect		Total		
		Value	Range	Value	Range	Value	Range	
Cult. and Harvest.:								
- N Fertiliser	*ha.a*	-	-	*0.371*	*±0.062*	*0.371*	*±0.062*	(a)
- P Fertiliser	*ha.a*	-	-	*0.002*	-	*0.002*	-	(b, c)
- K Fertiliser	*ha.a*	-	-	*0.003*	-	*0.003*	-	(c, d)
- Pesticides	*ha.a*	-	-	*0.001*	-	*0.001*	-	(c, e)
- Herbicide	*ha.a*	-	-	-	-	-	-	(c, f)
- Insecticide	*ha.a*	-	-	-	-	-	-	(c, g)
- Seed	*ha.a*	-	-	*0.008*	*±0.001*	*0.008*	*±0.001*	(c, h)
- Diesel Fuel	*ha.a*	*0.005*	*±0.005*	*0.181*	*±0.027*	*0.186*	*±0.028*	(c, i)
Reference System:								
- Diesel Fuel	*ha.a*	*- 0.001*	*±0.001*	*- 0.019*	*±0.003*	*- 0.020*	*±0.003*	(c, j)
Sub-Totals	*ha.a*	*0.004*	*±0.005*	*0.547*	*±0.068*	*0.551*	*±0.068*	
	t be	**0.001**	**±0.001**	**0.088**	**±0.011**	**0.089**	**±0.011**	(k)
Transport:								
- Diesel Fuel	*t ssb*	-	-	*0.002*	-	*0.002*	-	(l)
	t be	**-**	**-**	**0.018**	**-**	**0.018**	**-**	(m)
Washing, Shredding and Diffusion:								
- Natural Gas	*t csb*	*0.001*	*±0.001*	*0.042*	*±0.006*	*0.043*	*±0.007*	(c, n - p)
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	(q)
- Gypsum	*t csb*	-	-	-	-	-	-	(c, r)
- Hydrochloric Acid	*t csb*	-	-	-	-	-	-	(s)
- Formaldehyde	*t csb*	-	-	-	-	-	-	(c, t)
- Biocide	*t csb*	-	-	-	-	-	-	(c, u)
- Foam Oil	*t csb*	-	-	-	-	-	-	(v)
Credits:								
- Soil	*t csb*	-	-	-	-	-	-	(c, w)
- Stones	*t csb*	-	-	-	-	-	-	(c, x)
Sub-Totals	*t csb*	*0.001*	*±0.001*	*0.042*	*±0.006*	*0.043*	*±0.007*	
	t be	**0.008**	**±0.008**	**0.353**	**±0.050**	**0.361**	**±0.051**	(y)
Purification, Concentration, Fermentation, Distillation and Dehydration:								
- Natural Gas	*t csb*	*0.003*	*±0.003*	*0.097*	*±0.015*	*0.100*	*±0.015*	(c,n,p, z)
- Sulphur	*t csb*	-	-	-	-	-	-	(aa)
- Soda	*t csb*	-	-	-	-	-	-	(bb)
- Anti-Scalant	*t csb*	-	-	-	-	-	-	(cc)
- EDTA	*t csb*	-	-	-	-	-	-	(dd)
- Limestone	*t csb*	-	-	-	-	-	-	(ee)
- Coke	*t csb*	-	-	-	-	-	-	(c, ff)
- Anti-Foam	*t csb*	-	-	-	-	-	-	(c, gg)
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	(hh)
Credit:								
- Electricity	*t csb*	-	-	*- 0.009*	*±0.001*	*- 0.009*	*±0.001*	(c, ii)
- LimeX	*t csb*	-	-	-	-	-	-	(c, jj)
Sub-Totals	*t csb*	*0.003*	*±0.003*	*0.088*	*±0.015*	*0.091*	*±0.015*	
	t be	**0.032**	**±0.032**	**0.949**	**±0.162**	**0.981**	**±0.165**	(kk)
Plant Construction	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(ll)
Plant Maintenance	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(mm)
Distribution	**t be**	**-**	**-**	**0.008**	**-**	**0.008**	**-**	(nn)
Totals	**t be**	**0.041**	**±0.033**	**1.416**	**±0.170**	**1.457**	**±0.173**	

Biofuel Specifications

Density of bioethanol	= 0.79 kg/l
Net calorific value of bioethanol	= 26.72 MJ/kg
Gross calorific value of bioethanol	= 29.74 MJ/kg

Abbreviations

ha.a	= hectare year
t csb	= tonne of clean sugar beet
t ssb	= tonne of soiled sugar beet
t be	= tonne of bioethanol

Notes

(a) Nitrogen fertiliser application rate of 103.0 kg N/ha.a (Ref. 5) 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 (Ref. 6).

(b) Phosphate fertiliser application rates of 38.0 kg P/ha.a (Ref. 5), or 87.0 kg P_2O_5/ ha.a assuming 2.290 kg P_2O_5/kg P, and a total methane requirement for phosphate fertiliser of 2.3×10^{-5} kg CH_4/kg P_2O_5 (Ref. 7).

(c) Assuming an error bar of ±15% based on similar analyses (Ref. 8).

(d) Potash fertiliser application rate of 104.0 kg K/ha.a (Ref. 5), or 125.3 kg K_2O/ha.a assuming 1.205 kg K_2O/kg K, and a total methane requirement for potash fertiliser of 2.1×10^{-5} kg CH_4/ kg K_2O (Ref. 7).

(e) Pesticide application rate of 2.90 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.8×10^{-4} kg CH_4/kg (Ref. 7).

(f) Herbicide application rate of 0.40 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.8×10^{-4} kg CH_4/kg (Ref. 7).

(g) Insecticide application rate of 0.24 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.8×10^{-4} kg CH_4/kg (Ref. 7).

(h) Sowing rate of 3.8 kg/ha.a, consisting of 1.2 kg/ha.a of seed and 2.6 kg/ha.a pelletising material (Ref. 10), and a total methane requirement of 0.002 kg CH_4 /kg of seed (Ref. 7).

(i) Diesel fuel consumption of 8,870 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides and insecticides, and harvesting (Ref. 2) 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. 11).

(j) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 7) 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. 11).

(k) Land requirement of 0.255 ha.a/t of bioethanol, partitioning between13.296 t of sugar beet at farm with a price of £22/t (Ref. 1) and 1.507 t sugar beet tops (dry matter) with an effective price of £10.00/t, based on an average market price of £2.00/t (wet basis) 80% moisture content (Ref. 2), and partitioning between 14.560 t of thin juice with an effective price of £16.2/t and an effective average price for 25.996 t of pulp with a moisture content of 97% of £2.56/t, derived from an average price for animal feed pellets with a moisture content of 15% of £72.50/t (Ref. 2), and an assumed price of bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solid and 66.5% sugar purity), based on the price of thick juice, giving an allocation of 95.1% x 78.0% x 85.7% = 63.6% to bioethanol.

(l) Average round trip distance of 94 km (Ref. 2) 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. 12).

(m) Soiled sugar beet requirement of 13.296 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(n) Natural gas-fired combined heat and power plant based on a steam turbine with an overall efficiency of 84%, consuming 248,427 MJ/hr of natural gas to provide 67 t/hr or 181,578 MJ/hr of steam (matched to bioethanol plant requirements) and 7.5 MW (6.1 MW for bioethanol plant and 1.4 MW surplus) of electricity equal to 7,500 kWh/hr or 27,000 MJ/hr (Ref. 2), resulting in 0.109 MJ of electricity and 0.731 MJ of steam from each MJ of natural gas, or a natural gas consumption rate of 1.190 MJ/MJ of energy output in the form of electricity or steam, and a direct methane requirement of 3.7×10^{-6} kg CH_4/MJ, an indirect methane requirement of 1.1×10^{-4} kg CH_4/MJ and a total methane requirement of 1.1×10^{-4} kg CH_4/MJ for natural gas in the UK in 1996 (Ref. 11).

(o) Steam consumption rate for washing, shredding and diffusion of 14 t/hr, assumed to be 50% of total steam requirements of sugar plant (Ref. 2), equivalent to 1.190 x 181,578 x 14/67 = 45,151 MJ/hr of natural gas, and an electricity consumption rate for washing, shredding and diffusion of 3.5 MW (Ref. 2), equivalent to 1.190 x 27,000 x 3.5/7.5 = 14,994 MJ/hr of natural gas, resulting in a total natural gas consumption rate of 60,145 MJ/hr.

(p) Total clean sugar beet input of 1,257,774 t/a and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 2), giving a clean sugar beet input rate of 156 t/hr.

(q) Sulphuric acid (93% concentration) consumption rate of 0.18 kg/t of clean sugar beet (Ref. 2) and a methane requirement of $2.7 \times 10^{-4} \pm 3.0 \times 10^{-4}$ kg CH_4/kg for sulphuric acid (Ref. 13).

(r) Gypsum (calcium sulphate) consumption rate of 1.06 kg/t of clean sugar beet (Ref. 2) and a methane requirement of 2.1×10^{-5} kg CH_4/kg for gypsum (Ref. 13).

(s) Hydrochloric acid (100% concentration) consumption rate of 0.025 kg/t of clean sugar beet (Ref. 2) and a methane requirement of 0.01 ± 0.001 kg CH_4/kg for hydrochloric acid (Ref. 13).

(t) Formaldehyde consumption rate of 0.15 kg/t of clean sugar beet (Ref. 2) and a methane requirement of 4.0×10^{-7} kg CH_4/kg for formaldehyde (Refs. 2 and 14 to 16).

(u) Biocide consumption rate of 0.024 kg/t of clean sugar beet (Ref. 2) and a methane requirement of 3.0×10^{-7} kg CH_4/kg for biocide (Refs. 2 and 14 to 16).

(v) Foam oil consumption rate of 0.03 kg/t of clean sugar beet (Ref. 2) and, assuming foam oil is similar to refined rapeseed oil, a methane requirement of $7.7 \times 10^{-4} \pm 7.0 \times 10^{-5}$ kg CH_4/kg of refined rapeseed oil (Ref. 17).

(w) Soil recovery rate of 5.32% of clean sugar beet (Ref. 2), or 53.2 kg/t of clean sugar beet, and, assuming soil production is similar to sand extraction, a methane requirement of 1.6×10^{-6} kg CH_4/kg for sand (Ref. 18).

(x) Stone recovery rate of 0.39% of clean sugar beet (Ref. 2), or 3.9 kg/t of clean sugar beet, and, assuming stone production is similar to sand extraction, a methane requirement of 1.6×10^{-6} kg CH_4/kg for sand (Ref. 18).

(y) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(z) Steam consumption rate for purification of 1 t/hr and for fermentation, distillation and dehydration of 38 t/hr (Ref. 2), resulting in a total steam consumption rate of 39 t/hr or equivalent to 1.190 x 181,578 x 39/67 = 125,777 MJ/hr of natural gas, and an electricity consumption rate for diffusion of 1.4 MW and for fermentation, distillation and dehydration of 1.2 MW (Ref. 2), equivalent to 1.190 x 27,000 x 2.6/7.5 = 11,138 MJ/hr of natural gas, resulting in a total natural gas consumption rate for diffusion of 136,915 MJ/hr.

(aa) Sulphur (as SO_2) consumption rate of 0.13 kg/t of clean sugar beet and a methane requirement of $2.5 \times 10^{-5} \pm 7.0 \times 10^{-6}$ kg CH_4/kg for sulphur (Ref. 13).

(bb) Soda (sodium carbonate) consumption rate of 0.05 kg/t of clean sugar beet (Ref. 2) and a methane requirement of $7.2 \times 10^{-4} \pm 2.0 \times 10^{-5}$ kg CH_4/kg for soda (Ref. 13).

(cc) Anti-scalant consumption rate of 0.04 kg/t of clean sugar beet (Ref. 2) and a methane requirement of 4.0×10^{-6} kg CH_4/kg for anti-scalant (Refs. 2 and 14 to 16).

(dd) EDTA consumption rate of 0.055 kg/t of clean sugar beet (Ref. 2) and a methane requirement of 1.0×10^{-6} kg CH_4/kg for EDTA (Refs. 2 and 14 to 16).

(ee) Limestone consumption rate of 2.3% of clean sugar beet (Ref. 2), or 23 kg/t of clean sugar beet, and a methane requirement of 2.1×10^{-5} kg CH_4/kg for limestone (Ref. 18).

(ff) Coke consumption rate of 0.18% of clean sugar beet (Ref. 2), or 1.8 kg/t of clean sugar beet, and a direct methane requirement of $9.5 \times 10^{-6} \times 28.1 = 2.7 \times 10^{-4}$ kg CH_4/kg and an indirect methane requirement of 9.2×10^{-3} kg CH_4/kg for coke in the UK in 1996 (Ref. 11).

(gg) Anti-foam consumption rate of 253,344 kg/a (Ref. 2), or 0.20 kg/t of clean sugar beet, and, assuming similarity with anti-scalant, a methane requirement of 4.0×10^{-6} kg CH_4/kg of anti-foam (Refs. 2 and 14 to 16).

(hh) Sulphuric acid (93% concentration) consumption rate of 380,016 kg/a, or 0.30 kg/t of clean sugar beet (Ref. 2) and a methane requirement of $2.7 \times 10^{-4} \pm 3.0 \times 10^{-4}$ kg CH_4/kg for sulphuric acid (Ref. 13).

(ii) Surplus electricity of 1.4 MW for 8,064 hr/a resulting in 11,289,600 kWh/a or 40,642,560 MJ/a of electricity exported for sale, equivalent to 32 MJ/t of clean sugar beet, and a methane requirement of 4.0×10^{-4} kg CH_4/MJ for displaced grid electricity supplies in the UK in 1996 (Ref. 11),), less 1.190 x 32 of natural gas used to produce the surplus amount with a direct methane requirement of 3.7×10^{-6} kg CH_4/MJ, an indirect methane requirement of 1.1 x 10^{-4} kg CH_4/MJ and a total methane requirement of 1.1 x 10^{-4} kg CH_4/MJ for natural gas in the UK in 1996 (Ref. 11).

(jj) LimeX production rate of 45 kg/t of clean sugar beet (Ref. 2) and a methane requirement 3.9 x 10^{-6} kg CH_4/kg for lime (Ref. 7).

(kk) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 85.7% to bioethanol.

(ll) Primary energy input of 950,000 GJ for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £38.0 m (Ref. 2) and an estimated total methane requirement of 1.192 x 10^{-7} kg CH_4/MJ of primary energy input to plant construction (Ref. 16).

(mm) Primary energy input of annual plant maintenance assumed to be 1.5% of primary energy input to plant construction (Ref. 2).

(nn) Average round trip distance of 450 km (Ref. 19) by bulk road carrier transport with a direct methane requirement of 4.900 x 10^{-7} ± 2.000 x 10^{-8} kg CH_4/t-km, an indirect methane requirement of 1.672 x 10^{-5} ± 6.3 x 10^{-7} kg CH_4/t-km and a total methane requirement of 1.721 x 10^{-5} ± 6.5 x 10^{-7} kg CH_4/t-km (Ref. 11).

References

1. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 28 April 2003.

2. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 2 May 2003.

3. Private communication with D. Darby of British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication with G. Punter of British Sugar plc., Peterborough, United Kingdom, 8 May 2003.

5. "British Sugar Field Crop Survey 2001"

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Report No. 20/1, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003, for the Department for the Environment, Food and Rural Affairs, www.defra.

7. "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.

8. "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.

9. "Pesticide Use Survey Reports" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. British Sugar Internal Survey 2001

11. "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.

12. "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.

13. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

14. "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.

15. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

16. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

17. "Carbon and Energy Balances for a Range of Biofuel Options" by M. A. Elsayed, R. Matthews and N. D. Mortimer, B/B6/00784/REP, Energy Technology Support Unit, Harwell, United Kingdom, March 2003, www.shu.ac.uk/rru/projects/biofuels/biofuels.html.

18. "Handbook of Industrial Energy Analysis" by I. Boustead and G. Hancock, Ellis Horwood, Chichester, United Kingdom, 1979.

19. "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.

Spreadsheet for Nitrous Oxide Outputs from Bioethanol Production from Sugar Beet using a Natural Gas-fired Combined Heat and Power Plant with a Steam Turbine (Model 4a)

Functional Unit:	Bioethanol at point of distribution derived from sugar beet using natural gas-fired combined heat and power with a steam turbine during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on a market price for 13.296 tonnes of sugar beet on the farm of £22.00/t (Ref. 1) and an effective price for 1.507 tonnes of sugar beet tops (dry matter) of £10.0/t, based on an average market price of £2.00/t (wet basis) with a 80% moisture content (Ref. 2), substitution of 0.669 tonnes of soil from washing by soil from main sources, substitution of 0.049 tonnes of stones from washing by stones from quarrying, an effective average price for 14.560 tonnes of thin juice (15% solids and 88% sugar purity) of £16.2/t, derived from a price for thick juice (67% solids and 92% sugar purity) of £72.48/t (Ref. 3), and an effective average price for 25.996 tonnes of pulp (97% moisture content) of £2.56/t, derived from an average market price for animal feed pellets (15% moisture content) of £72.50/t (Ref. 2), substitution of 0.566 tonnes of LimeX by agricultural lime, and an assumed price for bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solids and 66.5% sugar purity) of £122.15/t, based on the price of thick juice (Ref. 4).

Contribution	Per Unit	Nitrous Oxide Output (kg N_2O)						Notes
		Direct		Indirect		Total		
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	*ha.a*	*0.371*	*±0.125*	*1.514*	*±0.253*	*1.885*	*±0.283*	(a)
- P Fertiliser	*ha.a*	-	-	*0.004*	*±0.001*	*0.004*	*±0.001*	(b, c)
- K Fertiliser	*ha.a*	-	-	*0.001*	-	*0.001*	-	(c, d)
- Pesticides	*ha.a*	-	-	*0.004*	*±0.001*	*0.004*	*±0.001*	(c, e)
- Herbicide	*ha.a*	-	-	*0.001*	-	*0.001*	-	(c, f)
- Insecticide	*ha.a*	-	-	-	-	-	-	(c, g)
- Seed	*ha.a*	-	-	*0.004*	*±0.001*	*0.004*	*±0.001*	(c, h)
- Diesel Fuel	*ha.a*	*0.005*	*±0.001*	-	-	*0.005*	*±0.001*	(c, i)
Reference System:								
- Diesel Fuel	*ha.a*	*- 0.001*	-	-	-	*- 0.001*	-	(c, j)
Sub-Totals	*ha.a*	*0.375*	*±0.125*	*1.528*	*±0.253*	*1.903*	*±0.283*	
	t be	**0.061**	**±0.020**	**0.248**	**±0.041**	**0.309**	**±0.046**	(k)
Transport:								
- Diesel Fuel	*t ssb*	-	-	-	-	-	-	(l)
	t be	**-**	**-**	**-**	**-**	**-**	**-**	(m)
Washing, Shredding and Diffusion:								
- Natural Gas	*t csb*	-	-	-	-	-	-	(c, n - p)
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	(q)
- Gypsum	*t csb*	-	-	-	-	-	-	(c, r)
- Hydrochloric Acid	*t csb*	-	-	-	-	-	-	(s)
- Formaldehyde	*t csb*	-	-	-	-	-	-	(c, t)
- Biocide	*t csb*	-	-	-	-	-	-	(c, u)
- Foam Oil	*t csb*	-	-	-	-	-	-	(v)
Credits:								
- Soil	*t csb*	-	-	-	-	-	-	(c, w)
- Stones	*t csb*	-	-	-	-	-	-	(c, x)
Sub-Totals	*t csb*	-	-	-	-	-	-	
	t be	**-**	**-**	**-**	**-**	**-**	**-**	(y)
Purification, Concentration, Fermentation, Distillation and Dehydration:								
- Natural Gas	*t csb*	-	-	-	-	-	-	(c,n,p, z)
- Sulphur	*t csb*	-	-	-	-	-	-	(aa)
- Soda	*t csb*	-	-	-	-	-	-	(bb)
- Anti-Scalant	*t csb*	-	-	-	-	-	-	(cc)
- EDTA	*t csb*	-	-	-	-	-	-	(dd)
- Limestone	*t csb*	-	-	-	-	-	-	(ee)
- Coke	*t csb*	-	-	-	-	-	-	(c, ff)
- Anti-Foam	*t csb*	-	-	-	-	-	-	(c, gg)
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	(hh)
Credit:								
- Electricity	*t csb*	-	-	-	-	-	-	(c, ii)
- LimeX	*t csb*	-	-	*- 0.001*	-	*- 0.001*	-	(c, jj)
Sub-Totals	*t csb*	-	-	*- 0.001*	-	*- 0.001*	-	
	t be	**-**	**-**	**- 0.011**	**-**	**- 0.011**	**-**	(kk)
Plant Construction	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(ll)
Plant Maintenance	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(mm)
Distribution	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(nn)
Totals	**t be**	**0.061**	**±0.020**	**0.237**	**±0.041**	**0.298**	**±0.046**	

Biofuel Specifications

Density of bioethanol	= 0.79 kg/l
Net calorific value of bioethanol	= 26.72 MJ/kg
Gross calorific value of bioethanol	= 29.74 MJ/kg

Abbreviations

ha.a	= hectare year
t csb	= tonne of clean sugar beet
t ssb	= tonne of soiled sugar beet
t be	= tonne of bioethanol

Notes

(a) Nitrogen fertiliser application rate of 103.0 kg N/ha.a (Ref. 5) and a direct nitrous oxide requirement of 0.0036 kg N_2O/kg N (Ref. 5), an indirect nitrous oxide requirement of 0.0147 kg N_2O/kg N (Ref. 7) and a total nitrous oxide requirement for ammonium nitrate of 0.0183 kg N_2O/kg N (Ref. 6).

(b) Assuming an error bar of ±15% based on similar analyses (Ref. 8).

(c) Phosphate fertiliser application rates of 38.0 kg P/ha.a (Ref. 5), or 87.0 kg P_2O_5/ ha.a and a total nitrous oxide requirement for phosphate fertiliser of 4.2 x 10^{-5} kg N_2O/kg P_2O_5 (Ref. 7).

(d) Potash fertiliser application rate of 104.0 kg K/ha.a (Ref. 5), or 125.3 kg K_2O/ha.a and a total nitrous oxide requirement for potash fertiliser of 9.4 x 10^{-6} kg N_2O/ kg K_2O (Ref. 7).

(e) Pesticide application rate of 2.90 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.51 x 10^{-3} kg N_2O/kg (Ref. 7).

(f) Herbicide application rate of 0.40 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.51 x 10^{-3} kg N_2O/kg (Ref. 7).

(g) Insecticide application rate of 0.24 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.51 x 10^{-3} kg N_2O/kg (Ref. 7).

(h) Sowing rate of 3.8 kg/ha.a, consisting of 1.2 kg/ha.a of seed and 2.6 kg/ha.a pelletising material (Ref. 10), and a total methane requirement of 0.001 kg N_2O /kg of seed (Ref. 7).

(i) Diesel fuel consumption of 8,870 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides and insecticides, and harvesting (Ref. 2) 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. 11).

(j) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 7) 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. 11).

(k) Land requirement of 0.255 ha.a/t of bioethanol, partitioning between13.296 t of sugar beet at farm with a price of £22/t (Ref. 1) and 1.507 t sugar beet tops (dry matter) with an effective price of £10.00/t, based on an average market price of £2.00/t (wet basis) 80% moisture content (Ref. 2), and partitioning between 14.560 t of thin juice with an effective price of £16.2/t and an effective average price for 25.996 t of pulp with a moisture content of 97% of £2.56/t, derived from an average price for animal feed pellets with a moisture content of 15% of £72.50/t (Ref. 2), and an assumed price of bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solid and 66.5% sugar purity), based on the price of thick juice, giving an allocation of 95.1% x 78.0% x 85.7% = 63.6% to bioethanol.

(l) Average round trip distance of 94 km (Ref. 2) 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. 12).

(m) Soiled sugar beet requirement of 13.296 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(n) Natural gas-fired combined heat and power plant based on a steam turbine with an overall efficiency of 84%, consuming 248,427 MJ/hr of natural gas to provide 67 t/hr or 181,578 MJ/hr of steam (matched to bioethanol plant requirements) and 7.5 MW (6.1 MW for bioethanol plant and 1.4 MW surplus) of electricity equal to 7,500 kWh/hr or 27,000 MJ/hr (Ref. 2), resulting in 0.109 MJ of electricity and 0.731 MJ of steam from each MJ of natural gas, or a natural gas consumption rate of 1.190 MJ/MJ of energy output in the form of electricity or steam, and a direct nitrous oxide 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. 11).

(o) Steam consumption rate for washing, shredding and diffusion of 14 t/hr, assumed to be 50% of total steam requirements of sugar plant (Ref. 2), equivalent to 1.190 x 181,578 x 14/67 = 45,151 MJ/hr of natural gas, and an electricity consumption rate for washing, shredding and diffusion of 3.5 MW (Ref. 2), equivalent to 1.190 x 27,000 x 3.5/7.5 = 14,994 MJ/hr of natural gas, resulting in a total natural gas consumption rate of 60,145 MJ/hr.

(p) Total clean sugar beet input of 1,257,774 t/a and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 2), giving a clean sugar beet input rate of 156 t/hr.

(q) Sulphuric acid (93% concentration) consumption rate of 0.18 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of $2.7 \times 10^{-7} \pm 3.0 \times 10^{-7}$ kg N_2O/kg for sulphuric acid (Ref. 13).

(r) Gypsum (calcium sulphate) consumption rate of 1.06 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of 5.9×10^{-7} kg N_2O/kg for gypsum (Ref. 13).

(s) Hydrochloric acid (100% concentration) consumption rate of 0.025 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of 3.0×10^{-4} kg N_2O/kg for hydrochloric acid (Ref. 13)

(t) Formaldehyde consumption rate of 0.15 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of 6.0×10^{-9} kg N_2O/kg for formaldehyde (Refs. 2 and 14 to 16).

(u) Biocide consumption rate of 0.024 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of 5.0×10^{-9} kg N_2O/kg for biocide (Refs. 2 and 14 to 16).

(v) Foam oil consumption rate of 0.03 kg/t of clean sugar beet (Ref. 2) and, assuming foam oil is similar to refined rapeseed oil, a nitrous oxide requirement of $1.79 \times 10^{-3} \pm 2.20 \times 10^{-4}$ kg N_2O/kg of refined rapeseed oil (Ref. 17).

(w) Soil recovery rate of 5.32% of clean sugar beet (Ref. 2), or 53.2 kg/t of clean sugar beet, and, assuming soil production is similar to sand extraction, a nitrous oxide requirement of 4.2×10^{-8} kg N_2O/kg for sand (Ref. 18).

(x) Stone recovery rate of 0.39% of clean sugar beet (Ref. 2), or 3.9 kg/t of clean sugar beet, and, assuming stone production is similar to sand extraction, a nitrous oxide requirement of 4.2×10^{-8} kg N_2O/kg for sand (Ref. 18).

(y) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(z) Steam consumption rate for purification of 1 t/hr and for fermentation, distillation and dehydration of 38 t/hr (Ref. 2), resulting in a total steam consumption rate of 39 t/hr or equivalent to 1.190 x 181,578 x 39/67 = 125,777 MJ/hr of natural gas, and an electricity consumption rate for diffusion of 1.4 MW and for fermentation, distillation and dehydration of 1.2 MW (Ref. 2), equivalent to 1.190 x 27,000 x 2.6/7.5 = 11,138 MJ/hr of natural gas, resulting in a total natural gas consumption rate for diffusion of 136,915 MJ/hr.

(aa) Sulphur (as SO_2) consumption rate of 0.13 kg/t of clean sugar beet and a nitrous oxide requirement of $6.6 \times 10^{-6} \pm 1.8 \times 10^{-6}$ kg N_2O/kg for sulphur (Ref. 13).

(bb) Soda (sodium carbonate) consumption rate of 0.05 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of $1.8 \times 10^{-5} \pm 0.5 \times 10^{-6}$ kg N_2O/kg for soda (Ref. 13).

(cc) Anti-scalant consumption rate of 0.04 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of 6.0×10^{-8} kg N_2O/kg for anti-scalant (Refs. 2 and 14 to 16).

(dd) EDTA consumption rate of 0.055 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of 2.0×10^{-8} kg N_2O/kg for EDTA (Refs. 2 and 14 to 16).

(ee) Limestone consumption rate of 2.3% of clean sugar beet (Ref. 2), or 23 kg/t of clean sugar beet, and a nitrous oxide requirement of 3.5×10^{-7} kg N_2O/kg for limestone (Ref. 18).

(ff) Coke consumption rate of 0.18% of clean sugar beet (Ref. 2), or 1.8 kg/t of clean sugar beet, and a direct nitrous oxide requirement of $4.0 \times 10^{-9} \times 28.1 = 1.1 \times 10^{-7}$ kg N_2O/kg and an indirect nitrous oxide requirement of 1.3×10^{-6} kg N_2O/kg for coke in the UK in 1996 (Ref. 11).

(gg) Anti-foam consumption rate of 253,344 kg/a (Ref. 2), or 0.20 kg/t of clean sugar beet, and, assuming similarity with anti-scalant, a nitrous oxide requirement of 6.0×10^{-8} kg N_2O/kg of anti-foam (Refs. 2 and 14 to 16).

(hh) Sulphuric acid (93% concentration) consumption rate of 380,016 kg/a, or 0.30 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of $2.0 \times 10^{-7} \pm 3.0 \times 10^{-7}$ kg N_2O/kg for sulphuric acid (Ref. 13).

(ii) Surplus electricity of 1.4 MW for 8,064 hr/a resulting in 11,289,600 kWh/a or 40,642,560 MJ/a of electricity exported for sale, equivalent to 32 MJ/t of clean sugar beet, and a nitrous oxide requirement of 5.6×10^{-6} kg N_2O/MJ for displaced grid electricity supplies in the UK in 1996 (Ref. 11), less 1.190 x 32 of natural gas used to produce the surplus amount with a direct nitrous oxide requirement of 8.9×10^{-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. 11).

(jj) LimeX production rate of 45 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement 1.6 x 10^{-5} kg N_2O/kg for lime (Ref. 7).

(kk) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 85.7% to bioethanol.

(ll) Primary energy input of 950,000 GJ for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £38.0 m (Ref. 2) and an estimated total nitrous oxide requirement of 1.866 x 10^{-9} kg N_2O/MJ of primary energy input to plant construction (Ref. 16).

(mm) Nitrous oxide output of annual plant maintenance assumed to be 1.5% of primary energy input to plant construction (Ref. 2).

(nn) Average round trip distance of 450 km (Ref. 19) 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. 11).

References

1. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 28 April 2003.

2. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 2 May 2003.

3. Private communication with D. Darby of British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication with G. Punter of British Sugar plc., Peterborough, United Kingdom, 8 May 2003.

5. "British Sugar Field Crop Survey 2001"

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Report No. 20/1, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003, for the Department for the Environment, Food and Rural Affairs, www.defra.

7. "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.

8. "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.

9. "Pesticide Use Survey Reports" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. British Sugar Internal Survey 2001

11. "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.

12. "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.

13. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

14. "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.

15. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

16. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

17. "Carbon and Energy Balances for a Range of Biofuel Options" by M. A. Elsayed, R. Matthews and N. D. Mortimer, B/B6/00784/REP, Energy Technology Support Unit, Harwell, United Kingdom, March 2003, www.shu.ac.uk/rru/projects/biofuels/biofuels.html.

18. "Handbook of Industrial Energy Analysis" by I. Boustead and G. Hancock, Ellis Horwood, Chichester, United Kingdom, 1979.

19. "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.

<u>Spreadsheet for Total Greenhouse Gas Outputs from Bioethanol Production from Sugar Beet using a Natural Gas-fired Combined Heat and Power Plant with a Steam Turbine</u> (Model 4a)

Functional Unit:	Bioethanol at point of distribution derived from sugar beet using natural gas-fired combined heat and power with a steam turbine during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on a market price for 13.296 tonnes of sugar beet on the farm of £22.00/t (Ref. 1) and an effective price for 1.507 tonnes of sugar beet tops (dry matter) of £10.0/t, based on an average market price of £2.00/t (wet basis) with a 80% moisture content (Ref. 2), substitution of 0.669 tonnes of soil from washing by soil from main sources, substitution of 0.049 tonnes of stones from washing by stones from quarrying, an effective average price for 14.560 tonnes of thin juice (15% solids and 88% sugar purity) of £16.2/t, derived from a price for thick juice (67% solids and 92% sugar purity) of £72.48/t (Ref. 3), and an effective average price for 25.996 tonnes of pulp (97% moisture content) of £2.56/t, derived from an average market price for animal feed pellets (15% moisture content) of £72.50/t (Ref. 2), substitution of 0.566 tonnes of LimeX by agricultural lime, and an assumed price for bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solids and 66.5% sugar purity) of £122.15/t, based on the price of thick juice (Ref. 4).

Contribution	Per Unit	Total Greenhouse Gas Output (kg eq CO_2)						Notes
		Direct		Indirect		Total		
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	*ha.a*	*119*	*±40*	*690*	*±86*	*809*	*±95*	(a)
- P Fertiliser	*ha.a*	-	-	*62*	*±9*	*62*	*±9*	(a)
- K Fertiliser	*ha.a*	-	-	*57*	*±9*	*57*	*±9*	(a)
- Pesticides	*ha.a*	-	-	*15*	*±2*	*15*	*±2*	(a)
- Herbicide	*ha.a*	-	-	*2*	-	*2*	-	(a)
- Insecticide	*ha.a*	-	-	*1*	-	*1*	-	(a)
- Seed	*ha.a*	-	-	*8*	*±1*	*8*	*±1*	(a)
- Diesel Fuel	*ha.a*	*610*	*±96*	*76*	*±33*	*686*	*±102*	(a)
Reference System:								
- Diesel Fuel	*ha.a*	*- 63*	*±10*	*- 7*	*±3*	*- 70*	*±10*	(a)
Sub-Totals	*ha.a*	*666*	*±104*	*904*	*±93*	*1,570*	*±140*	
	t be	**108**	**±17**	**147**	**±15**	**255**	**±23**	(b)
Transport:								
- Diesel Fuel	*t ssb*	*5*	-	*2*	-	*7*	-	(a)
	t be	**44**	**-**	**18**	**-**	**62**	**-**	(c)
Washing, Shredding and Diffusion:								
- Natural Gas	*t csb*	*20*	*±3*	*2*	*±1*	*22*	*±3*	(a)
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	(a)
- Gypsum	*t csb*	-	-	-	-	-	-	(a)
- Hydrochloric Acid	*t csb*	-	-	-	-	-	-	(a)
- Formaldehyde	*t csb*	-	-	-	-	-	-	(a)
- Biocide	*t csb*	-	-	-	-	-	-	(a)
- Foam Oil	*t csb*	-	-	-	-	-	-	(a)
Credits:								
- Soil	*t csb*	-	-	-	-	-	-	(a)
- Stones	*t csb*	-	-	-	-	-	-	(a)
Sub-Totals	*t csb*	*20*	*±3*	*2*	*±1*	*22*	*±3*	
	t be	**168**	**±25**	**17**	**±8**	**185**	**±26**	(d)
Purification, Concentration, Fermentation, Distillation and Dehydration:								
- Natural Gas	*t csb*	*46*	*±7*	*3*	*±1*	*49*	*±7*	(a)
- Sulphur	*t csb*	-	-	-	-	-	-	(a)
- Soda	*t csb*	-	-	-	-	-	-	(a)
- Anti-Scalant	*t csb*	-	-	-	-	-	-	(a)
- EDTA	*t csb*	-	-	-	-	-	-	(a)
- Limestone	*t csb*	-	-	-	-	-	-	(a)
- Coke	*t csb*	*5*	*±1*	*1*	-	*6*	*±1*	(a)
- Anti-Foam	*t csb*	-	-	-	-	-	-	(a)
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	(a)
Credit:								
- Electricity	*t csb*	-	-	*- 3*	-	*- 3*	-	(a)
- LimeX	*t csb*	-	-	*- 8*	*±1*	*- 8*	*±1*	(a)
Sub-Totals	*t csb*	*51*	*±7*	*- 7*	*±1*	*44*	*±7*	
	t be	**550**	**±75**	**- 75**	**±11**	**475**	**±78**	(e)
Plant Construction	**t be**	**-**	**-**	**24**	**±4**	**24**	**±4**	(a)
Plant Maintenance	**t be**	**-**	**-**	**7**	**±1**	**7**	**±1**	(a)
Distribution	**t be**	**25**	**±1**	**7**	**±1**	**32**	**±1**	(a)
Totals	**t be**	**895**	**±81**	**145**	**±21**	**1,040**	**±85**	

Biofuel Specifications

Density of bioethanol	= 0.79 kg/l
Net calorific value of bioethanol	= 26.72 MJ/kg
Gross calorific value of bioethanol	= 29.74 MJ/kg

Abbreviations

ha.a	= hectare year
t csb	= tonne of clean sugar beet
t ssb	= tonne of soiled sugar beet
t be	= tonne of bioethanol

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 0.255 ha.a/t of bioethanol, partitioning between13.296 t of sugar beet at farm with a price of £22/t (Ref. 1) and 1.507 t sugar beet tops (dry matter) with an effective price of £10.00/t, based on an average market price of £2.00/t (wet basis) 80% moisture content (Ref. 2), and partitioning between 14.560 t of thin juice with an effective price of £16.2/t and an effective average price for 25.996 t of pulp with a moisture content of 97% of £2.56/t, derived from an average price for animal feed pellets with a moisture content of 15% of £72.50/t (Ref. 2), and an assumed price of bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solid and 66.5% sugar purity), based on the price of thick juice, giving an allocation of 95.1% x 78.0% x 85.7% = 63.6% to bioethanol.

(c) Soiled sugar beet requirement of 13.296 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(d) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(e) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 85.7% to bioethanol.

APPENDIX G:Model 4b

Spreadsheet for Primary Energy Inputs to Bioethanol Production from Sugar Beet using a Natural Gas-fired Combined Heat and Power Plant with a Gas Turbine (Model 4b)

Functional Unit:	Bioethanol at point of distribution derived from sugar beet using natural gas-fired combined heat and power with a gas turbine during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on a market price for 13.296 tonnes of sugar beet on the farm of £22.00/t (Ref. 1) and an effective price for 1.507 tonnes of sugar beet tops (dry matter) of £10.0/t, based on an average market price of £2.00/t (wet basis) with a 80% moisture content (Ref. 2), substitution of 0.669 tonnes of soil from washing by soil from main sources, substitution of 0.049 tonnes of stones from washing by stones from quarrying, an effective average price for 14.560 tonnes of thin juice (15% solids and 88% sugar purity) of £16.2/t, derived from a price for thick juice (67% solids and 92% sugar purity) of £72.48/t (Ref. 3), and an effective average price for 25.996 tonnes of pulp (97% moisture content) of £2.56/t, derived from an average market price for animal feed pellets (15% moisture content) of £72.50/t (Ref. 2), substitution of 0.566 tonnes of LimeX by agricultural lime, and an assumed price for bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solids and 66.5% sugar purity) of £122.15/t, based on the price of thick juice (Ref. 4).

Contribution	Per Unit	Primary Energy Input (MJ)								
		Direct		Indirect		Feedstock		Total		Notes
		Value	Range	Value	Range	Value	Range	Value	Range	
Cult. and Harvest:										
- N Fertiliser	*ha.a*	-	-	*1,443*	*±577*	*2,739*	*±109*	*4,182*	*±587*	(a)
- P Fertiliser	*ha.a*	-	-	*1,375*	*±206*	-	-	*1,375*	*±206*	(b, c)
- K Fertiliser	*ha.a*	-	-	*1,165*	*±175*	-	-	*1,165*	*±175*	(c, d)
- Pesticides	*ha.a*	-	-	*795*	*±119*	-	-	*795*	*±119*	(c, e)
- Herbicide	*ha.a*	-	-	*110*	*±16*	-	-	*110*	*±16*	(c, f)
- Insecticide	*ha.a*	-	-	*66*	*±10*	-	-	*66*	*±10*	(c, g)
- Seed	*ha.a*	-	-	*135*	*±20*	-	-	*135*	*±20*	(c, h)
- Diesel Fuel	*ha.a*	*8,870*	*±1,402*	*976*	*±465*	-	-	*9,846*	*±1,477*	(c, i)
Reference System:										
- Diesel Fuel	*ha.a*	*- 922*	*±146*	*- 101*	*±48*	-	-	*- 1,023*	*±154*	(c, j)
Sub-Totals	*ha.a*	*7,948*	*±1,410*	*5,964*	*±800*	*2,739*	*±109*	*16,651*	*±1,624*	
	t be	**1,289**	**±229**	**967**	**±130**	**444**	**±18**	**2,700**	**±263**	(k)
Transport:										
- Diesel Fuel	*t ssb*	*77*	*±3*	*27*	*±3*	-	-	*104*	*±4*	(l)
	t be	**684**	**±27**	**240**	**±27**	**-**	**-**	**924**	**±36**	(m)
Washing, Shredding and Diffusion:										
- Natural Gas	*t csb*	*386*	*±61*	*42*	*±20*	-	-	*428*	*±64*	(c, n-p)
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	-	-	(q)
- Gypsum	*t csb*	-	-	*1*	-	-	-	*1*	-	(c, r)
- Hydrochlor. Acid	*t csb*	-	-	*1*	-	-	-	*1*	-	(s)
- Formaldehyde	*t csb*	-	-	-	-	-	-	-	-	(c, t)
- Biocide	*t csb*	-	-	-	-	-	-	-	-	(c, u)
- Foam Oil	*t csb*	-	-	-	-	-	-	-	-	(v)
Credits:										
- Soil	*t csb*	-	-	*- 4*	*± 1*	-	-	*- 4*	*± 1*	(c, w)
- Stones	*t csb*	-	-	-	-	-	-	-	-	(c, x)
Sub-Totals	*t csb*	*386*	*±61*	*40*	*±20*	-	-	*426*	*±64*	
	t be	**3,243**	**±513**	**336**	**±168**	**-**	**-**	**3,579**	**±538**	(y)
Purification, Concentration, Fermentation, Distillation and Dehydration:										
- Natural Gas	*t csb*	*882*	*±141*	*97*	*±46*	-	-	*979*	*±148*	(c, n, p,z)
- Sulphur	*t csb*	-	-	*1*	-	-	-	*1*	-	(aa)
- Soda	*t csb*	-	-	*1*	-	-	-	*1*	-	(bb)
- Anti-Scalant	*t csb*	-	-	*1*	-	-	-	*1*	-	(cc)
- EDTA	*t csb*	-	-	-	-	-	-	-	-	(dd)
- Limestone	*t csb*	-	-	*13*	*±2*	-	-	*13*	*±2*	(ee)
- Coke	*t csb*	*51*	*±9*	*16*	*±5*	-	-	*67*	*±10*	(c, ff)
- Anti-Foam	*t csb*	-	-	*6*	*±1*	-	-	*6*	*±1*	(c, gg)
- Sulphuric Acid	*t csb*	-	-	*1*	*±1*	-	-	*1*	*±1*	(hh)
Credit:										
- Electricity	*t csb*	*562*	*±84*	*-1,412*	*±212*	-	-	*- 850*	*±228*	(c, ii)
- LimeX	*t csb*	-	-	*- 94*	*±14*	-	-	*- 94*	*±14*	(c, jj)
Sub-Totals	*t csb*	1,495	*±164*	*-1,370*	*±217*	-	-	*125*	*±272*	
	t be	**16,115**	**±1,768**	**-14,768**	**±2,339**	**-**	**-**	**1,347**	**±2,932**	(kk)
Plant Construction	**t be**	**-**	**-**	**475**	**±71**	**-**	**-**	**475**	**±71**	(ll)
Plant Maintenance	**t be**	**-**	**-**	**142**	**±21**	**-**	**-**	**142**	**±21**	(mm)
Distribution	**t be**	**369**	**±14**	**129**	**±16**	**-**	**-**	**498**	**±21**	(nn)
Totals	**t be**	**21,700**	**±1,855**	**-12,479**	**±2,350**	**444**	**±18**	**9,665**	**±2,994**	

Biofuel Specifications

Density of bioethanol	= 0.79 kg/l
Net calorific value of bioethanol	= 26.72 MJ/kg
Gross calorific value of bioethanol	= 29.74 MJ/kg

Abbreviations

ha.a	= hectare year
t ssb	= tonne of soiled sugar beet
t csb	= tonne of clean sugar beet
t be	= tonne of bioethanol

Notes

(a) Nitrogen fertiliser application rate of 103.0 kg N/ha.a (Ref. 5) 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 nitrogen fertiliser (Ref. 6).

(b) Phosphate fertiliser application rates of 38.0 kg P/ha.a (Ref. 5), or 87.0 kg P_2O_5/ ha.a assuming 2.290 kg P_2O_5/kg P, and a total energy requirement for phosphate fertiliser of 15.8 MJ/kg P_2O_5 (Ref. 7).

(c) Assuming an error bar of ±15% based on similar analyses (Ref. 8).

(d) Potash fertiliser application rate of 104.0 kg K/ha.a (Ref. 5), or 125.3 kg K_2O/ha.a assuming 1.205 kg K_2O/kg K, and a total energy requirement for potash fertiliser of 9.3 MJ/ kg K_2O (Ref. 7).

(e) Pesticide application rate of 2.90 kg/ha.a (Ref. 9) and a total energy requirement for general pesticides, herbicides and fungicides of 274.1 MJ/kg (Ref. 7).

(f) Herbicide application rate of 0.40 kg/ha.a (Ref. 9) and a total energy requirement for general pesticides, herbicides and fungicides of 274.1 MJ/kg (Ref. 7).

(g) Insecticide application rate of 0.24 kg/ha.a (Ref. 9) and a total energy requirement for general pesticides, herbicides and fungicides of 274.1 MJ/kg (Ref. 7).

(h) Sowing rate of 3.8 kg/ha.a, consisting of 1.2 kg/ha.a of seed and 2.6 kg/ha.a pelletising material (Ref. 10), and a total energy requirement of 35.5 MJ/kg of seed (Ref. 7).

(i) Diesel fuel consumption of 8,870 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides and insecticides, and harvesting (Ref. 2) and a gross energy requirement of 1.110 MJ/MJ for diesel fuel in the UK in 1996 (Ref. 11).

(j) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 7) and a gross energy requirement of 1.110 MJ/MJ for diesel fuel in the UK in 1996 (Ref. 11).

(k) Land requirement of 0.255 ha.a/t of bioethanol, partitioning between13.296 t of sugar beet at farm with a price of £22/t (Ref. 1) and 1.507 t sugar beet tops (dry matter) with an effective price of £10.00/t, based on an average market price of £2.00/t (wet basis) 80% moisture content (Ref. 2), and partitioning between 14.560 t of thin juice with an effective price of £16.2/t and an effective average price for 25.996 t of pulp with a moisture content of 97% of £2.56/t, derived from an average price for animal feed pellets with a moisture content of 15% of £72.50/t (Ref. 2), and an assumed price of bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solid and 66.5% sugar purity), based on the price of thick juice, giving an allocation of 95.1% x 78.0% x 85.7% = 63.6% to bioethanol.

(l) Average round trip distance of 94 km (Ref. 2) 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. 12).

(m) Soiled sugar beet requirement of 13.296 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(n) Natural gas-fired combined heat and power plant based on a gas turbine with an overall efficiency of 85%, consuming 331,000 MJ/hr of natural gas to provide 67 t/hr or 184,870 MJ/hr of steam (matched to bioethanol plant requirements) and 26.8MW (6.1 MW for bioethanol plant and 20.7 MW surplus) of electricity equal to 26,800 kWh/hr or 96,480 MJ/hr (Ref. 2), resulting in 0.29 MJ of electricity and 0.56 MJ of steam from each MJ of natural gas, or a natural gas consumption rate of 1.176 MJ/MJ of energy output in the form of electricity or steam, and a gross energy requirement of 1.110 MJ/MJ for natural gas in the UK in 1996 (Ref. 11).

(o) Steam consumption rate for washing, shredding and diffusion of 14 t/hr, assumed to be 50% of total steam requirements of sugar plant (Ref. 2), equivalent to 1.176 x 184,870 x 14/67 = 45,428 MJ/hr of natural gas, and an electricity consumption rate for washing, shredding and diffusion of 3.5 MW (Ref. 2), equivalent to 1.176 x 96,480 x 3.5/26.8 = 14,818 MJ/hr of natural gas, resulting in a total natural gas consumption rate of 60,246 MJ/hr.

(p) Total clean sugar beet input of 1,257,774 t/a and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 2), giving a clean sugar beet input rate of 156 t/hr.

(q) Sulphuric acid (93% concentration) consumption rate of 0.18 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 2.4 ± 2.7 MJ/kg for sulphuric acid (Ref. 13).

(r) Gypsum (calcium sulphate) consumption rate of 1.06 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 1 MJ/kg for gypsum (Ref. 13).

(s) Hydrochloric acid (100% concentration) consumption rate of 0.025 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 40 ± 3 MJ/kg for hydrochloric acid (Ref. 13).

(t) Formaldehyde consumption rate of 0.15 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 3 MJ/kg for formaldehyde (Refs. 2 and 14 to 16).

(u) Biocide consumption rate of 0.024 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 3 MJ/kg for biocide (Refs. 2 and 14 to 16).

(v) Foam oil consumption rate of 0.03 kg/t of clean sugar beet (Ref. 2) and, assuming foam oil is similar to refined rapeseed oil, an energy requirement of 11 ± 1 MJ/kg of refined rapeseed oil (Ref. 17).

(w) Soil recovery rate of 5.32% of clean sugar beet (Ref. 2), or 53.2 kg/t of clean sugar beet, and, assuming soil production is similar to sand extraction, an energy requirement of 0.08 MJ/kg for sand (Ref. 18).

(x) Stone recovery rate of 0.39% of clean sugar beet (Ref. 2), or 3.9 kg/t of clean sugar beet, and, assuming stone production is similar to sand extraction, an energy requirement of 0.08 MJ/kg for sand (Ref. 18).

(y) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(z) Steam consumption rate for purification of 1 t/hr and for fermentation, distillation and dehydration of 38 t/hr (Ref. 2), resulting in a total steam consumption rate of 39 t/hr or equivalent to 1.176 x 184,870 x 39/67 = 126,550 MJ/hr of natural gas, and an electricity consumption rate for diffusion of 1.4 MW and for fermentation, distillation and dehydration of 1.2 MW (Ref. 2), equivalent to 1.176 x 96,480 x 2.6/26.8 = 11,007 MJ/hr of natural gas, resulting in a total natural gas consumption rate for diffusion of 137,557 MJ/hr.

(aa) Sulphur (as SO_2) consumption rate of 0.13 kg/t of clean sugar beet and an energy requirement of 11 ± 3 MJ/kg for sulphur (Ref. 13).

(bb) Soda (sodium carbonate) consumption rate of 0.05 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 29 ± 8 MJ/kg for soda (Ref. 13).

(cc) Anti-scalant consumption rate of 0.04 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 32 MJ/kg for anti-scalant (Refs. 2 and 14 to 16).

(dd) EDTA consumption rate of 0.055 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 8 MJ/kg for EDTA (Refs. 2 and 14 to 16).

(ee) Limestone consumption rate of 2.3% of clean sugar beet (Ref. 2), or 23 kg/t of clean sugar beet, and an energy requirement of 0.58 MJ/kg for limestone (Ref. 18).

(ff) Coke consumption rate of 0.18% of clean sugar beet (Ref. 2), or 1.8 kg/t of clean sugar beet, and a gross energy requirement of 1.316 x 28.1 = 37 MJ/kg for coke in the UK in 1996 (Ref. 11).

(gg) Anti-foam consumption rate of 253,344 kg/a (Ref. 2), or 0.20 kg/t of clean sugar beet, and, assuming similarity with anti-scalant, an energy requirement of 32 MJ/kg of anti-foam (Refs. 2 and 14 to 16).

(hh) Sulphuric acid (93% concentration) consumption rate of 380,016 kg/a, or 0.30 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 2.4 ± 2.7 MJ/kg for sulphuric acid (Ref. 13).

(ii) Surplus electricity of 20.7 MW for 8,064 hr/a resulting in 600,929 GJ/a of electricity exported for sale, equivalent to 478 MJ/t of clean sugar beet, and an energy requirement of 3.083 MJ/MJ for displaced grid electricity supplies in the UK in 1996 (Ref. 11) less the energy requirement of 1.176 MJ/MJ for electricity generated from the gas-fired combined heat and power plant.

(jj) LimeX production rate of 45 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 2.1 MJ/kg for lime (Ref. 7).

(kk) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 85.7% to bioethanol.

(ll) Primary energy input of 950,000 GJ for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £38.0 m (Ref. 2) and an energy intensity of 25 MJ/£ (Ref. 14).

(mm) Primary energy input of annual plant maintenance assumed to be 1.5% of primary energy input to plant construction (Ref. 2).

(nn) Average round trip distance of 450 km (Ref. 19) 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. 11).

<u>References</u>

1. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 28 April 2003.

2. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 2 May 2003.

3. Private communication with D. Darby of British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication with G. Punter of British Sugar plc., Peterborough, United Kingdom, 8 May 2003.

5. "British Sugar Field Crop Survey 2001"

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Report No. 20/1, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003, for the Department for the Environment, Food and Rural Affairs, www.defra.

7. "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.

8. "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.

9. "Pesticide Use Survey Reports" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. British Sugar Internal Survey 2001

11. "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.

12. "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.

13. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

14. "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.

15. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

16. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

17. "Carbon and Energy Balances for a Range of Biofuel Options" by M. A. Elsayed, R. Matthews and N. D. Mortimer, B/B6/00784/REP, Energy Technology Support Unit, Harwell, United Kingdom, March 2003, www.shu.ac.uk/rru/projects/biofuels/biofuels.html.

18. "Handbook of Industrial Energy Analysis" by I. Boustead and G. Hancock, Ellis Horwood, Chichester, United Kingdom, 1979.

19. "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.

Spreadsheet for Carbon Dioxide Outputs from Bioethanol Production from Sugar Beet using a Natural Gas-fired Combined Heat and Power Plant with a Gas Turbine (Model 4b)

Functional Unit:	Bioethanol at point of distribution derived from sugar beet using natural gas-fired combined heat and power with a gas turbine during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on a market price for 13.296 tonnes of sugar beet on the farm of £22.00/t (Ref. 1) and an effective price for 1.507 tonnes of sugar beet tops (dry matter) of £10.0/t, based on an average market price of £2.00/t (wet basis) with a 80% moisture content (Ref. 2), substitution of 0.669 tonnes of soil from washing by soil from main sources, substitution of 0.049 tonnes of stones from washing by stones from quarrying, an effective average price for 14.560 tonnes of thin juice (15% solids and 88% sugar purity) of £16.2/t, derived from a price for thick juice (67% solids and 92% sugar purity) of £72.48/t (Ref. 3), and an effective average price for 25.996 tonnes of pulp (97% moisture content) of £2.56/t, derived from an average market price for animal feed pellets (15% moisture content) of £72.50/t (Ref. 2), substitution of 0.566 tonnes of LimeX by agricultural lime, and an assumed price for bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solids and 66.5% sugar purity) of £122.15/t, based on the price of thick juice (Ref. 4).

Contribution	Per Unit	Carbon Dioxide Output (kg CO_2)						
		Direct		Indirect		Total		Notes
		Value	Range	Value	Range	Value	Range	
Cult. and Harvest.:								
- N Fertiliser	*ha.a*	-	-	*196*	*±28*	*196*	*±28*	(a)
- P Fertiliser	*ha.a*	-	-	*61*	*±9*	*61*	*±9*	(b, c)
- K Fertiliser	*ha.a*	-	-	*57*	*±9*	*57*	*±9*	(c, d)
- Pesticides	*ha.a*	-	-	*14*	*±2*	*14*	*±2*	(c, e)
- Herbicide	*ha.a*	-	-	*2*	-	*2*	-	(c, f)
- Insecticide	*ha.a*	-	-	*1*	-	*1*	-	(c, g)
- Seed	*ha.a*	-	-	*7*	*±1*	*7*	*±1*	(c, h)
- Diesel Fuel	*ha.a*	*608*	*±96*	*72*	*±33*	*680*	*±102*	(c, i)
Reference System:								
- Diesel Fuel	*ha.a*	*- 63*	*±10*	*- 7*	*±3*	*- 70*	*±10*	(c, j)
Sub-Totals	*ha.a*	*545*	*±97*	*403*	*±45*	*948*	*±107*	
	t be	**88**	**±16**	**65**	**±7**	**153**	**±17**	(k)
Transport:								
- Diesel Fuel	*t ssb*	*5*	-	*2*	-	*7*	-	(l)
	t be	**44**	**-**	**18**	**-**	**62**	**-**	(m)
Washing, Shredding and Diffusion:								
- Natural Gas	*t csb*	*20*	*±3*	*1*	*±1*	*21*	*±3*	(c, n - p)
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	(q)
- Gypsum	*t csb*	-	-	-	-	-	-	(c, r)
- Hydrochloric Acid	*t csb*	-	-	-	-	-	-	(s)
- Formaldehyde	*t csb*	-	-	-	-	-	-	(c, t)
- Biocide	*t csb*	-	-	-	-	-	-	(c, u)
- Foam Oil	*t csb*	-	-	-	-	-	-	(v)
Credits:								
- Soil	*t csb*	-	-	-	-	-	-	(c, w)
- Stones	*t csb*	-	-	-	-	-	-	(c, x)
Sub-Totals	*t csb*	*20*	*±3*	*1*	*±1*	*21*	*±3*	
	t be	**168**	**±25**	**8**	**±8**	**176**	**±26**	(y)
Purification, Concentration, Fermentation, Distillation and Dehydration:								
- Natural Gas	*t csb*	*46*	*±7*	*2*	*±1*	*48*	*±7*	(c, n,p, z)
- Sulphur	*t csb*	-	-	-	-	-	-	(aa)
- Soda	*t csb*	-	-	-	-	-	-	(bb)
- Anti-Scalant	*t csb*	-	-	-	-	-	-	(cc)
- EDTA	*t csb*	-	-	-	-	-	-	(dd)
- Limestone	*t csb*	-	-	-	-	-	-	(ee)
- Coke	*t csb*	*5*	*±1*	*1*	-	*6*	*±1*	(c, ff)
- Anti-Foam	*t csb*	-	-	-	-	-	-	(c, gg)
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	(hh)
Credit:								
- Electricity	*t csb*	*29*	*±4*	*- 71*	*±11*	*-42*	*±12*	(c, ii)
- LimeX	*t csb*	-	-	*- 8*	*±1*	*- 8*	*±1*	(c, jj)
Sub-Totals	*t csb*	*80*	*±8*	*- 76*	*±11*	*4*	*±14*	
	t be	**862**	**±86**	**- 819**	**±118**	**43**	**±146**	(kk)
Plant Construction	**t be**	**-**	**-**	**24**	**±4**	**24**	**±4**	(ll)
Plant Maintenance	**t be**	**-**	**-**	**7**	**±1**	**7**	**±1**	(mm)
Distribution	**t be**	**25**	**±1**	**7**	**±1**	**32**	**±1**	(nn)
Totals	**t be**	**1,187**	**±91**	**- 690**	**±119**	**497**	**±149**	

Biofuel Specifications

Density of bioethanol	= 0.79 kg/l
Net calorific value of bioethanol	= 26.72 MJ/kg
Gross calorific value of bioethanol	= 29.74 MJ/kg

Abbreviations

ha.a	= hectare year
t csb	= tonne of clean sugar beet
t ssb	= tonne of soiled sugar beet
t be	= tonne of bioethanol

Notes

(a) Nitrogen fertiliser application rate of 103.0 kg N/ha.a (Ref. 4) and a total carbon requirement for ammonium nitrate of 1.904 ± 0.275 kg CO_2/kg N (Ref. 6).

(b) Phosphate fertiliser application rates of 38.0 kg P/ha.a (Ref. 5), or 87.0 kg P_2O_5/ ha.a assuming 2.290 kg P_2O_5/kg P, and a total carbon requirement for phosphate fertiliser of 0.700 kg CO_2/kg P_2O_5 (Ref. 7).

(c) Assuming an error bar of ±15% based on similar analyses (Ref. 8).

(d) Potash fertiliser application rate of 104.0 kg K/ha.a (Ref. 5), or 125.3 kg K_2O/ha.a assuming 1.205 kg K_2O/kg K, and a total carbon requirement for potash fertiliser of 0.453 kg CO_2/ kg K_2O (Ref. 7).

(e) Pesticide application rate of 2.90 kg/ha.a (Ref. 9) and a total carbon requirement for general pesticides, herbicides and fungicides of 4.921 kg CO_2/kg (Ref. 7).

(f) Herbicide application rate of 0.40 kg/ha.a (Ref. 9) and a total carbon requirement for general pesticides, herbicides and fungicides of 4.921 kg CO_2/kg (Ref. 7).

(g) Insecticide application rate of 0.24 kg/ha.a (Ref. 9) and a total carbon requirement for general pesticides, herbicides and fungicides of 4.921 kg CO_2/kg (Ref. 7).

(h) Sowing rate of 3.8 kg/ha.a, consisting of 1.2 kg/ha.a of seed and 2.6 kg/ha.a pelletising material (Ref. 10), and a total carbon requirement of 1.775 kg CO_2 /kg of seed (Ref. 7).

(i) Diesel fuel consumption of 8,870 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides and insecticides, and harvesting (Ref. 2) 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. 11).

(j) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 7) 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. 11).

(k) Land requirement of 0.255 ha.a/t of bioethanol, partitioning between13.296 t of sugar beet at farm with a price of £22/t (Ref. 1) and 1.507 t sugar beet tops (dry matter) with an effective price of £10.00/t, based on an average market price of £2.00/t (wet basis) 80% moisture content (Ref. 2), and partitioning between 14.560 t of thin juice with an effective price of £16.2/t and an effective average price for 25.996 t of pulp with a moisture content of 97% of £2.56/t, derived from an average price for animal feed pellets with a moisture content of 15% of £72.50/t (Ref. 2), and an assumed price of bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solid and 66.5% sugar purity), based on the price of thick juice, giving an allocation of 95.1% x 78.0% x 85.7% = 63.6% to bioethanol.

(l) Average round trip distance of 94 km (Ref. 2) 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. 12).

(m) Soiled sugar beet requirement of 13.296 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(n) Natural gas-fired combined heat and power plant based on a gas turbine with an overall efficiency of 85%, consuming 331,000 MJ/hr of natural gas to provide 67 t/hr or 184,870 MJ/hr of steam (matched to bioethanol plant requirements) and 26.8MW (6.1 MW for bioethanol plant and 20.7 MW surplus) of electricity equal to 26,800 kWh/hr or 96,480 MJ/hr (Ref. 2), resulting in 0.29 MJ of electricity and 0.56 MJ of steam from each MJ of natural gas, or a natural gas consumption rate of 1.176 MJ/MJ of energy output in the form of electricity or 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. 11).

(o) Steam consumption rate for washing, shredding and diffusion of 14 t/hr, assumed to be 50% of total steam requirements of sugar plant (Ref. 2), equivalent to 1.176 x 184,870 x 14/67 = 45,428 MJ/hr of natural gas, and an electricity consumption rate for washing, shredding and diffusion of 3.5 MW (Ref. 2), equivalent to

1.176 x 96,480 x 3.5/26.8 = 14,818 MJ/hr of natural gas, resulting in a total natural gas consumption rate of 60,246 MJ/hr.

(p) Total clean sugar beet input of 1,257,774 t/a and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 2), giving a clean sugar beet input rate of 156 t/hr.

(q) Sulphuric acid (93% concentration) consumption rate of 0.18 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 0.13 ± 0.16 kg CO_2/kg for sulphuric acid (Ref. 13).

(r) Gypsum (calcium sulphate) consumption rate of 1.06 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 0.08 kg CO_2/kg for gypsum (Ref. 13).

(s) Hydrochloric acid (100% concentration) consumption rate of 0.025 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 0.15 kg CO_2/kg for hydrochloric acid (Ref. 13).

(t) Formaldehyde consumption rate of 0.15 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 2.1×10^{-5} kg CO_2/kg for formaldehyde (Refs. 2 and 14 to 16).

(u) Biocide consumption rate of 0.024 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 0.12 kg CO_2/kg for biocide (Refs. 2 and 14 to 16).

(v) Foam oil consumption rate of 0.03 kg/t of clean sugar beet (Ref. 2) and, assuming foam oil is similar to refined rapeseed oil, a carbon requirement of 0.59 ± 0.04 kg CO_2/kg of refined rapeseed oil (Ref. 17).

(w) Soil recovery rate of 5.32% of clean sugar beet (Ref. 2), or 53.2 kg/t of clean sugar beet, and, assuming soil production is similar to sand extraction, a carbon requirement of 5.7×10^{-3} kg CO_2/kg for sand (Ref. 18).

(x) Stone recovery rate of 0.39% of clean sugar beet (Ref. 2), or 3.9 kg/t of clean sugar beet, and, assuming stone production is similar to sand extraction, a carbon requirement of 5.7×10^{-3} kg CO_2/kg for sand (Ref. 18).

(y) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(z) Steam consumption rate for purification of 1 t/hr and for fermentation, distillation and dehydration of 38 t/hr (Ref. 2), resulting in a total steam consumption rate of 39 t/hr or equivalent to 1.176 x 184,870 x 39/67 = 126,550 MJ/hr of natural gas, and an electricity consumption rate for diffusion of 1.4 MW and for fermentation, distillation and dehydration of 1.2 MW (Ref. 2), equivalent to 1.176 x 96,480 x 2.6/26.8 = 11,007 MJ/hr of natural gas, resulting in a total natural gas consumption rate for diffusion of 137,557 MJ/hr.

(aa) Sulphur (as SO_2) consumption rate of 0.13 kg/t of clean sugar beet and a carbon requirement of 0.89 ± 0.24 kg CO_2/kg for sulphur (Ref. 13).

(bb) Soda (sodium carbonate) consumption rate of 0.05 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 2.13 ± 0.64 kg CO_2/kg for soda (Ref. 13).

(cc) Anti-scalant consumption rate of 0.04 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 1.52 kg CO_2/kg for anti-scalant (Refs. 2 and 14 to 16).

(dd) EDTA consumption rate of 0.055 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 0.40 kg CO_2/kg for EDTA (Refs. 2 and 14 to 16).

(ee) Limestone consumption rate of 2.3% of clean sugar beet (Ref. 2), or 23 kg/t of clean sugar beet, and a carbon requirement of 0.02 kg CO_2/kg for limestone (Ref. 18).

(ff) Coke consumption rate of 0.18% of clean sugar beet (Ref. 2), or 1.8 kg/t of clean sugar beet, and a direct carbon requirement of 0.104 x 28.1 = 2.92 kg CO_2/kg and an indirect carbon requirement of 0.37 kg CO_2/kg for coke in the UK in 1996 (Ref. 11).

(gg) Anti-foam consumption rate of 253,344 kg/a (Ref. 2), or 0.20 kg/t of clean sugar beet, and, assuming similarity with anti-scalant, a carbon requirement of 1.52 kg CO_2/kg of anti-foam (Refs. 2 and 14 to 16).

(hh) Sulphuric acid (93% concentration) consumption rate of 380,016 kg/a, or 0.30 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 0.13 ± 016 kg CO_2/kg for sulphuric acid (Ref. 13).

(ii) Surplus electricity of 20.7 MW for 8,064 hr/a resulting in 600,929 GJ/a of electricity exported for sale, equivalent to 478 MJ/t of clean sugar beet, and a carbon requirement of 0.15 kg CO_2/MJ for displaced grid electricity supplies in the UK in 1996 (Ref. 11), less 1.176 x 478 of natural gas used to produce the surplus amount with 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. 11).

(jj) LimeX production rate of 45 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 0.18 kg CO_2/kg for lime (Ref. 6), excluding carbon dioxide from calcination which is not accounted for in the bioethanol plant.

(kk) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 85.7% to bioethanol.

(ll) Carbon dioxide output of 47,500 tonnes of CO_2 for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £38.0 m (Ref. 2) and a carbon intensity of 1.25 kg CO_2/£ (Ref. 14).

(mm) Carbon dioxide output of annual plant maintenance assumed to be 1.5% of carbon dioxide output of plant construction (Ref. 2).

(nn) Average round trip distance of 450 km (Ref. 19) 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. 11).

References

1. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 28 April 2003.

2. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 2 May 2003.

3. Private communication with D. Darby of British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication with G. Punter of British Sugar plc., Peterborough, United Kingdom, 8 May 2003.

5. "British Sugar Field Crop Survey 2001"

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Report No. 20/1, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003, for the Department for the Environment, Food and Rural Affairs, www.defra.

7. "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.

8. "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.

9. "Pesticide Use Survey Reports" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. British Sugar Internal Survey 2001

11. "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.

12. "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.

13. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

14. "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.

15. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

16. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

17. "Carbon and Energy Balances for a Range of Biofuel Options" by M. A. Elsayed, R. Matthews and N. D. Mortimer, B/B6/00784/REP, Energy Technology Support Unit, Harwell, United Kingdom, March 2003, www.shu.ac.uk/rru/projects/biofuels/biofuels.html.

18. "Handbook of Industrial Energy Analysis" by I. Boustead and G. Hancock, Ellis Horwood, Chichester, United Kingdom, 1979.

19. "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.

Spreadsheet for Methane Outputs from Bioethanol Production from Sugar Beet using a Natural Gas-fired Combined Heat and Power Plant with a Gas Turbine (Model 4b)

Functional Unit:	Bioethanol at point of distribution derived from sugar beet using natural gas-fired combined heat and power with a gas turbine during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on a market price for 13.296 tonnes of sugar beet on the farm of £22.00/t (Ref. 1) and an effective price for 1.507 tonnes of sugar beet tops (dry matter) of £10.0/t, based on an average market price of £2.00/t (wet basis) with a 80% moisture content (Ref. 2), substitution of 0.669 tonnes of soil from washing by soil from main sources, substitution of 0.049 tonnes of stones from washing by stones from quarrying, an effective average price for 14.560 tonnes of thin juice (15% solids and 88% sugar purity) of £16.2/t, derived from a price for thick juice (67% solids and 92% sugar purity) of £72.48/t (Ref. 3), and an effective average price for 25.996 tonnes of pulp (97% moisture content) of £2.56/t, derived from an average market price for animal feed pellets (15% moisture content) of £72.50/t (Ref. 2), substitution of 0.566 tonnes of LimeX by agricultural lime, and an assumed price for bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solids and 66.5% sugar purity) of £122.15/t, based on the price of thick juice (Ref. 4).

Contribution	Per Unit	Methane Output (kg CH_4)						Notes
		Direct		Indirect		Total		
		Value	Range	Value	Range	Value	Range	
Cult. and Harvest.:								
- N Fertiliser	*ha.a*	-	-	*0.371*	*±0.062*	*0.371*	*±0.062*	(a)
- P Fertiliser	*ha.a*	-	-	*0.002*	-	*0.002*	-	(b, c)
- K Fertiliser	*ha.a*	-	-	*0.003*	-	*0.003*	-	(c, d)
- Pesticides	*ha.a*	-	-	*0.001*	-	*0.001*	-	(c, e)
- Herbicide	*ha.a*	-	-	-	-	-	-	(c, f)
- Insecticide	*ha.a*	-	-	-	-	-	-	(c, g)
- Seed	*ha.a*	-	-	*0.008*	*±0.001*	*0.008*	*±0.001*	(c, h)
- Diesel Fuel	*ha.a*	*0.005*	*±0.005*	*0.181*	*±0.027*	*0.186*	*±0.028*	(c, i)
Reference System:								
- Diesel Fuel	*ha.a*	*- 0.001*	*±0.001*	*- 0.019*	*±0.003*	*- 0.020*	*±0.003*	(c, j)
Sub-Totals	*ha.a*	*0.004*	*±0.005*	*0.547*	*±0.068*	*0.551*	*±0.068*	
	t be	**0.001**	**±0.001**	**0.088**	**±0.011**	**0.089**	**±0.011**	(k)
Transport:								
- Diesel Fuel	*t ssb*	-	-	*0.002*	-	*0.002*	-	(l)
	t be	**-**	**-**	**0.018**	**-**	**0.018**	**-**	(m)
Washing, Shredding and Diffusion:								
- Natural Gas	*t csb*	*0.001*	*±0.001*	*0.042*	*±0.006*	*0.043*	*±0.007*	(c, n - p)
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	(q)
- Gypsum	*t csb*	-	-	-	-	-	-	(c, r)
- Hydrochloric Acid	*t csb*	-	-	-	-	-	-	(s)
- Formaldehyde	*t csb*	-	-	-	-	-	-	(c, t)
- Biocide	*t csb*	-	-	-	-	-	-	(c, u)
- Foam Oil	*t csb*	-	-	-	-	-	-	(v)
Credits:								
- Soil	*t csb*	-	-	-	-	-	-	(c, w)
- Stones	*t csb*	-	-	-	-	-	-	(c, x)
Sub-Totals	*t csb*	*0.001*	*±0.001*	*0.042*	*±0.006*	*0.043*	*±0.007*	
	t be	**0.008**	**±0.008**	**0.353**	**±0.050**	**0.361**	**±0.051**	(y)
Purification, Concentration, Fermentation, Distillation and Dehydration:								
- Natural Gas	*t csb*	*0.003*	*±0.003*	*0.097*	*±0.015*	*0.100*	*±0.015*	(c,n,p, z)
- Sulphur	*t csb*	-	-	-	-	-	-	(aa)
- Soda	*t csb*	-	-	-	-	-	-	(bb)
- Anti-Scalant	*t csb*	-	-	-	-	-	-	(cc)
- EDTA	*t csb*	-	-	-	-	-	-	(dd)
- Limestone	*t csb*	-	-	-	-	-	-	(ee)
- Coke	*t csb*	-	-	-	-	-	-	(c, ff)
- Anti-Foam	*t csb*	-	-	-	-	-	-	(c, gg)
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	(hh)
Credit:								
- Electricity	*t csb*	*0.002*	-	*- 0.129*	*±0.029*	*- 0.127*	*±0.029*	(c, ii)
- LimeX	*t csb*	-	-	-	-	-	-	(c, jj)
Sub-Totals	*t csb*	*0.005*	*±0.003*	*- 0.032*	*±0.033*	*-0.027*	*±0.033*	
	t be	**0.054**	**±0.032**	**- 0.345**	**±0.356**	**-0.291**	**±0.356**	(kk)
Plant Construction	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(ll)
Plant Maintenance	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(mm)
Distribution	**t be**	**-**	**-**	**0.008**	**-**	**0.008**	**-**	(nn)
Totals	**t be**	**0.063**	**±0.033**	**0.122**	**±0.359**	**0.185**	**±0.361**	

Biofuel Specifications

Density of bioethanol	= 0.79 kg/l
Net calorific value of bioethanol	= 26.72 MJ/kg
Gross calorific value of bioethanol	= 29.74 MJ/kg

Abbreviations

ha.a	= hectare year
t csb	= tonne of clean sugar beet
t ssb	= tonne of soiled sugar beet
t be	= tonne of bioethanol

Notes

(a) Nitrogen fertiliser application rate of 103.0 kg N/ha.a (Ref. 5) 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 (Ref. 6).

(b) Phosphate fertiliser application rates of 38.0 kg P/ha.a (Ref. 5), or 87.0 kg P_2O_5/ ha.a assuming 2.290 kg P_2O_5/kg P, and a total methane requirement for phosphate fertiliser of 2.3×10^{-5} kg CH_4/kg P_2O_5 (Ref. 7).

(c) Assuming an error bar of ±15% based on similar analyses (Ref. 8).

(d) Potash fertiliser application rate of 104.0 kg K/ha.a (Ref. 5), or 125.3 kg K_2O/ha.a assuming 1.205 kg K_2O/kg K, and a total methane requirement for potash fertiliser of 2.1×10^{-5} kg CH_4/ kg K_2O (Ref. 7).

(e) Pesticide application rate of 2.90 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.8×10^{-4} kg CH_4/kg (Ref. 7).

(f) Herbicide application rate of 0.40 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.8×10^{-4} kg CH_4/kg (Ref. 7).

(g) Insecticide application rate of 0.24 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.8×10^{-4} kg CH_4/kg (Ref. 7).

(h) Sowing rate of 3.8 kg/ha.a, consisting of 1.2 kg/ha.a of seed and 2.6 kg/ha.a pelletising material (Ref. 10), and a total methane requirement of 0.002 kg CH_4 /kg of seed (Ref. 7).

(i) Diesel fuel consumption of 8,870 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides and insecticides, and harvesting (Ref. 2) 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. 11).

(j) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 7) 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. 11).

(k) Land requirement of 0.255 ha.a/t of bioethanol, partitioning between13.296 t of sugar beet at farm with a price of £22/t (Ref. 1) and 1.507 t sugar beet tops (dry matter) with an effective price of £10.00/t, based on an average market price of £2.00/t (wet basis) 80% moisture content (Ref. 2), and partitioning between 14.560 t of thin juice with an effective price of £16.2/t and an effective average price for 25.996 t of pulp with a moisture content of 97% of £2.56/t, derived from an average price for animal feed pellets with a moisture content of 15% of £72.50/t (Ref. 2), and an assumed price of bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solid and 66.5% sugar purity), based on the price of thick juice, giving an allocation of 95.1% x 78.0% x 85.7% = 63.6% to bioethanol.

(l) Average round trip distance of 94 km (Ref. 2) 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. 12).

(m) Soiled sugar beet requirement of 13.296 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(n) Natural gas-fired combined heat and power plant based on a gas turbine with an overall efficiency of 85%, consuming 331,000 MJ/hr of natural gas to provide 67 t/hr or 184,870 MJ/hr of steam (matched to bioethanol plant requirements) and 26.8MW (6.1 MW for bioethanol plant and 20.7 MW surplus) of electricity equal to 26,800 kWh/hr or 96,480 MJ/hr (Ref. 2), resulting in 0.29 MJ of electricity and 0.56 MJ of steam from each MJ of natural gas, or a natural gas consumption rate of 1.176 MJ/MJ of energy output in the form of electricity or steam, and a direct methane requirement of 3.7×10^{-6} kg CH_4/MJ, an indirect methane requirement of 1.1×10^{-4} kg CH_4/MJ and a total methane requirement of 1.1×10^{-4} kg CH_4/MJ for natural gas in the UK in 1996 (Ref. 11).

(o) Steam consumption rate for washing, shredding and diffusion of 14 t/hr, assumed to be 50% of total steam requirements of sugar plant (Ref. 2), equivalent to 1.176 x 184,870 x 14/67 = 45,428 MJ/hr of natural gas,

and an electricity consumption rate for washing, shredding and diffusion of 3.5 MW (Ref. 2), equivalent to 1.176 x 96,480 x 3.5/26.8 = 14,818 MJ/hr of natural gas, resulting in a total natural gas consumption rate of 60,246 MJ/hr.

(p) Total clean sugar beet input of 1,257,774 t/a and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 2), giving a clean sugar beet input rate of 156 t/hr.

(q) Sulphuric acid (93% concentration) consumption rate of 0.18 kg/t of clean sugar beet (Ref. 2) and a methane requirement of $2.7 \times 10^{-4} \pm 3.0 \times 10^{-4}$ kg CH_4/kg for sulphuric acid (Ref. 13).

(r) Gypsum (calcium sulphate) consumption rate of 1.06 kg/t of clean sugar beet (Ref. 2) and a methane requirement of 2.1×10^{-5} kg CH_4/kg for gypsum (Ref. 13).

(s) Hydrochloric acid (100% concentration) consumption rate of 0.025 kg/t of clean sugar beet (Ref. 2) and a methane requirement of 0.01 ± 0.001 kg CH_4/kg for hydrochloric acid (Ref. 13).

(t) Formaldehyde consumption rate of 0.15 kg/t of clean sugar beet (Ref. 2) and a methane requirement of 4.0×10^{-7} kg CH_4/kg for formaldehyde (Refs. 2 and 14 to 16).

(u) Biocide consumption rate of 0.024 kg/t of clean sugar beet (Ref. 2) and a methane requirement of 3.0×10^{-7} kg CH_4/kg for biocide (Refs. 2 and 14 to 16).

(v) Foam oil consumption rate of 0.03 kg/t of clean sugar beet (Ref. 2) and, assuming foam oil is similar to refined rapeseed oil, a methane requirement of $7.7 \times 10^{-4} \pm 7.0 \times 10^{-5}$ kg CH_4/kg of refined rapeseed oil (Ref. 17).

(w) Soil recovery rate of 5.32% of clean sugar beet (Ref. 2), or 53.2 kg/t of clean sugar beet, and, assuming soil production is similar to sand extraction, a methane requirement of 1.6×10^{-6} kg CH_4/kg for sand (Ref. 18).

(x) Stone recovery rate of 0.39% of clean sugar beet (Ref. 2), or 3.9 kg/t of clean sugar beet, and, assuming stone production is similar to sand extraction, a methane requirement of 1.6×10^{-6} kg CH_4/kg for sand (Ref. 18).

(y) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(z) Steam consumption rate for purification of 1 t/hr and for fermentation, distillation and dehydration of 38 t/hr (Ref. 2), resulting in a total steam consumption rate of 39 t/hr or equivalent to 1.176 x 184,870 x 39/67 = 126,550 MJ/hr of natural gas, and an electricity consumption rate for diffusion of 1.4 MW and for fermentation, distillation and dehydration of 1.2 MW (Ref. 2), equivalent to 1.176 x 96,480 x 2.6/26.8 = 11,007 MJ/hr of natural gas, resulting in a total natural gas consumption rate for diffusion of 137,557 MJ/hr.

(aa) Sulphur (as SO_2) consumption rate of 0.13 kg/t of clean sugar beet and a methane requirement of $2.5 \times 10^{-5} \pm 7.0 \times 10^{-6}$ kg CH_4/kg for sulphur (Ref. 13).

(bb) Soda (sodium carbonate) consumption rate of 0.05 kg/t of clean sugar beet (Ref. 2) and a methane requirement of $7.2 \times 10^{-4} \pm 2.0 \times 10^{-5}$ kg CH_4/kg for soda (Ref. 13).

(cc) Anti-scalant consumption rate of 0.04 kg/t of clean sugar beet (Ref. 2) and a methane requirement of 4.0×10^{-6} kg CH_4/kg for anti-scalant (Refs. 2 and 14 to 16).

(dd) EDTA consumption rate of 0.055 kg/t of clean sugar beet (Ref. 2) and a methane requirement of 1.0×10^{-6} kg CH_4/kg for EDTA (Refs. 2 and 14 to 16).

(ee) Limestone consumption rate of 2.3% of clean sugar beet (Ref. 2), or 23 kg/t of clean sugar beet, and a methane requirement of 2.1×10^{-5} kg CH_4/kg for limestone (Ref. 18).

(ff) Coke consumption rate of 0.18% of clean sugar beet (Ref. 2), or 1.8 kg/t of clean sugar beet, and a direct methane requirement of $9.5 \times 10^{-6} \times 28.1 = 2.7 \times 10^{-4}$ kg CH_4/kg and an indirect methane requirement of 9.2×10^{-3} kg CH_4/kg for coke in the UK in 1996 (Ref. 11).

(gg) Anti-foam consumption rate of 253,344 kg/a (Ref. 2), or 0.20 kg/t of clean sugar beet, and, assuming similarity with anti-scalant, a methane requirement of 4.0×10^{-6} kg CH_4/kg of anti-foam (Refs. 2 and 14 to 16).

(hh) Sulphuric acid (93% concentration) consumption rate of 380,016 kg/a, or 0.30 kg/t of clean sugar beet (Ref. 2) and a methane requirement of $2.7 \times 10^{-4} \pm 3.0 \times 10^{-4}$ kg CH_4/kg for sulphuric acid (Ref. 13).

(ii) Surplus electricity of 20.7 MW for 8,064 hr/a resulting in 600,929 GJ/a of electricity exported for sale, equivalent to 478 MJ/t of clean sugar beet, and a methane requirement of 4.0×10^{-4} kg CH_4/MJ for displaced grid electricity supplies in the UK in 1996 (Ref. 11), less 1.176 x 478 of natural gas used to produce the surplus amount with a direct methane requirement of 3.7×10^{-6} kg CH_4/MJ, an indirect methane requirement of 1.1×10^{-4} kg CH_4/MJ and a total methane requirement of 1.1×10^{-4} kg CH_4/MJ for natural gas in the UK in 1996 (Ref. 11).

(jj) LimeX production rate of 45 kg/t of clean sugar beet (Ref. 2) and a methane requirement 3.9×10^{-6} kg CH_4/kg for lime (Ref. 7).

(kk) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 85.7% to bioethanol.

(ll) Primary energy input of 950,000 GJ for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £38.0 m (Ref. 2) and an estimated total methane requirement of 1.192×10^{-7} kg CH_4/MJ of primary energy input to plant construction (Ref. 16).

(mm) Primary energy input of annual plant maintenance assumed to be 1.5% of primary energy input to plant construction (Ref. 2).

(nn) Average round trip distance of 450 km (Ref. 19) 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. 11).

References

1. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 28 April 2003.

2. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 2 May 2003.

3. Private communication with D. Darby of British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication with G. Punter of British Sugar plc., Peterborough, United Kingdom, 8 May 2003.

5. "British Sugar Field Crop Survey 2001"

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Report No. 20/1, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003, for the Department for the Environment, Food and Rural Affairs, www.defra.

7. "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.

8. "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.

9. "Pesticide Use Survey Reports" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. British Sugar Internal Survey 2001

11. "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.

12. "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.

13. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

14. "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.

15. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

16. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

17. "Carbon and Energy Balances for a Range of Biofuel Options" by M. A. Elsayed, R. Matthews and N. D. Mortimer, B/B6/00784/REP, Energy Technology Support Unit, Harwell, United Kingdom, March 2003, www.shu.ac.uk/rru/projects/biofuels/biofuels.html.

18. "Handbook of Industrial Energy Analysis" by I. Boustead and G. Hancock, Ellis Horwood, Chichester, United Kingdom, 1979.

19. "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.

Spreadsheet for Nitrous Oxide Outputs from Bioethanol Production from Sugar Beet using a Natural Gas-fired Combined Heat and Power Plant with a Gas Turbine (Model 4b)

Functional Unit:	Bioethanol at point of distribution derived from sugar beet using natural gas-fired combined heat and power with a gas turbine during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on a market price for 13.296 tonnes of sugar beet on the farm of £22.00/t (Ref. 1) and an effective price for 1.507 tonnes of sugar beet tops (dry matter) of £10.0/t, based on an average market price of £2.00/t (wet basis) with a 80% moisture content (Ref. 2), substitution of 0.669 tonnes of soil from washing by soil from main sources, substitution of 0.049 tonnes of stones from washing by stones from quarrying, an effective average price for 14.560 tonnes of thin juice (15% solids and 88% sugar purity) of £16.2/t, derived from a price for thick juice (67% solids and 92% sugar purity) of £72.48/t (Ref. 3), and an effective average price for 25.996 tonnes of pulp (97% moisture content) of £2.56/t, derived from an average market price for animal feed pellets (15% moisture content) of £72.50/t (Ref. 2), substitution of 0.566 tonnes of LimeX by agricultural lime, and an assumed price for bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solids and 66.5% sugar purity) of £122.15/t, based on the price of thick juice (Ref. 4).

Contribution	Per Unit	Nitrous Oxide Output (kg N_2O)						Notes
		Direct		Indirect		Total		
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	*ha.a*	*0.371*	*±0.125*	*1.514*	*±0.253*	*1.885*	*±0.283*	(a)
- P Fertiliser	*ha.a*	-	-	*0.004*	*±0.001*	*0.004*	*±0.001*	(b, c)
- K Fertiliser	*ha.a*	-	-	*0.001*	-	*0.001*	-	(c, d)
- Pesticides	*ha.a*	-	-	*0.004*	*±0.001*	*0.004*	*±0.001*	(c, e)
- Herbicide	*ha.a*	-	-	*0.001*	-	*0.001*	-	(c, f)
- Insecticide	*ha.a*	-	-	-	-	-	-	(c, g)
- Seed	*ha.a*	-	-	*0.004*	*±0.001*	*0.004*	*±0.001*	(c, h)
- Diesel Fuel	*ha.a*	*0.005*	*±0.001*	-	-	*0.005*	*±0.001*	(c, i)
Reference System:								
- Diesel Fuel	*ha.a*	*- 0.001*	-	-	-	*- 0.001*	-	(c, j)
Sub-Totals	*ha.a*	*0.375*	*±0.125*	*1.528*	*±0.253*	*1.903*	*±0.283*	
	t be	**0.061**	**±0.020**	**0.248**	**±0.041**	**0.309**	**±0.046**	(k)
Transport:								
- Diesel Fuel	*t ssb*	-	-	-	-	-	-	(l)
	t be	**-**	**-**	**-**	**-**	**-**	**-**	(m)
Washing, Shredding and Diffusion:								
- Natural Gas	*t csb*	-	-	-	-	-	-	(c, n - p)
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	(q)
- Gypsum	*t csb*	-	-	-	-	-	-	(c, r)
- Hydrochloric Acid	*t csb*	-	-	-	-	-	-	(s)
- Formaldehyde	*t csb*	-	-	-	-	-	-	(c, t)
- Biocide	*t csb*	-	-	-	-	-	-	(c, u)
- Foam Oil	*t csb*	-	-	-	-	-	-	(v)
Credits:								
- Soil	*t csb*	-	-	-	-	-	-	(c, w)
- Stones	*t csb*	-	-	-	-	-	-	(c, x)
Sub-Totals	*t csb*	-	-	-	-	-	-	
	t be	**-**	**-**	**-**	**-**	**-**	**-**	(y)
Purification, Concentration, Fermentation, Distillation and Dehydration:								
- Natural Gas	*t csb*	-	-	-	-	-	-	(c,n,p, z)
- Sulphur	*t csb*	-	-	-	-	-	-	(aa)
- Soda	*t csb*	-	-	-	-	-	-	(bb)
- Anti-Scalant	*t csb*	-	-	-	-	-	-	(cc)
- EDTA	*t csb*	-	-	-	-	-	-	(dd)
- Limestone	*t csb*	-	-	-	-	-	-	(ee)
- Coke	*t csb*	-	-	-	-	-	-	(c, ff)
- Anti-Foam	*t csb*	-	-	-	-	-	-	(c, gg)
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	(hh)
Credit:								
- Electricity	*t csb*	-	-	*-0.003*	*±0.001*	*-0.003*	*±0.001*	(c, ii)
- LimeX	*t csb*	-	-	*- 0.001*	-	*- 0.001*	-	(c, jj)
Sub-Totals	*t csb*	-	-	*- 0.004*	*±0.001*	*- 0.004*	*±0.001*	
	t be	**-**	**-**	**- 0.043**	*±0.011*	**- 0.043**	*±0.011*	(kk)
Plant Construction	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(ll)
Plant Maintenance	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(mm)
Distribution	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(nn)
Totals	**t be**	**0.061**	**±0.020**	**0.205**	**±0.042**	**0.266**	**±0.047**	

Biofuel Specifications

Density of bioethanol	= 0.79 kg/l
Net calorific value of bioethanol	= 26.72 MJ/kg
Gross calorific value of bioethanol	= 29.74 MJ/kg

Abbreviations

ha.a	= hectare year
t csb	= tonne of clean sugar beet
t ssb	= tonne of soiled sugar beet
t be	= tonne of bioethanol

Notes

(a) Nitrogen fertiliser application rate of 103.0 kg N/ha.a (Ref. 5) and a direct nitrous oxide requirement of 0.0036 kg N_2O/kg N (Ref. 5), an indirect nitrous oxide requirement of 0.0147 kg N_2O/kg N (Ref. 7) and a total nitrous oxide requirement for ammonium nitrate of 0.0183 kg N_2O/kg N (Ref. 6).

(b) Assuming an error bar of ±15% based on similar analyses (Ref. 8).

(c) Phosphate fertiliser application rates of 38.0 kg P/ha.a (Ref. 5), or 87.0 kg P_2O_5/ ha.a and a total nitrous oxide requirement for phosphate fertiliser of 4.2 x 10^{-5} kg N_2O/kg P_2O_5 (Ref. 7).

(d) Potash fertiliser application rate of 104.0 kg K/ha.a (Ref. 5), or 125.3 kg K_2O/ha.a and a total nitrous oxide requirement for potash fertiliser of 9.4 x 10^{-6} kg N_2O/ kg K_2O (Ref. 7).

(e) Pesticide application rate of 2.90 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.51 x 10^{-3} kg N_2O/kg (Ref. 7).

(f) Herbicide application rate of 0.40 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.51 x 10^{-3} kg N_2O/kg (Ref. 7).

(g) Insecticide application rate of 0.24 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.51 x 10^{-3} kg N_2O/kg (Ref. 7).

(h) Sowing rate of 3.8 kg/ha.a, consisting of 1.2 kg/ha.a of seed and 2.6 kg/ha.a pelletising material (Ref. 10), and a total methane requirement of 0.001 kg N_2O /kg of seed (Ref. 7).

(i) Diesel fuel consumption of 8,870 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides and insecticides, and harvesting (Ref. 2) 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. 11).

(j) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 7) 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. 11).

(k) Land requirement of 0.255 ha.a/t of bioethanol, partitioning between13.296 t of sugar beet at farm with a price of £22/t (Ref. 1) and 1.507 t sugar beet tops (dry matter) with an effective price of £10.00/t, based on an average market price of £2.00/t (wet basis) 80% moisture content (Ref. 2), and partitioning between 14.560 t of thin juice with an effective price of £16.2/t and an effective average price for 25.996 t of pulp with a moisture content of 97% of £2.56/t, derived from an average price for animal feed pellets with a moisture content of 15% of £72.50/t (Ref. 2), and an assumed price of bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solid and 66.5% sugar purity), based on the price of thick juice, giving an allocation of 95.1% x 78.0% x 85.7% = 63.6% to bioethanol.

(l) Average round trip distance of 94 km (Ref. 2) 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. 12).

(m) Soiled sugar beet requirement of 13.296 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(n) Natural gas-fired combined heat and power plant based on a gas turbine with an overall efficiency of 85%, consuming 331,000 MJ/hr of natural gas to provide 67 t/hr or 184,870 MJ/hr of steam (matched to bioethanol plant requirements) and 26.8MW (6.1 MW for bioethanol plant and 20.7 MW surplus) of electricity equal to 26,800 kWh/hr or 96,480 MJ/hr (Ref. 2), resulting in 0.29 MJ of electricity and 0.56 MJ of steam from each MJ of natural gas, or a natural gas consumption rate of 1.176 MJ/MJ of energy output in the form of electricity or steam, and a direct nitrous oxide 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. 11).

(o) Steam consumption rate for washing, shredding and diffusion of 14 t/hr, assumed to be 50% of total steam requirements of sugar plant (Ref. 2), equivalent to 1.176 x 184,870 x 14/67 = 45,428 MJ/hr of natural gas,

and an electricity consumption rate for washing, shredding and diffusion of 3.5 MW (Ref. 2), equivalent to 1.176 x 96,480 x 3.5/26.8 = 14,818 MJ/hr of natural gas, resulting in a total natural gas consumption rate of 60,246 MJ/hr.

(p) Total clean sugar beet input of 1,257,774 t/a and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 2), giving a clean sugar beet input rate of 156 t/hr.

(q) Sulphuric acid (93% concentration) consumption rate of 0.18 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of $2.7 \times 10^{-7} \pm 3.0 \times 10^{-7}$ kg N_2O/kg for sulphuric acid (Ref. 13).

(r) Gypsum (calcium sulphate) consumption rate of 1.06 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of 5.9×10^{-7} kg N_2O/kg for gypsum (Ref. 13).

(s) Hydrochloric acid (100% concentration) consumption rate of 0.025 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of 3.0×10^{-4} kg N_2O/kg for hydrochloric acid (Ref. 13)

(t) Formaldehyde consumption rate of 0.15 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of 6.0×10^{-9} kg N_2O/kg for formaldehyde (Refs. 2 and 14 to 16).

(u) Biocide consumption rate of 0.024 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of 5.0×10^{-9} kg N_2O/kg for biocide (Refs. 2 and 14 to 16).

(v) Foam oil consumption rate of 0.03 kg/t of clean sugar beet (Ref. 2) and, assuming foam oil is similar to refined rapeseed oil, a nitrous oxide requirement of $1.79 \times 10^{-3} \pm 2.20 \times 10^{-4}$ kg N_2O/kg of refined rapeseed oil (Ref. 17).

(w) Soil recovery rate of 5.32% of clean sugar beet (Ref. 2), or 53.2 kg/t of clean sugar beet, and, assuming soil production is similar to sand extraction, a nitrous oxide requirement of 4.2×10^{-8} kg N_2O/kg for sand (Ref. 18).

(x) Stone recovery rate of 0.39% of clean sugar beet (Ref. 2), or 3.9 kg/t of clean sugar beet, and, assuming stone production is similar to sand extraction, a nitrous oxide requirement of 4.2×10^{-8} kg N_2O/kg for sand (Ref. 18).

(y) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(z) Steam consumption rate for purification of 1 t/hr and for fermentation, distillation and dehydration of 38 t/hr (Ref. 2), resulting in a total steam consumption rate of 39 t/hr or equivalent to 1.176 x 184,870 x 39/67 = 126,550 MJ/hr of natural gas, and an electricity consumption rate for diffusion of 1.4 MW and for fermentation, distillation and dehydration of 1.2 MW (Ref. 2), equivalent to 1.176 x 96,480 x 2.6/26.8 = 11,007 MJ/hr of natural gas, resulting in a total natural gas consumption rate for diffusion of 137,557 MJ/hr.

(aa) Sulphur (as SO_2) consumption rate of 0.13 kg/t of clean sugar beet and a nitrous oxide requirement of $6.6 \times 10^{-6} \pm 1.8 \times 10^{-6}$ kg N_2O/kg for sulphur (Ref. 13).

(bb) Soda (sodium carbonate) consumption rate of 0.05 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of $1.8 \times 10^{-5} \pm 0.5 \times 10^{-6}$ kg N_2O/kg for soda (Ref. 13).

(cc) Anti-scalant consumption rate of 0.04 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of 6.0×10^{-8} kg N_2O/kg for anti-scalant (Refs. 2 and 14 to 16).

(dd) EDTA consumption rate of 0.055 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of 2.0×10^{-8} kg N_2O/kg for EDTA (Refs. 2 and 14 to 16).

(ee) Limestone consumption rate of 2.3% of clean sugar beet (Ref. 2), or 23 kg/t of clean sugar beet, and a nitrous oxide requirement of 3.5×10^{-7} kg N_2O/kg for limestone (Ref. 18).

(ff) Coke consumption rate of 0.18% of clean sugar beet (Ref. 2), or 1.8 kg/t of clean sugar beet, and a direct nitrous oxide requirement of $4.0 \times 10^{-9} \times 28.1 = 1.1 \times 10^{-7}$ kg N_2O/kg and an indirect nitrous oxide requirement of 1.3×10^{-6} kg N_2O/kg for coke in the UK in 1996 (Ref. 11).

(gg) Anti-foam consumption rate of 253,344 kg/a (Ref. 2), or 0.20 kg/t of clean sugar beet, and, assuming similarity with anti-scalant, a nitrous oxide requirement of 6.0×10^{-8} kg N_2O/kg of anti-foam (Refs. 2 and 14 to 16).

(hh) Sulphuric acid (93% concentration) consumption rate of 380,016 kg/a, or 0.30 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of $2.0 \times 10^{-7} \pm 3.0 \times 10^{-7}$ kg N_2O/kg for sulphuric acid (Ref. 13).

(ii) Surplus electricity of 20.7 MW for 8,064 hr/a resulting in 600,929 GJ/a of electricity exported for sale, equivalent to 478 MJ/t of clean sugar beet, and a nitrous oxide requirement of 5.6×10^{-6} kg N_2O/MJ for displaced grid electricity supplies in the UK in 1996 (Ref. 11), less 1.176 x 478 of natural gas used to produce the surplus amount with a direct nitrous oxide requirement of 8.9×10^{-8} kg N_2O/MJ, an indirect nitrous oxide requirement of 1.1×10^{-8} kg N_2O/MJ and a total nitrous oxide requirement of 1.0×10^{-7} kg N_2O/MJ for natural gas in the UK in 1996 (Ref. 11).

(jj) LimeX production rate of 45 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement 1.6 x 10^{-5} kg N_2O/kg for lime (Ref. 7).

(kk) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 85.7% to bioethanol.

(ll) Primary energy input of 950,000 GJ for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £38.0 m (Ref. 2) and an estimated total nitrous oxide requirement of 1.866 x 10^{-9} kg N_2O/MJ of primary energy input to plant construction (Ref. 16).

(mm) Nitrous oxide output of annual plant maintenance assumed to be 1.5% of primary energy input to plant construction (Ref. 2).

(nn) Average round trip distance of 450 km (Ref. 19) 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. 11).

References

1. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 28 April 2003.

2. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 2 May 2003.

3. Private communication with D. Darby of British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication with G. Punter of British Sugar plc., Peterborough, United Kingdom, 8 May 2003.

5. "British Sugar Field Crop Survey 2001"

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Report No. 20/1, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003, for the Department for the Environment, Food and Rural Affairs, www.defra.

7. "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.

8. "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.

9. "Pesticide Use Survey Reports" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. British Sugar Internal Survey 2001

11. "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.

12. "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.

13. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

14. "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.

15. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

16. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

17. "Carbon and Energy Balances for a Range of Biofuel Options" by M. A. Elsayed, R. Matthews and N. D. Mortimer, B/B6/00784/REP, Energy Technology Support Unit, Harwell, United Kingdom, March 2003, www.shu.ac.uk/rru/projects/biofuels/biofuels.html.

18. "Handbook of Industrial Energy Analysis" by I. Boustead and G. Hancock, Ellis Horwood, Chichester, United Kingdom, 1979.

19. "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.

<u>Spreadsheet for Total Greenhouse Gas Outputs from Bioethanol Production from Sugar Beet using a Natural Gas-fired Combined Heat and Power Plant with a Gas Turbine</u> (Model 4b)

Functional Unit:	Bioethanol at point of distribution derived from sugar beet using natural gas-fired combined heat and power with a gas turbine during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on a market price for 13.296 tonnes of sugar beet on the farm of £22.00/t (Ref. 1) and an effective price for 1.507 tonnes of sugar beet tops (dry matter) of £10.0/t, based on an average market price of £2.00/t (wet basis) with a 80% moisture content (Ref. 2), substitution of 0.669 tonnes of soil from washing by soil from main sources, substitution of 0.049 tonnes of stones from washing by stones from quarrying, an effective average price for 14.560 tonnes of thin juice (15% solids and 88% sugar purity) of £16.2/t, derived from a price for thick juice (67% solids and 92% sugar purity) of £72.48/t (Ref. 3), and an effective average price for 25.996 tonnes of pulp (97% moisture content) of £2.56/t, derived from an average market price for animal feed pellets (15% moisture content) of £72.50/t (Ref. 2), substitution of 0.566 tonnes of LimeX by agricultural lime, and an assumed price for bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solids and 66.5% sugar purity) of £122.15/t, based on the price of thick juice (Ref. 4).

Contribution	Per Unit	Total Greenhouse Gas Output (kg eq CO_2)						Notes
		Direct		Indirect		Total		
		Value	Range	Value	Range	Value	Range	
Cultiv. and Harvesting:								
- N Fertiliser	*ha.a*	*119*	*±40*	*690*	*±86*	*809*	*±95*	(a)
- P Fertiliser	*ha.a*	-	-	*62*	*±9*	*62*	*±9*	(a)
- K Fertiliser	*ha.a*	-	-	*57*	*±9*	*57*	*±9*	(a)
- Pesticides	*ha.a*	-	-	*15*	*±2*	*15*	*±2*	(a)
- Herbicide	*ha.a*	-	-	*2*	-	*2*	-	(a)
- Insecticide	*ha.a*	-	-	*1*	-	*1*	-	(a)
- Seed	*ha.a*	-	-	*8*	*±1*	*8*	*±1*	(a)
- Diesel Fuel	*ha.a*	*610*	*±96*	*76*	*±33*	*686*	*±102*	(a)
Reference System:								
- Diesel Fuel	*ha.a*	*- 63*	*±10*	*- 7*	*±3*	*- 70*	*±10*	(a)
Sub-Totals	*ha.a*	*666*	*±104*	*904*	*±93*	*1,570*	*±140*	
	t be	**108**	**±17**	**147**	**±15**	**255**	**±23**	(b)
Transport:								
- Diesel Fuel	*t ssb*	*5*	-	*2*	-	*7*	-	(a)
	t be	**44**	**-**	**18**	**-**	**62**	**-**	(c)
Washing, Shredding and Diffusion:								
- Natural Gas	*t csb*	*20*	*±3*	*2*	*±1*	*22*	*±3*	(a)
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	(a)
- Gypsum	*t csb*	-	-	-	-	-	-	(a)
- Hydrochloric Acid	*t csb*	-	-	-	-	-	-	(a)
- Formaldehyde	*t csb*	-	-	-	-	-	-	(a)
- Biocide	*t csb*	-	-	-	-	-	-	(a)
- Foam Oil	*t csb*	-	-	-	-	-	-	(a)
Credits:								
- Soil	*t csb*	-	-	-	-	-	-	(a)
- Stones	*t csb*	-	-	-	-	-	-	(a)
Sub-Totals	*t csb*	*20*	*±3*	*2*	*±1*	*22*	*±3*	
	t be	**168**	**±25**	**17**	**±8**	**185**	**±26**	(d)
Purification, Concentration, Fermentation, Distillation and Dehydration:								
- Natural Gas	*t csb*	*46*	*±7*	*4*	*±1*	*50*	*±7*	(a)
- Sulphur	*t csb*	-	-	-	-	-	-	(a)
- Soda	*t csb*	-	-	-	-	-	-	(a)
- Anti-Scalant	*t csb*	-	-	-	-	-	-	(a)
- EDTA	*t csb*	-	-	-	-	-	-	(a)
- Limestone	*t csb*	-	-	-	-	-	-	(a)
- Coke	*t csb*	*5*	*±1*	*1*	-	*6*	*±1*	(a)
- Anti-Foam	*t csb*	-	-	-	-	-	-	(a)
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	(a)
Credit:								
- Electricity	*t csb*	*29*	*±4*	*- 74*	*±11*	*- 45*	*±12*	(a)
- LimeX	*t csb*	-	-	*- 8*	*±1*	*- 8*	*±1*	(a)
Sub-Totals	*t csb*	**80**	*±8*	*- 77*	*±11*	*3*	*±14*	
	t be	**862**	**±86**	**- 830**	**±118**	**32**	**±146**	(e)
Plant Construction	**t be**	**-**	**-**	**24**	**±4**	**24**	**±4**	(a)
Plant Maintenance	**t be**	**-**	**-**	**7**	**±1**	**7**	**±1**	(a)
Distribution	**t be**	**25**	**±1**	**7**	**±1**	**32**	**±1**	(a)
Totals	**t be**	**1,207**	**±91**	**- 610**	**±119**	**597**	**±150**	

Biofuel Specifications

Density of bioethanol	= 0.79 kg/l
Net calorific value of bioethanol	= 26.72 MJ/kg
Gross calorific value of bioethanol	= 29.74 MJ/kg

Abbreviations

ha.a	= hectare year
t csb	= tonne of clean sugar beet
t ssb	= tonne of soiled sugar beet
t be	= tonne of bioethanol

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 0.255 ha.a/t of bioethanol, partitioning between13.296 t of sugar beet at farm with a price of £22/t (Ref. 1) and 1.507 t sugar beet tops (dry matter) with an effective price of £10.00/t, based on an average market price of £2.00/t (wet basis) 80% moisture content (Ref. 2), and partitioning between 14.560 t of thin juice with an effective price of £16.2/t and an effective average price for 25.996 t of pulp with a moisture content of 97% of £2.56/t, derived from an average price for animal feed pellets with a moisture content of 15% of £72.50/t (Ref. 2), and an assumed price of bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solid and 66.5% sugar purity), based on the price of thick juice, giving an allocation of 95.1% x 78.0% x 85.7% = 63.6% to bioethanol.

(c) Soiled sugar beet requirement of 13.296 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(d) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(e) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 85.7% to bioethanol.

APPENDIX H: Model 8

Spreadsheet for Primary Energy Inputs to Bioethanol Production from Sugar Beet using a Straw-fired Combined Heat and Power Plant with a Steam Turbine (Model 8)

Functional Unit:	Bioethanol at point of distribution derived from sugar beet using straw-fired combined heat and power with a steam turbine during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on a market price for 13.296 tonnes of sugar beet on the farm of £22.00/t (Ref. 1) and an effective price for 1.507 tonnes of sugar beet tops (dry matter) of £10.0/t, based on an average market price of £2.00/t (wet basis) with a 80% moisture content (Ref. 2), substitution of 0.669 tonnes of soil from washing by soil from main sources, substitution of 0.049 tonnes of stones from washing by stones from quarrying, an effective average price for 14.560 tonnes of thin juice (15% solids and 88% sugar purity) of £16.2/t, derived from a price for thick juice (67% solids and 92% sugar purity) of £72.48/t (Ref. 3), and an effective average price for 25.996 tonnes of pulp (97% moisture content) of £2.56/t, derived from an average market price for animal feed pellets (15% moisture content) of £72.50/t (Ref. 2), substitution of 0.566 tonnes of LimeX by agricultural lime, and an assumed price for bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solids and 66.5% sugar purity) of £122.15/t, based on the price of thick juice (Ref. 4).

Contribution	Per Unit	Primary Energy Input (MJ)								Notes
		Direct		Indirect		Feedstock		Total		
		Value	Range	Value	Range	Value	Range	Value	Range	
Cultivation and Harvest:										
- N Fertiliser	*ha.a*	-	-	*1,443*	*±577*	*2,739*	*±109*	*4,182*	*±587*	(a)
- P Fertiliser	*ha.a*	-	-	*1,375*	*±206*	-	-	*1,375*	*±206*	(b, c)
- K Fertiliser	*ha.a*	-	-	*1,165*	*±175*	-	-	*1,165*	*±175*	(c, d)
- Pesticides	*ha.a*	-	-	*795*	*±119*	-	-	*795*	*±119*	(c, e)
- Herbicide	*ha.a*	-	-	*110*	*±16*	-	-	*110*	*±16*	(c, f)
- Insecticide	*ha.a*	-	-	*66*	*±10*	-	-	*66*	*±10*	(c, g)
- Seed	*ha.a*	-	-	*135*	*±20*	-	-	*135*	*±20*	(c, h)
- Diesel Fuel	*ha.a*	*8,870*	*±1,402*	*976*	*±465*	-	-	*9,846*	*±1,477*	(c, i)
Reference System:										
- Diesel Fuel	*ha.a*	*- 922*	*±146*	*- 101*	*±48*	-	-	*- 1,023*	*±154*	(c, j)
Sub-Totals	*ha.a*	*7,948*	*±1,410*	*5,964*	*±800*	*2,739*	*±109*	*16,651*	*±1,624*	
	t be	**1,289**	**±229**	**967**	**±130**	**444**	**±18**	**2,700**	**±263**	(k)
Transport:										
- Diesel Fuel	*t ssb*	*77*	*±3*	*27*	*±3*	-	-	*104*	*±4*	(l)
	t be	**684**	**±27**	**240**	**±27**	**-**	**-**	**924**	**±36**	(m)
Straw Baling:										
- N Fertiliser	*ha.a*	-	-	*830*	*±332*	*1,577*	*±63*	*2,407*	*±338*	(n)
- P Fertiliser	*ha.a*	-	-	*387*	*±58*	-	-	*381*	*±58*	(c, o)
- K Fertiliser	*ha.a*	-	-	*1,151*	*±173*	-	-	*1,129*	*±173*	(c, p)
- Diesel Fuel	*ha.a*	*343*	*±51*	*25*	*±4*	-	-	*368*	*±51*	(c, q)
- Machinery	*ha.a*	-	-	*403*	*±60*	-	-	*403*	*±60*	(c, r)
- Twine	*ha.a*	-	-	-	-	*94*	*±14*	*94*	*±14*	(c,s)
- Maintenance	*ha.a*	-	-	*175*	*±26*	-	-	*175*	*±26*	(c, t)
Sub-Totals	*ha.a*	*343*	*±51*	*2,971*	*±512*	*1,671*	*±63*	*4,985*	*±518*	
	t be	**181**	**±27**	**1,567**	**±270**	**881**	**±33**	**2,629**	**±273**	(u - w)
Straw Transport:										
- Diesel Fuel	*t bws*	*66*	*±2*	*23*	*±3*	-	-	*89*	*±4*	(x)
	t be	**120**	**±4**	**42**	**±5**	**-**	**-**	**162**	**±7**	(u, v, y)
Straw Storage:										
- Diesel Fuel	*t bws*	*66*	*±10*	*7*	*±3*	-	-	*73*	*±11*	(c, z)
- Sheeting	*t bws*	-	-	*94*	*±14*	*92*	*±14*	*186*	*±20*	(c, aa)
- Machinery	*t bws*	-	-	*21*	*±3*	-	-	*21*	*±3*	(c, bb)
- Maintenance	*t bws*	-	-	*7*	*±1*	-	-	*7*	*±1*	(c, cc)
Sub-Totals	*t bws*	*66*	*±10*	*129*	*±15*	*92*	*±14*	*287*	*±23*	
	t be	**120**	**±18**	**235**	**±27**	**168**	**±26**	**523**	**±42**	(u, v, y)
Wash, Shred and Diff.:										
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	-	-	(c, dd)
- Gypsum	*t csb*	-	-	-	-	-	-	-	-	(c, ee)
- Hydrochlor. Acid	*t csb*	-	-	*1*	-	-	-	*1*	-	(c, ff)
- Formaldehyde	*t csb*	-	-	*1*	-	-	-	*1*	-	(c, gg)
- Biocide	*t csb*	-	-	-	-	-	-	-	-	(c, hh)
- Foam Oil	*t csb*	-	-	-	-	-	-	-	-	(c, ii)
Credits:										
- Soil	*t csb*	-	-	*- 4*	*± 1*	-	-	*- 4*	*± 1*	(c, jj)
- Stones	*t csb*	-	-	-	-	-	-	-	-	(c, kk)
Sub-Totals	*t csb*	-	-	*- 2*	*±1*	-	-	*- 2*	*±1*	
	t be	**-**	-	**- 17**	**±8**	**-**	**-**	**- 17**	**±8**	(ll)
Purif., Conc., Ferment., Distill. and Dehydration:										
- Sulphur	*t csb*	-	-	*1*	-	-	-	*1*	-	(c, mm)
- Soda	*t csb*	-	-	*1*	-	-	-	*1*	-	(c, nn)
- Anti-Scalant	*t csb*	-	-	*1*	-	-	-	*1*	-	(c, oo)
- EDTA	*t csb*	-	-	-	-	-	-	-	-	(c, pp)
- Limestone	*t csb*	-	-	*13*	*±2*	-	-	*13*	*±2*	(c, qq)
- Coke	*t csb*	*51*	*±9*	*16*	*±5*	-	-	*67*	*±10*	(c, rr)
- Anti-Foam	*t csb*	-	-	*6*	*±1*	-	-	*6*	*±1*	(c, ss)
- Sulphuric Acid	*t csb*	-	-	*1*	*±1*	-	-	*1*	*±1*	(c, tt)
Credit:										
- Electricity	*t csb*	*- 2,140*	*±321*	-	-	-	-	*- 2,140*	*±321*	(c, uu)
- LimeX	*t csb*	-	-	*- 94*	*±14*	-	-	*- 94*	*±14*	(c, vv)
Sub-Totals	*t csb*	*- 2,089*	*±321*	*- 55*	*±15*	-	-	*- 2,144*	*±321*	
	t be	**- 22,518**	**±3,461**	**- 593**	**±162**	**-**	**-**	**- 23,110**	**±3,465**	(ww)
Plant Construction	**t be**	**-**	**-**	**1,314**	**±144**	**-**	**-**	**1,314**	**±144**	(xx, yy)
Plant Maintenance	**t be**	**-**	**-**	**456**	**±52**	**-**	**-**	**456**	**±52**	(xx - zz)
Ash Disposal:	*t ash*	66	±2	23	±3	-	-	89	±4	(ab)
	t be	**6**	**-**	**2**	-	**-**	**-**	**8**	**-**	(ac)
Distribution	**t be**	**369**	**±14**	**129**	**±16**	**-**	**-**	**498**	**±21**	(ad)
Totals	**t be**	**- 19,749**	**±3,469**	**4,340**	**±378**	**1,493**	**±46**	**- 13,916**	**±3,490**	

Biofuel Specifications

Density of bioethanol	= 0.79 kg/l
Net calorific value of bioethanol	= 26.72 MJ/kg
Gross calorific value of bioethanol	= 29.74 MJ/kg

Abbreviations

ha.a	= hectare year
t ssb	= tonne of soiled sugar beet
t csb	= tonne of clean sugar beet
t be	= tonne of bioethanol
t bws	= tonne of baled wheat straw
t ash	= tonne of ash

Notes

(a) Nitrogen fertiliser application rate of 103.0 kg N/ha.a (Ref. 5) 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 nitrogen fertiliser (Ref. 6).

(b) Phosphate fertiliser application rates of 38.0 kg P/ha.a (Ref. 5), or 87.0 kg P_2O_5/ ha.a assuming 2.290 kg P_2O_5/kg P, and a total energy requirement for phosphate fertiliser of 15.8 MJ/kg P_2O_5 (Ref. 7).

(c) Assuming an error bar of ±15% based on similar analyses (Ref. 8).

(d) Potash fertiliser application rate of 104.0 kg K/ha.a (Ref. 5), or 125.3 kg K_2O/ha.a assuming 1.205 kg K_2O/kg K, and a total energy requirement for potash fertiliser of 9.3 MJ/ kg K_2O (Ref. 7).

(e) Pesticide application rate of 2.90 kg/ha.a (Ref. 9) and a total energy requirement for general pesticides, herbicides and fungicides of 274.1 MJ/kg (Ref. 7).

(f) Herbicide application rate of 0.40 kg/ha.a (Ref. 9) and a total energy requirement for general pesticides, herbicides and fungicides of 274.1 MJ/kg (Ref. 7).

(g) Insecticide application rate of 0.24 kg/ha.a (Ref. 9) and a total energy requirement for general pesticides, herbicides and fungicides of 274.1 MJ/kg (Ref. 7).

(h) Sowing rate of 3.8 kg/ha.a, consisting of 1.2 kg/ha.a of seed and 2.6 kg/ha.a pelletising material (Ref. 10), and a total energy requirement of 35.5 MJ/kg of seed (Ref. 7).

(i) Diesel fuel consumption of 8,870 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides and insecticides, and harvesting (Ref. 2) and a gross energy requirement of 1.110 MJ/MJ for diesel fuel in the UK in 1996 (Ref. 11).

(j) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 7) and a gross energy requirement of 1.110 MJ/MJ for diesel fuel in the UK in 1996 (Ref. 11).

(k) Land requirement of 0.255 ha.a/t of bioethanol, partitioning between13.296 t of sugar beet at farm with a price of £22/t (Ref. 1) and 1.507 t sugar beet tops (dry matter) with an effective price of £10.00/t, based on an average market price of £2.00/t (wet basis) 80% moisture content (Ref. 2), and partitioning between 14.560 t of thin juice with an effective price of £16.2/t and an effective average price for 25.996 t of pulp with a moisture content of 97% of £2.56/t, derived from an average price for animal feed pellets with a moisture content of 15% of £72.50/t (Ref. 2), and an assumed price of bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solid and 66.5% sugar purity), based on the price of thick juice, giving an allocation of 95.1% x 78.0% x 85.7% = 63.6% to bioethanol.

(l) Average round trip distance of 94 km (Ref. 2) 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. 12).

(m) Soiled sugar beet requirement of 13.296 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(n) Ammonium nitrate fertiliser application rate of 59.31 kg N /ha.a to replace straw removal, based on Canadian data (Ref. 21) adjusted pro rata to an average wheat straw yield of 3.5 t/ha.a (Ref.1) with 2.28 t straw collected for fuel from 0.651 ha.a/t bioethanol, 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 (Ref. 6).

(o) Phosphate fertiliser application rate of 24.54 kg P_2O_5/ ha.a to replace straw removal, based on Canadian data (Ref. 20) adjusted pro rata to an average wheat straw yield of 3.5 t/ha.a (Ref.1) with 2.28 t straw collected for fuel from 0.651 ha.a/t bioethanol, and a total energy requirement for phosphate fertiliser of 15.8 MJ/kg P_2O_5 (Ref. 7).

(p) Potash fertiliser application rate of 123.8 kg K_2O/ha.a to replace straw removal, based on Canadian data (Ref. 20) adjusted pro rata to an average wheat straw yield of 3.5 t/ha.a (Ref.1) with 2.28 t straw collected for fuel from 0.651 ha.a/t bioethanol, and a total energy requirement for potash fertiliser of 9.3 MJ/ kg K_2O (Ref. 7).

(q) Diesel fuel consumption for baling of 215 MJ/ha.a and loading in the field of 128 MJ/ha.a, based on data for straw fuel recovery (Ref. 21) adjusted for collection of 2.28 t straw collected for fuel from 0.651 ha.a/t bioethanol, and a gross energy requirement of 1.110 MJ/MJ for diesel fuel in the UK in 1996 (Ref. 11).

(r) Primary energy input to manufacture of tractor for baling of 52 MJ/ha.a, Hesston baler of 312 MJ/ha.a and telescopic handler for loading in field of 41 MJ/ha.a, based on data for straw fuel recovery (Ref. 21) adjusted for collection of 2.28 t straw from 0.651 ha.a/t bioethanol.

(s) Primary energy input to manufacture of baling twine of 94.3 MJ/ha.a, based on data for straw fuel recovery (Ref. 21) adjusted for collection of 2.28 t straw from 0.651 ha.a/t bioethanol.

(t) Primary energy input to maintenance and repair of tractor for baling of 13.25 MJ/ha.a, of Hesston baler of 147 MJ/ha.a and of telescopic handler for loading in the field of 14.1MJ/ha.a, based on data for straw fuel recovery (Ref. 21) adjusted for collection of 2.28 t straw from 0.0.651 ha.a/t bioethanol.

(u) Straw-fired combined heat and power plant based on a steam turbine with an overall efficiency of 85% and a load factor of 91%, consuming 202,827 t of straw (at 15% moisture content and 14.8 MJ/kg calorific value) to provide 67 t/hr or 186,126 MJ/hr of steam (matched to bioethanol plant requirements) and 36 MW (6.1 MW for bioethanol plant and 29.9 MW surplus) of electricity equal to 130,288 MJ/hr (Ref. 2). This provides total heat supplies of 1,193 MJ/t of clean sugar beet and total electricity supplies of 835 MJ/t of clean sugar beet (consisting of 141 MJ/t of clean sugar beet for bioethanol processing and 964 MJ/t of clean sugar beet of surplus for sale). Assuming 11% losses during baling and transport, 227,640 t of straw are required. Heat and electricity supplied by a straw-fired combined heat and power plant for washing, shredding and diffusion which requires 14 t/hr of steam, assumed to be 50% of total steam requirements of sugar plant (Ref. 2), equivalent to 186,126 x 14/67 = 38,892 MJ/hr, and an electricity consumption rate for washing, shredding and diffusion of 3.5 MW (Ref. 2). Heat and electricity supplied by a straw-fired combined heat and power plant for a steam consumption rate for purification of 1 t/hr and for fermentation, distillation and dehydration of 38 t/hr (Ref. 2), resulting in a total steam consumption rate of 39 t/hr or equivalent to 186,126 x 39/67 = 108,342 MJ/hr, and an electricity consumption rate for diffusion of 1.4 MW and for fermentation, distillation and dehydration of 1.2 MW (Ref. 2).

(v) Total clean sugar beet input of 1,257,774 t/a and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 2), giving a clean sugar beet input rate of 156 t/hr.

(w) Land requirement of 0.651 ha.a/t bioethanol and partitioning, based on relative energy, with heat and electricity measured on an equivalent basis, to washing, shredding and diffusion (25%), to purification, concentration, fermentation, distillation and dehydration (75%), and allocation between bioethanol, pulp and vinasses (66.8%), and between bioethanol and vinasses (85.7%) resulting in a total allocation to bioethanol of (25% x 66.8%)+ (75% x 85.7%) = 81%.

(x) Average round trip distance of 80 km (Ref. 20) 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. 12).

(y) Baled straw requirement of 2.25 t/t bioethanol and partitioning, based on relative energy, with heat and electricity measured on an equivalent basis, , to washing, shredding and diffusion (25%), to purification, concentration, fermentation, distillation and dehydration (75%), and allocation between bioethanol, pulp and vinasses (66.8%), and between bioethanol and vinasses (85.7%) resulting in a total allocation to bioethanol of (25% x 66.8%)+ (75% x 85.7%) = 81%.

(z) Diesel fuel consumption for baled straw handling in storage of 65.8 MJ/t of baled wheat straw (Ref. 21) and a gross energy requirement of 1.110 MJ/MJ for diesel fuel in the UK in 1996 (Ref. 11).

(aa) Based on 2 tonnes of polyethylene sheeting used to protect each storage stack of 1,000 tonnes of baled wheat straw, with a life of 1 year and a direct energy requirement of 47 MJ/kg and a feedstock energy requirement of 46 MJ/kg for low density polyethylene (Ref. 21).

(bb) Primary energy input for manufacture of telescopic handler of 21.0 MJ/t of baled wheat straw (Ref. 21).

(cc) Primary energy input to maintenance and repair of telescopic handler of 7.2 MJ/t of baled wheat straw (Ref. 21).

(dd) Sulphuric acid (93% concentration) consumption rate of 0.18 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 2.4 $\pm$ 2.7 MJ/kg for sulphuric acid (Ref. 13).

(ee) Gypsum (calcium sulphate) consumption rate of 1.06 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 1 MJ/kg for gypsum (Ref. 13).

(ff) Hydrochloric acid (100% concentration) consumption rate of 0.025 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 40 $\pm$ 3 MJ/kg for hydrochloric acid (Ref. 13).

(gg) Formaldehyde consumption rate of 0.15 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 3 MJ/kg for formaldehyde (Refs. 2 and 14 to 16).

(hh) Biocide consumption rate of 0.024 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 3 MJ/kg for biocide (Refs. 2 and 14 to 16).

(ii) Foam oil consumption rate of 0.03 kg/t of clean sugar beet (Ref. 2) and, assuming foam oil is similar to refined rapeseed oil, an energy requirement of 11 ± 1 MJ/kg of refined rapeseed oil (Ref. 17).

(jj) Soil recovery rate of 5.32% of clean sugar beet (Ref. 2), or 53.2 kg/t of clean sugar beet, and, assuming soil production is similar to sand extraction, an energy requirement of 0.08 MJ/kg for sand (Ref. 18).

(kk) Stone recovery rate of 0.39% of clean sugar beet (Ref. 2), or 3.9 kg/t of clean sugar beet, and, assuming stone production is similar to sand extraction, an energy requirement of 0.08 MJ/kg for sand (Ref. 18).

(ll) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(mm) Sulphur (as SO_2) consumption rate of 0.13 kg/t of clean sugar beet and an energy requirement of 11 ± 3 MJ/kg for sulphur (Ref. 13).

(nn) Soda (sodium carbonate) consumption rate of 0.05 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 29 ± 8 MJ/kg for soda (Ref. 13).

(oo) Anti-scalant consumption rate of 0.04 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 32 MJ/kg for anti-scalant (Refs. 2 and 14 to 16).

(pp) EDTA consumption rate of 0.055 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 8 MJ/kg for EDTA (Refs. 2 and 14 to 16).

(qq) Limestone consumption rate of 2.3% of clean sugar beet (Ref. 2), or 23 kg/t of clean sugar beet, and an energy requirement of 0.58 MJ/kg for limestone (Ref. 18).

(rr) Coke consumption rate of 0.18% of clean sugar beet (Ref. 2), or 1.8 kg/t of clean sugar beet, and a gross energy requirement of 1.316 x 28.1 = 37 MJ/kg for coke in the UK in 1996 (Ref. 11).

(ss) Anti-foam consumption rate of 253,344 kg/a (Ref. 2), or 0.20 kg/t of clean sugar beet, and, assuming similarity with anti-scalant, an energy requirement of 32 MJ/kg of anti-foam (Refs. 2 and 14 to 16).

(tt) Sulphuric acid (93% concentration) consumption rate of 380,016 kg/a, or 0.30 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 2.4 ± 2.7 MJ/kg for sulphuric acid (Ref. 13).

(uu) Surplus electricity of 29.9 MW for 8,064 hr/a resulting in 868,009 GJ/a of electricity exported for sale, equivalent to 694 MJ/t of clean sugar beet, and an energy requirement of 3.083 MJ/MJ for displaced grid electricity supplies in the UK in 1996 (Ref. 11)

(vv) LimeX production rate of 45 kg/t of clean sugar beet (Ref. 2) and an energy requirement of 2.1 MJ/kg for lime (Ref. 7).

(ww) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 85.7% to bioethanol.

(xx) Primary energy input of 950,000 GJ for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £38.0 m (Ref. 2) and an energy intensity of 25 MJ/£ (Ref. 14).

(yy) Primary energy input of 2,588,400 GJ for construction of a straw-fired combined heat and power plant with a 67t/hr steam output and a 36 MW rated electricity output, based pro rata on data for a straw-fired combined heat and power plant with a 13.0 MW rated heat output and a 5.0 MW rated electricity output (Ref. 21), with a 25 year life.

(zz) Primary energy input of annual plant maintenance assumed to be 1.5% of primary energy input to plant construction (Ref.2).

(ab) Ash sent for spreading as a fertiliser on fields at an average round trip distance of 80km (Ref.21) 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. 12).

(ac) Ash output of 5.5% of straw fuel feed (Ref. 21) and straw requirement of 2.03 t/t of bioethanol.

(ad) Average round trip distance of 450 km (Ref. 19) 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. 12).

References

1. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 28 April 2003.

2. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 2 May 2003.

3. Private communication with D. Darby of British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication with G. Punter of British Sugar plc., Peterborough, United Kingdom, 8 May 2003.

5. "British Sugar Field Crop Survey 2001"

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Report No. 20/1, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003, for the Department for the Environment, Food and Rural Affairs, www.defra.

7. "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.

8. "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.

9. "Pesticide Use Survey Reports" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. British Sugar Internal Survey 2001

11. "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.

12. "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.

13. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

14. "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.

15. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

16. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

17. "Carbon and Energy Balances for a Range of Biofuel Options" by M. A. Elsayed, R. Matthews and N. D. Mortimer, B/B6/00784/REP, Energy Technology Support Unit, Harwell, United Kingdom, March 2003, www.shu.ac.uk/rru/projects/biofuels/biofuels.html.

18. "Handbook of Industrial Energy Analysis" by I. Boustead and G. Hancock, Ellis Horwood, Chichester, United Kingdom, 1979.

19. "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.

20. "Assessment of Net Emissions of Greenhouse Gases from Ethanol-Blended Gasolines in Canada: Lignocellulosic Feedstocks" R-2000-2, Levelton Engineering Ltd., Richmond, Canada, December 1998.

21. "Energy and Carbon Analysis of Using Straw as a Fuel" by J. F. Grant, R. Hetherington, R. E. Horne and N. D. Mortimer, Report ETSU B/M4/00487/01, Energy Technology Support Unit, Harwell, United Kingdom, 1995.

<u>Spreadsheet for Carbon Dioxide Outputs from Bioethanol Production from Sugar Beet using a Straw-fired Combined Heat and Power Plant with a Steam Turbine</u> (Model 8)

Functional Unit:	Bioethanol at point of distribution derived from sugar beet using natural steam-fired combined heat and power with a steam turbine during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on a market price for 13.296 tonnes of sugar beet on the farm of £22.00/t (Ref. 1) and an effective price for 1.507 tonnes of sugar beet tops (dry matter) of £10.0/t, based on an average market price of £2.00/t (wet basis) with a 80% moisture content (Ref. 2), substitution of 0.669 tonnes of soil from washing by soil from main sources, substitution of 0.049 tonnes of stones from washing by stones from quarrying, an effective average price for 14.560 tonnes of thin juice (15% solids and 88% sugar purity) of £16.2/t, derived from a price for thick juice (67% solids and 92% sugar purity) of £72.48/t (Ref. 3), and an effective average price for 25.996 tonnes of pulp (97% moisture content) of £2.56/t, derived from an average market price for animal feed pellets (15% moisture content) of £72.50/t (Ref. 2), substitution of 0.566 tonnes of LimeX by agricultural lime, and an assumed price for bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solids and 66.5% sugar purity) of £122.15/t, based on the price of thick juice (Ref. 4).

Contribution	Per Unit	Carbon Dioxide Output (kg CO_2)						Notes
		Direct		Indirect		Total		
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	*ha.a*	-	-	*196*	*±28*	*196*	*±28*	(a)
- P Fertiliser	*ha.a*	-	-	*61*	*±9*	*61*	*±9*	(b, c)
- K Fertiliser	*ha.a*	-	-	*57*	*±9*	*57*	*±9*	(c, d)
- Pesticides	*ha.a*	-	-	*14*	*±2*	*14*	*±2*	(c, e)
- Herbicide	*ha.a*	-	-	*2*	-	*2*	-	(c, f)
- Insecticide	*ha.a*	-	-	*1*	-	*1*	-	(c, g)
- Seed	*ha.a*	-	-	*7*	*±1*	*7*	*±1*	(c, h)
- Diesel Fuel	*ha.a*	*608*	*±96*	*72*	*±33*	*680*	*±102*	(c, i)
Reference System:								
- Diesel Fuel	*ha.a*	*- 63*	*±10*	*- 7*	*±3*	*- 70*	*±10*	(c, j)
Sub-Totals	*ha.a*	*545*	*±97*	*403*	*±45*	*948*	*±107*	
	t be	**88**	**±16**	**65**	**±7**	**153**	**±17**	(k)
Transport:								
- Diesel Fuel	*t ssb*	*5*	-	*2*	-	*7*	-	(l)
	t be	**44**	**-**	**18**	**-**	**62**	**-**	(m)
Straw Baling:								
- N Fertiliser	*ha.a*	-	-	*113*	*±16*	*113*	*±16*	(n)
- P Fertiliser	*ha.a*	-	-	*17*	*±3*	*17*	*±3*	(c, o)
- K Fertiliser	*ha.a*	-	-	*56*	*±8*	*56*	*±8*	(c, p)
- Diesel Fuel	*ha.a*	*23*	*±3*	*3*	-	*26*	*±3*	(c, q)
- Machinery	*ha.a*	-	-	*19*	*±3*	*19*	*±3*	(c, r)
- Twine	*ha.a*	-	-	*7*	*±1*	*7*	*±1*	(c, s)
- Maintenance	*ha.a*	-	-	*8*	*±1*	*8*	*±1*	(c, t)
Sub-Totals	*ha.a*	*23*	*±3*	223	*±18*	*246*	*±19*	
	t be	**12**	**±2**	**118**	**±10**	**130**	**±10**	(u - w)
Straw Transport:								
- Diesel Fuel	*t bws*	*4*	*±1*	*1*	-	*5*	*±1*	(x)
	t be	**7**	**±2**	**2**	**-**	**9**	**±2**	(u, v, y)
Straw Storage:								
- Diesel Fuel	*t bws*	*5*	*±1*	*1*	-	*6*	*±1*	(c, z)
- Sheeting	*t bws*	-	-	*12*	*±2*	*12*	*±2*	(c, aa)
- Machinery	*t bws*	-	-	*1*	-	*1*	-	(c, bb)
- Maintenance	*t bws*	-	-	-	-	-	-	(c, cc)
Sub-Totals	*t bws*	*5*	*±1*	*14*	*±2*	*19*	*±2*	
	t be	**9**	**±2**	**26**	**±4**	**35**	**±4**	(u, v, y)
Wash., Shred. and Diffusion:								
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	(c, dd)
- Gypsum	*t csb*	-	-	-	-	-	-	(c, ee)
- Hydrochloric Acid	*t csb*	-	-	-	-	-	-	(c, ff)
- Formaldehyde	*t csb*	-	-	-	-	-	-	(c, gg)
- Biocide	*t csb*	-	-	-	-	-	-	(c, hh)
- Foam Oil	*t csb*	-	-	-	-	-	-	(c, ii)
Credits:								
- Soil	*t csb*	-	-	-	-	-	-	(c, jj)
- Stones	*t csb*	-	-	-	-	-	-	(c, kk)
Sub-Totals	*t csb*	-	-	-	-	-	-	
	t be	**-**	**-**	**-**	**-**	**-**	**-**	(ll)
Purific., Conc., Ferment., Distillation and Dehydration:								
- Sulphur	*t csb*	-	-	-	-	-	-	(c, mm)
- Soda	*t csb*	-	-	-	-	-	-	(c, nn)
- Anti-Scalant	*t csb*	-	-	-	-	-	-	(c, oo)
- EDTA	*t csb*	-	-	-	-	-	-	(c, pp)
- Limestone	*t csb*	-	-	-	-	-	-	(c, qq)
- Coke	*t csb*	-	-	-	-	-	-	(c, rr)
- Anti-Foam	*t csb*	*5*	*±1*	*1*	-	*6*	*±1*	(c, ss)
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	(c, tt)
Credit:								
- Electricity	*t csb*	*- 321*	*±48*	-	-	*- 321*	*±48*	(c, uu)
- LimeX	*t csb*	-	-	*- 8*	*±1*	*- 8*	*±1*	(c, vv)
Sub-Totals	*t csb*	*- 316*	*±48*	*- 7*	*±1*	*- 323*	*±48*	
	t be	**- 3,406**	**±517**	**- 75**	**±11**	**- 3,481**	**±517**	(ww)
Plant Construction	**t be**	**-**	**-**	**69**	**±8**	**69**	**±8**	(xx, yy)
Plant Maintenance	**t be**	**-**	**-**	**24**	**±3**	**24**	**±3**	(xx - zz)
Ash Disposal:	*t ash*	*4*	-	-	-	*4*	-	(ab)
	t be	**-**	**-**	**-**	**-**	**-**	**-**	(ac)
Distribution	**t be**	**25**	**±1**	**7**	**±1**	**32**	**±1**	(ad)
Totals	**t be**	**- 3,221**	**±517**	**254**	**±119**	**- 2,967**	**±530**	

Biofuel Specifications

Density of bioethanol	= 0.79 kg/l
Net calorific value of bioethanol	= 26.72 MJ/kg
Gross calorific value of bioethanol	= 29.74 MJ/kg

Abbreviations

ha.a	= hectare year
t csb	= tonne of clean sugar beet
t ssb	= tonne of soiled sugar beet
t be	= tonne of bioethanol
t bws	= tonne of baled wheat straw
t ash	= tonne of ash

Notes

(a) Nitrogen fertiliser application rate of 103.0 kg N/ha.a (Ref. 4) and a total carbon requirement for ammonium nitrate of 1.904 ± 0.275 kg CO_2/kg N (Ref. 6).

(b) Phosphate fertiliser application rates of 38.0 kg P/ha.a (Ref. 5), or 87.0 kg P_2O_5/ ha.a assuming 2.290 kg P_2O_5/kg P, and a total carbon requirement for phosphate fertiliser of 0.700 kg CO_2/kg P_2O_5 (Ref. 7).

(c) Assuming an error bar of ±15% based on similar analyses (Ref. 8).

(d) Potash fertiliser application rate of 104.0 kg K/ha.a (Ref. 5), or 125.3 kg K_2O/ha.a assuming 1.205 kg K_2O/kg K, and a total carbon requirement for potash fertiliser of 0.453 kg CO_2/ kg K_2O (Ref. 7).

(e) Pesticide application rate of 2.90 kg/ha.a (Ref. 9) and a total carbon requirement for general pesticides, herbicides and fungicides of 4.921 kg CO_2/kg (Ref. 7).

(f) Herbicide application rate of 0.40 kg/ha.a (Ref. 9) and a total carbon requirement for general pesticides, herbicides and fungicides of 4.921 kg CO_2/kg (Ref. 7).

(g) Insecticide application rate of 0.24 kg/ha.a (Ref. 9) and a total carbon requirement for general pesticides, herbicides and fungicides of 4.921 kg CO_2/kg (Ref. 7).

(h) Sowing rate of 3.8 kg/ha.a, consisting of 1.2 kg/ha.a of seed and 2.6 kg/ha.a pelletising material (Ref. 10), and a total carbon requirement of 1.775 kg CO_2 /kg of seed (Ref. 7).

(i) Diesel fuel consumption of 8,870 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides and insecticides, and harvesting (Ref. 2) 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. 11).

(j) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 7) 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. 11).

(k) Land requirement of 0.255 ha.a/t of bioethanol, partitioning between13.296 t of sugar beet at farm with a price of £22/t (Ref. 1) and 1.507 t sugar beet tops (dry matter) with an effective price of £10.00/t, based on an average market price of £2.00/t (wet basis) 80% moisture content (Ref. 2), and partitioning between 14.560 t of thin juice with an effective price of £16.2/t and an effective average price for 25.996 t of pulp with a moisture content of 97% of £2.56/t, derived from an average price for animal feed pellets with a moisture content of 15% of £72.50/t (Ref. 2), and an assumed price of bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solid and 66.5% sugar purity), based on the price of thick juice, giving an allocation of 95.1% x 78.0% x 85.7% = 63.6% to bioethanol.

(l) Average round trip distance of 94 km (Ref. 2) 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. 12).

(m) Soiled sugar beet requirement of 13.296 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(n) Ammonium nitrate fertiliser application rate of 59.31 kg N /ha.a to replace straw removal, based on Canadian data (Ref. 20) adjusted pro rata to an average wheat straw yield of 3.5 t/ha.a (Ref. 1) with 2.28 t straw collected for fuel from 0.651ha.a/t bioethanol, and a total carbon requirement of 1.904±0.275 kg CO_2/MJ N for ammonium nitrate (Ref. 6).

(o) Phosphate fertiliser application rate of 24.54 kg P_2O_5/ ha.a to replace straw removal, based on Canadian data (Ref. 20) adjusted pro rata to an average wheat straw yield of 3.5 t/ha.a (Ref. 1) with 2.28 t straw collected for fuel from 0.651 ha.a/t bioethanol, and a total carbon requirement for phosphate fertiliser of 0.700 kg CO2/kg P_2O_5 (Ref. 7).

(p) Potash fertiliser application rate of 123.8 kg K_2O/ha.a to replace straw removal, based on Canadian data (Ref. 20) adjusted pro rata to an average wheat straw yield of 3.5 t/ha.a (Ref. 1) with 2.28 t straw collected for fuel from 0.651ha.a/t bioethanol, and a total carbon requirement for potash fertiliser of 0.453 kg CO2/ kg K_2O (Ref. 7).

(q) Diesel fuel consumption for baling of 232 MJ/ha.a and loading in the field of 138 MJ/ha.a, based on data for straw fuel recovery (Ref. 20) adjusted for collection of 2.28 t straw from 0.651 ha.a/t bioethanol, 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. 12).

(r) Carbon dioxide output from manufacture of tractor for baling of 2.4 kg CO_2/ha.a, Hesston baler of 14.4 kg CO_2/ha.a and telescopic handler for loading in field of 1.9 kg CO_2/ha.a, based on data for straw fuel recovery (Ref. 21) adjusted for collection of 2.28 t straw from 0.0.651 ha.a/t bioethanol.

(s) Carbon dioxide output from manufacture of baling twine of 7.01 kg CO_2/ha.a, based on data for straw fuel recovery (Ref. 21) adjusted for collection of 2.28 t straw from 0.0.651 ha.a/t bioethanol.

(t) Carbon dioxide output from maintenance and repair of tractor for baling of 0.61 kg CO_2/ha.a, of Hesston baler of 6.8 kg CO_2/ha.a and of telescopic handler for loading in the field of 0.65 kg CO_2/ha.a, based on data for straw fuel recovery (Ref. 21) adjusted for collection of 2.28 t straw from 0.0.651 ha.a/t bioethanol.

(u) Straw-fired combined heat and power plant based on a steam turbine with an overall efficiency of 85% and a load factor of 91%, consuming 202,827 t of straw (at 15% moisture content and 14.8 MJ/kg calorific value) to provide 67 t/hr or 186,126 MJ/hr of steam (matched to bioethanol plant requirements) and 36 MW (6.1 MW for bioethanol plant and 29.9 MW surplus) of electricity equal to 130,288 MJ/hr (Ref. 2). This provides total heat supplies of 1,193 MJ/t of clean sugar beet and total electricity supplies of 835 MJ/t of clean sugar beet (consisting of 141 MJ/t of clean sugar beet for bioethanol processing and 964 MJ/t of clean sugar beet of surplus for sale). Assuming 11% losses during baling and transport, 227,640 t of straw are required. Heat and electricity supplied by a straw-fired combined heat and power plant for washing, shredding and diffusion which requires 14 t/hr of steam, assumed to be 50% of total steam requirements of sugar plant (Ref. 2), equivalent to 186,126 x 14/67 = 38,892 MJ/hr, and an electricity consumption rate for washing, shredding and diffusion of 3.5 MW (Ref. 2). Heat and electricity supplied by a straw-fired combined heat and power plant for a steam consumption rate for purification of 1 t/hr and for fermentation, distillation and dehydration of 38 t/hr (Ref. 2), resulting in a total steam consumption rate of 39 t/hr or equivalent to 186,126 x 39/67 = 108,342 MJ/hr, and an electricity consumption rate for diffusion of 1.4 MW and for fermentation, distillation and dehydration of 1.2 MW (Ref. 2).

(v) Total clean sugar beet input of 1,257,774 t/a and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 2), giving a clean sugar beet input rate of 156 t/hr.

(w) Land requirement of 0.651 ha.a/t bioethanol and partitioning, based on relative energy, with heat and electricity measured on an equivalent basis, to washing, shredding and diffusion (25%), to purification, concentration, fermentation, distillation and dehydration (75%), and allocation between bioethanol, pulp and vinasses (66.8%), and between bioethanol and vinasses (85.7%) resulting in a total allocation to bioethanol of (25% x 66.8%)+ (75% x 85.7%) = 81%.

(x) Average round trip distance of 80 km (Ref. 20) 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. 12).

(y) Baled straw requirement of 2.25 t/t bioethanol and partitioning, based on relative energy, with heat and electricity measured on an equivalent basis, , to washing, shredding and diffusion (25%), to purification, concentration, fermentation, distillation and dehydration (75%), and allocation between bioethanol, pulp and vinasses (66.8%), and between bioethanol and vinasses (85.7%) resulting in a total allocation to bioethanol of (25% x 66.8%)+ (75% x 85.7%) = 81%.

(z) Diesel fuel consumption for baled straw handling in storage of 65.8 MJ/t of baled wheat straw (Ref. 21), 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. 11).

(aa) Based on 2 tonnes of polyethylene sheeting used to protect each storage stack of 1,000 tonnes of baled wheat straw, with a life of 1 year and a carbon requirement of 6.2 kg CO_2/kg for low density polyethylene (Ref. 21).

(bb) Carbon dioxide output from manufacture of telescopic handler of 1.0 kg CO_2/t of baled wheat straw (Ref. 21).

(cc) Carbon dioxide output from maintenance and repair of telescopic handler of 0.3 kg CO_2/t of baled wheat straw (Ref. 21).

(dd) Sulphuric acid (93% concentration) consumption rate of 0.18 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 0.13 $\pm$ 0.16 kg CO_2/kg for sulphuric acid (Ref. 13).

(ee) Gypsum (calcium sulphate) consumption rate of 1.06 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 0.08 kg CO_2/kg for gypsum (Ref. 13).

(ff) Hydrochloric acid (100% concentration) consumption rate of 0.025 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 0.15 kg CO_2/kg for hydrochloric acid (Ref. 13).

(gg) Formaldehyde consumption rate of 0.15 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 2.1 x 10^{-5} kg CO_2/kg for formaldehyde (Refs. 2 and 14 to 16).

(hh) Biocide consumption rate of 0.024 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 0.12 kg CO_2/kg for biocide (Refs. 2 and 14 to 16).

(ii) Foam oil consumption rate of 0.03 kg/t of clean sugar beet (Ref. 2) and, assuming foam oil is similar to refined rapeseed oil, a carbon requirement of 0.59 ± 0.04 kg CO_2/kg of refined rapeseed oil (Ref. 17).

(jj) Soil recovery rate of 5.32% of clean sugar beet (Ref. 2), or 53.2 kg/t of clean sugar beet, and, assuming soil production is similar to sand extraction, a carbon requirement of 5.7 x 10^{-3} kg CO_2/kg for sand (Ref. 18).

(kk) Stone recovery rate of 0.39% of clean sugar beet (Ref. 2), or 3.9 kg/t of clean sugar beet, and, assuming stone production is similar to sand extraction, a carbon requirement of 5.7 x 10^{-3} kg CO_2/kg for sand (Ref. 18).

(ll) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(mm) Sulphur (as SO_2) consumption rate of 0.13 kg/t of clean sugar beet and a carbon requirement of 0.89 ± 0.24 kg CO_2/kg for sulphur (Ref. 13).

(nn) Soda (sodium carbonate) consumption rate of 0.05 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 2.13 ± 0.64 kg CO_2/kg for soda (Ref. 13).

(oo) Anti-scalant consumption rate of 0.04 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 1.52 kg CO_2/kg for anti-scalant (Refs. 2 and 14 to 16).

(pp) EDTA consumption rate of 0.055 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 0.40 kg CO_2/kg for EDTA (Refs. 2 and 14 to 16).

(qq) Limestone consumption rate of 2.3% of clean sugar beet (Ref. 2), or 23 kg/t of clean sugar beet, and a carbon requirement of 0.02 kg CO_2/kg for limestone (Ref. 18).

(rr) Coke consumption rate of 0.18% of clean sugar beet (Ref. 2), or 1.8 kg/t of clean sugar beet, and a direct carbon requirement of 0.104 x 28.1 = 2.92 kg CO_2/kg and an indirect carbon requirement of 0.37 kg CO_2/kg for coke in the UK in 1996 (Ref. 11).

(ss) Anti-foam consumption rate of 253,344 kg/a (Ref. 2), or 0.20 kg/t of clean sugar beet, and, assuming similarity with anti-scalant, a carbon requirement of 1.52 kg CO_2/kg of anti-foam (Refs. 2 and 14 to 16).

(tt) Sulphuric acid (93% concentration) consumption rate of 380,016 kg/a, or 0.30 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 0.13 ± 016 kg CO_2/kg for sulphuric acid (Ref. 13).

(uu) Surplus electricity of 29.9 MW for 8,064 hr/a resulting in 868,009 GJ/a of electricity exported for sale, equivalent to 694 MJ/t of clean sugar beet, with a carbon requirement of 0.15 kg CO_2/ MJ for the UK in 1996 (Ref. 11) and assuming 85.7% contribution to bioethanol by price of co-products.

(vv) LimeX production rate of 45 kg/t of clean sugar beet (Ref. 2) and a carbon requirement of 0.18 kg CO_2/kg for lime (Ref. 6), excluding carbon dioxide from calcination which is not accounted for in the bioethanol plant.

(ww) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 85.7% to bioethanol.

(xx) Carbon dioxide output of 47,500 tonnes of CO_2 for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £38.0 m (Ref. 2) and a carbon intensity of 1.25 kg CO_2/£ (Ref. 14).

(yy) Carbon dioxide output of 138,485 tonnes of CO_2 for construction of a straw-fired combined heat and power plant with a 67t/hr steam output and a 36 MW rated electricity output, based pro rata on data for a straw-fired combined heat and power plant with a 13.0 MW rated heat output and a 5.0 MW rated electricity output (Ref. 21), with a 25 year life.

(zz) Carbon dioxide output of annual plant maintenance assumed to be 1.5% of carbon dioxide output of plant construction (Ref. 2).

(ab) Ash sent for spreading as a fertiliser on fields at an average round trip distance of 80 km (Ref. 21) 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. 12).

(ab) Ash output of 5.5% of straw fuel feed (Ref. 21) and straw requirement of 2.03 t/t of bioethanol.

(ac) Average round trip distance of 450 km (Ref. 19) 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. 11).

References

1. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 28 April 2003.

2. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 2 May 2003.

3. Private communication with D. Darby of British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication with G. Punter of British Sugar plc., Peterborough, United Kingdom, 8 May 2003.

5. "British Sugar Field Crop Survey 2001"

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Report No. 20/1, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003, for the Department for the Environment, Food and Rural Affairs, www.defra.

7. "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.

8. "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.

9. "Pesticide Use Survey Reports" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. British Sugar Internal Survey 2001

11. "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.

12. "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.

13. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

14. "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.

15. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

16. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

17. "Carbon and Energy Balances for a Range of Biofuel Options" by M. A. Elsayed, R. Matthews and N. D. Mortimer, B/B6/00784/REP, Energy Technology Support Unit, Harwell, United Kingdom, March 2003, www.shu.ac.uk/rru/projects/biofuels/biofuels.html.

18. "Handbook of Industrial Energy Analysis" by I. Boustead and G. Hancock, Ellis Horwood, Chichester, United Kingdom, 1979.

19. "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.

20. "Assessment of Net Emissions of Greenhouse Gases from Ethanol-Blended Gasolines in Canada: Lignocellulosic Feedstocks" R-2000-2, Levelton Engineering Ltd., Richmond, Canada, December 1998.

21. "Energy and Carbon Analysis of Using Straw as a Fuel" by J. F. Grant, R. Hetherington, R. E. Horne and N. D. Mortimer, Report ETSU B/M4/00487/01, Energy Technology Support Unit, Harwell, United Kingdom, 1995.

Spreadsheet for Methane Outputs from Bioethanol Production from Sugar Beet using a Straw-fired Combined Heat and Power Plant with a Steam Turbine (Model 8)

Functional Unit:	Bioethanol at point of distribution derived from sugar beet using straw-fired combined heat and power with a steam turbine during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on a market price for 13.296 tonnes of sugar beet on the farm of £22.00/t (Ref. 1) and an effective price for 1.507 tonnes of sugar beet tops (dry matter) of £10.0/t, based on an average market price of £2.00/t (wet basis) with a 80% moisture content (Ref. 2), substitution of 0.669 tonnes of soil from washing by soil from main sources, substitution of 0.049 tonnes of stones from washing by stones from quarrying, an effective average price for 14.560 tonnes of thin juice (15% solids and 88% sugar purity) of £16.2/t, derived from a price for thick juice (67% solids and 92% sugar purity) of £72.48/t (Ref. 3), and an effective average price for 25.996 tonnes of pulp (97% moisture content) of £2.56/t, derived from an average market price for animal feed pellets (15% moisture content) of £72.50/t (Ref. 2), substitution of 0.566 tonnes of LimeX by agricultural lime, and an assumed price for bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solids and 66.5% sugar purity) of £122.15/t, based on the price of thick juice (Ref. 4).

Contribution	Per Unit	Methane Output (kg CH_4)						Notes
		Direct		Indirect		Total		
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	ha.a	-	-	0.371	±0.062	0.371	±0.062	(a)
- P Fertiliser	ha.a	-	-	0.002	-	0.002	-	(b, c)
- K Fertiliser	ha.a	-	-	0.003	-	0.003	-	(c, d)
- Pesticides	ha.a	-	-	0.001	-	0.001	-	(c, e)
- Herbicide	ha.a	-	-	-	-	-	-	(c, f)
- Insecticide	ha.a	-	-	-	-	-	-	(c, g)
- Seed	ha.a	-	-	0.008	±0.001	0.008	±0.001	(c, h)
- Diesel Fuel	ha.a	0.005	±0.005	0.181	±0.027	0.186	±0.028	(c, i)
Reference System:								
- Diesel Fuel	ha.a	- 0.001	±0.001	- 0.019	±0.003	- 0.020	±0.003	(c, j)
Sub-Totals	ha.a	0.004	±0.005	0.547	±0.068	0.551	±0.068	
	t be	**0.001**	**±0.001**	**0.088**	**±0.011**	**0.089**	**±0.011**	(k)
Transport:								
- Diesel Fuel	t ssb	-	-	0.002	-	0.002	-	(l)
	t be	-	-	**0.018**	-	**0.018**	-	(m)
Straw Baling:								
- N Fertiliser	ha.a	-	-	0.213	±0.036	0.213	±0.036	(n)
- P Fertiliser	ha.a	-	-	0.001	-	0.001	-	(c, o)
- K Fertiliser	ha.a	-	-	0.003	-	0.003	-	(c, p)
- Diesel Fuel	ha.a	-	-	0.007	-	0.007	-	(c, q)
- Machinery	ha.a	-	-	-	-	-	-	(c, r)
- Twine	ha.a	-	-	-	-	-	-	(c, s)
- Maintenance	ha.a	-	-	-	-	-	-	(c, t)
Sub-Totals	ha.a	-	-	0.224	±0.036	0.224	±0.036	
	t be	-	-	**0.118**	**±0.019**	**0.118**	**±0.019**	(u - w)
Straw Transport:								
- Diesel Fuel	t bws	-	-	0.001	-	0.001	-	(x)
	t be	-	-	**0.002**	-	**0.002**	-	(u, v, y)
Straw Storage:								
- Diesel Fuel	t bws	-	-	0.001	-	0.001	-	(c, z)
- Sheeting	t bws	-	-	-	-	-	-	(c, aa)
- Machinery	t bws	-	-	-	-	-	-	(c, bb)
- Maintenance	t bws	-	-	-	-	-	-	(c, cc)
Sub-Totals	t bws	-	-	0.001	-	0.001	-	
	t be	-	-	**0.002**	-	**0.002**	-	(u, v, y)
Wash., Shred. and Diffusion:								
- Sulphuric Acid	t csb	-	-	-	-	-	-	(c, dd)
- Gypsum	t csb	-	-	-	-	-	-	(c, ee)
- Hydrochloric Acid	t csb	-	-	-	-	-	-	(c, ff)
- Formaldehyde	t csb	-	-	-	-	-	-	(c, gg)
- Biocide	t csb	-	-	-	-	-	-	(c, hh)
- Foam Oil	t csb	-	-	-	-	-	-	(c, ii)
Credits:								
- Soil	t csb	-	-	-	-	-	-	(c, jj)
- Stones	t csb	-	-	-	-	-	-	(c, kk)
Sub-Totals	t csb	-	-	-	-	-	-	
	t be	-	-	-	-	-	-	(ll)
Purific., Conc., Ferment., Distillation and Dehydration:								
- Sulphur	t csb	-	-	-	-	-	-	(c, mm)
- Soda	t csb	-	-	-	-	-	-	(c, nn)
- Anti-Scalant	t csb	-	-	-	-	-	-	(c, oo)
- EDTA	t csb	-	-	-	-	-	-	(c, pp)
- Limestone	t csb	-	-	-	-	-	-	(c, qq)
- Coke	t csb	-	-	-	-	-	-	(c, rr)
- Anti-Foam	t csb	-	-	-	-	-	-	(c, ss)
- Sulphuric Acid	t csb	-	-	-	-	-	-	(c, tt)
Credit:								
- Electricity	t csb	- 0.863	±0.129	-		- 0.863	±0.129	(c, uu)
- LimeX	t csb	-	-	-	-	-	-	(c, vv)
Sub-Totals	t csb	- 0.863	±0.129	-	-	- 0.863	±0.129	
	t be	**- 9.302**	**±1.391**	-	-	- 9.302	**±1.391**	(ww)
Direct Emissions	**t be**	**0.051**	**±0.007**	-	-	**0.051**	**±0.007**	(xx)
Plant Construction	**t be**	-	-	-	-	-	-	(yy - zz)
Plant Maintenance	**t be**	-	-	-	-	-	-	(yy - ab)
Ash Disposal	t ash	-	-	0.001	-	0.001	-	(ac)
	t be	-	-	-	-	-	-	(ad)
Distribution	**t be**	-	-	**0.008**	-	**0.008**	-	(ae)
Totals	**t be**	**- 9.250**	**±1.391**	**0.236**	**±0.022**	**- 9.014**	**±1.391**	

Biofuel Specifications

Density of bioethanol	= 0.79 kg/l
Net calorific value of bioethanol	= 26.72 MJ/kg
Gross calorific value of bioethanol	= 29.74 MJ/kg

Abbreviations

ha.a	= hectare year
t csb	= tonne of clean sugar beet
t ssb	= tonne of soiled sugar beet
t be	= tonne of bioethanol
t bws	= tonne of baled wheat straw
t ash	= tonne of ash

Notes

(a) Nitrogen fertiliser application rate of 103.0 kg N/ha.a (Ref. 5) 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 (Ref. 6).

(b) Phosphate fertiliser application rates of 38.0 kg P/ha.a (Ref. 5), or 87.0 kg P_2O_5/ ha.a assuming 2.290 kg P_2O_5/kg P, and a total methane requirement for phosphate fertiliser of 2.3×10^{-5} kg CH_4/kg P_2O_5 (Ref. 7).

(c) Assuming an error bar of ±15% based on similar analyses (Ref. 8).

(d) Potash fertiliser application rate of 104.0 kg K/ha.a (Ref. 5), or 125.3 kg K_2O/ha.a assuming 1.205 kg K_2O/kg K, and a total methane requirement for potash fertiliser of 2.1×10^{-5} kg CH_4/ kg K_2O (Ref. 7).

(e) Pesticide application rate of 2.90 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.8×10^{-4} kg CH_4/kg (Ref. 7).

(f) Herbicide application rate of 0.40 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.8×10^{-4} kg CH_4/kg (Ref. 7).

(g) Insecticide application rate of 0.24 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.8×10^{-4} kg CH_4/kg (Ref. 7).

(h) Sowing rate of 3.8 kg/ha.a, consisting of 1.2 kg/ha.a of seed and 2.6 kg/ha.a pelletising material (Ref. 10), and a total methane requirement of 0.002 kg CH_4 /kg of seed (Ref. 7).

(i) Diesel fuel consumption of 8,870 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides and insecticides, and harvesting (Ref. 2) 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. 11).

(j) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 7) 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. 11).

(k) Land requirement of 0.255 ha.a/t of bioethanol, partitioning between13.296 t of sugar beet at farm with a price of £22/t (Ref. 1) and 1.507 t sugar beet tops (dry matter) with an effective price of £10.00/t, based on an average market price of £2.00/t (wet basis) 80% moisture content (Ref. 2), and partitioning between 14.560 t of thin juice with an effective price of £16.2/t and an effective average price for 25.996 t of pulp with a moisture content of 97% of £2.56/t, derived from an average price for animal feed pellets with a moisture content of 15% of £72.50/t (Ref. 2), and an assumed price of bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solid and 66.5% sugar purity), based on the price of thick juice, giving an allocation of 95.1% x 78.0% x 85.7% = 63.6% to bioethanol.

(l) Average round trip distance of 94 km (Ref. 2) 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. 12).

(m) Soiled sugar beet requirement of 13.296 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(n) Ammonium nitrate fertiliser application rate of 59.31 kg N /ha.a to replace straw removal, based on Canadian data (Ref. 21) adjusted pro rata to an average wheat straw yield of 3.5 t/ha.a (Ref. 12) with 2.28 t straw collected for fuel from 0.651 ha.a/t bioethanol, and a total methane requirement of $3.6 \times 10^{-3} \pm 0.6 \times 10^{-3}$ kg CH_4/MJ N for ammonium nitrate (Ref. 6).

(o) Phosphate fertiliser application rate of 24.54 kg P_2O_5/ ha.a to replace straw removal, based on Canadian data (Ref. 21) adjusted pro rata to an average wheat straw yield of 3.5 t/ha.a (Ref. 12) with 2.28 t straw collected for fuel from 0.651 ha.a/t bioethanol, and a total methane requirement for phosphate fertiliser of 2.3×10^{-5} kg CH_4/kg P_2O_5 (Ref. 7).

(p) Potash fertiliser application rate of 123.8 kg K_2O/ha.a to replace straw removal, based on Canadian data (Ref. 21) adjusted pro rata to an average wheat straw yield of 3.5 t/ha.a (Ref. 12) with 2.28 t straw collected for fuel from 0.651 ha.a/t bioethanol, and a total methane requirement for potash fertiliser of 2.1 x 10^{-5} kg CH_4/ kg K_2O (Ref. 7).

(q) Diesel fuel consumption for baling of 232 MJ/ha.a and loading in the field of 138 MJ/ha.a, based on data for straw fuel recovery (Ref. 21) adjusted for collection of 1.394 t straw from 0.398 ha.a/t bioethanol, and a direct methane requirement of 6.0 x 10^{-7} kg CH_4/ MJ, an indirect methane requirement of 2.04 x 10^{-5} kg CH_4/ MJ and a total methane requirement of 2.1 x 10^{-5} kg CH_4/ MJ for diesel fuel in the UK in 1996 (Ref. 11).

(r) Primary energy input to manufacture of tractor for baling of 52 MJ/ha.a, Hesston baler of 312 MJ/ha.a and telescopic handler for loading in field of 41 MJ/ha.a, based on data for straw fuel recovery (Ref. 21) adjusted for collection of 2.28 t straw collected for fuel from 0.651 ha.a/t bioethanol and an estimated total methane requirement of 1.192 x 10^{-7} kg CH_4/ MJ primary energy input to manufacturing (Ref. 16).

(s) Primary energy input to manufacture of baling twine of 94.3 MJ/ha.a, based on data for straw fuel recovery (Ref. 21) adjusted for collection of 2.28 t straw collected for fuel from 0.651 ha.a/t bioethanol and an estimated total methane requirement of 1.192 x 10^{-7} kg CH_4/ MJ primary energy input to manufacturing (Ref. 16).

(t) Primary energy input to maintenance and repair of tractor for baling of 13.25 MJ/ha.a, of Hesston baler of 147 MJ/ha.a and of telescopic handler for loading in the field of 14.1MJ/ha.a, based on data for straw fuel recovery (Ref. 21) adjusted for collection of 2.28 t straw from 0.651ha.a/t bioethanol and an estimated total methane requirement of 1.192 x 10^{-7} kg CH_4/ MJ primary energy input to manufacturing (Ref. 16).

(u) Straw-fired combined heat and power plant based on a steam turbine with an overall efficiency of 85% and a load factor of 91%, consuming 202,827 t of straw (at 15% moisture content and 14.8 MJ/kg calorific value) to provide 67 t/hr or 186,126 MJ/hr of steam (matched to bioethanol plant requirements) and 36 MW (6.1 MW for bioethanol plant and 29.9 MW surplus) of electricity equal to 130,288 MJ/hr (Ref. 2). This provides total heat supplies of 1,193 MJ/t of clean sugar beet and total electricity supplies of 835 MJ/t of clean sugar beet (consisting of 141 MJ/t of clean sugar beet for bioethanol processing and 964 MJ/t of clean sugar beet of surplus for sale). Assuming 11% losses during baling and transport, 227,640 t of straw are required. Heat and electricity supplied by a straw-fired combined heat and power plant for washing, shredding and diffusion which requires 14 t/hr of steam, assumed to be 50% of total steam requirements of sugar plant (Ref. 2), equivalent to 186,126 x 14/67 = 38,892 MJ/hr, and an electricity consumption rate for washing, shredding and diffusion of 3.5 MW (Ref. 2). Heat and electricity supplied by a straw-fired combined heat and power plant for a steam consumption rate for purification of 1 t/hr and for fermentation, distillation and dehydration of 38 t/hr (Ref. 2), resulting in a total steam consumption rate of 39 t/hr or equivalent to 186,126 x 39/67 = 108,342 MJ/hr, and an electricity consumption rate for diffusion of 1.4 MW and for fermentation, distillation and dehydration of 1.2 MW (Ref. 2).

(v) Total clean sugar beet input of 1,257,774 t/a and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 2), giving a clean sugar beet input rate of 156 t/hr.

(w) Land requirement of 0.651 ha.a/t bioethanol and partitioning, based on relative energy, with heat and electricity measured on an equivalent basis, to washing, shredding and diffusion (25%), to purification, concentration, fermentation, distillation and dehydration (75%), and allocation between bioethanol, pulp and vinasses (66.8%), and between bioethanol and vinasses (85.7%) resulting in a total allocation to bioethanol of (25% x 66.8%)+ (75% x 85.7%) = 81%.

(x) Average round trip distance of 80 km (Ref. 21) by bulk road carrier transport with a direct methane requirement of 4.900 x 10^{-7} ± 2.000 x 10^{-8} kg CH_4/t-km, an indirect methane requirement of 1.672 x 10^{-5} ± 6.3 x 10^{-7} kg CH_4/t-km and a total methane requirement of 1.721 x 10^{-5} ± 6.5 x 10^{-7} kg CH_4/t-km (Ref. 12).

(y) Baled straw requirement of 2.25 t/t bioethanol and partitioning, based on relative energy, with heat and electricity measured on an equivalent basis, to washing, shredding and diffusion (25%), to purification, concentration, fermentation, distillation and dehydration (75%), and allocation between bioethanol, pulp and vinasses (66.8%), and between bioethanol and vinasses (85.7%) resulting in a total allocation to bioethanol of (25% x 66.8%)+ (75% x 85.7%) = 81%.

(z) Diesel fuel consumption for baled straw handling in storage of 65.8 MJ/t of baled wheat straw (Ref. 21), and a direct methane requirement of 6.0 x 10^{-7} kg CH_4/ MJ, an indirect methane requirement of 2.04 x 10^{-5} kg CH_4/ MJ and a total methane requirement of 2.1 x 10^{-5} kg CH_4/ MJ for diesel fuel in the UK in 1996 (Ref. 11).

(aa) Based on 2 tonnes of polyethylene sheeting used to protect each storage stack of 1,000 tonnes of baled wheat straw, with a life of 1 year and a direct energy requirement of 47 MJ/kg and a feedstock energy requirement of 46 MJ/kg for low density polyethylene (Ref. 22) and an estimated total methane requirement of 1.192 x 10^{-7} kg CH_4/ MJ primary energy input to manufacturing (Ref. 16).

(bb) Primary energy input for manufacture of telescopic handler of 21.0 MJ/t of baled wheat straw (Ref. 21) and an estimated total methane requirement of 1.192 x 10^{-7} kg CH_4/ MJ primary energy input to manufacturing (Ref. 16).

(cc) Primary energy input to maintenance and repair of telescopic handler of 7.2 MJ/t of baled wheat straw (Ref. 21) and an estimated total methane requirement of 1.192 x 10^{-7} kg CH_4/ MJ primary energy input to manufacturing (Ref. 16).

(dd) Sulphuric acid (93% concentration) consumption rate of 0.18 kg/t of clean sugar beet (Ref. 2) and a methane requirement of 2.7 x 10^{-4} ± 3.0 x 10^{-4} kg CH_4/kg for sulphuric acid (Ref. 13).

(ee) Gypsum (calcium sulphate) consumption rate of 1.06 kg/t of clean sugar beet (Ref. 2) and a methane requirement of 2.1 x 10^{-5} kg CH_4/kg for gypsum (Ref. 13).

(ff) Hydrochloric acid (100% concentration) consumption rate of 0.025 kg/t of clean sugar beet (Ref. 2) and a methane requirement of 0.01 ± 0.001 kg CH_4/kg for hydrochloric acid (Ref. 13).

(gg) Formaldehyde consumption rate of 0.15 kg/t of clean sugar beet (Ref. 2) and a methane requirement of 4.0 x 10^{-7} kg CH_4/kg for formaldehyde (Refs. 2 and 14 to 16).

(hh) Biocide consumption rate of 0.024 kg/t of clean sugar beet (Ref. 2) and a methane requirement of 3.0 x 10^{-7} kg CH_4/kg for biocide (Refs. 2 and 14 to 16).

(ii) Foam oil consumption rate of 0.03 kg/t of clean sugar beet (Ref. 2) and, assuming foam oil is similar to refined rapeseed oil, a methane requirement of 7.7 x 10^{-4} ± 7.0 x 10^{-5} kg CH_4/kg of refined rapeseed oil (Ref. 17).

(jj) Soil recovery rate of 5.32% of clean sugar beet (Ref. 2), or 53.2 kg/t of clean sugar beet, and, assuming soil production is similar to sand extraction, a methane requirement of 1.6 x 10^{-6} kg CH_4/kg for sand (Ref. 18).

(kk) Stone recovery rate of 0.39% of clean sugar beet (Ref. 2), or 3.9 kg/t of clean sugar beet, and, assuming stone production is similar to sand extraction, a methane requirement of 1.6 x 10^{-6} kg CH_4/kg for sand (Ref. 18).

(ll) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(mm) Sulphur (as SO_2) consumption rate of 0.13 kg/t of clean sugar beet and a methane requirement of 2.5 x 10^{-5} ± 7.0 x 10^{-6} kg CH_4/kg for sulphur (Ref. 13).

(nn) Soda (sodium carbonate) consumption rate of 0.05 kg/t of clean sugar beet (Ref. 2) and a methane requirement of 7.2 x 10^{-4} ± 2.0 x 10^{-5} kg CH_4/kg for soda (Ref. 13).

(oo) Anti-scalant consumption rate of 0.04 kg/t of clean sugar beet (Ref. 2) and a methane requirement of 4.0 x 10^{-6} kg CH_4/kg for anti-scalant (Refs. 2 and 14 to 16).

(pp) EDTA consumption rate of 0.055 kg/t of clean sugar beet (Ref. 2) and a methane requirement of 1.0 x 10^{-6} kg CH_4/kg for EDTA (Refs. 2 and 14 to 16).

(qq) Limestone consumption rate of 2.3% of clean sugar beet (Ref. 2), or 23 kg/t of clean sugar beet, and a methane requirement of 2.1 x 10^{-5} kg CH_4/kg for limestone (Ref. 18).

(rr) Coke consumption rate of 0.18% of clean sugar beet (Ref. 2), or 1.8 kg/t of clean sugar beet, and a direct methane requirement of 9.5 x 10^{-6} x 28.1 = 2.7 x 10^{-4} kg CH_4/kg and an indirect methane requirement of 9.2 x 10^{-3} kg CH_4/kg for coke in the UK in 1996 (Ref. 11).

(ss) Anti-foam consumption rate of 253,344 kg/a (Ref. 2), or 0.20 kg/t of clean sugar beet, and, assuming similarity with anti-scalant, a methane requirement of 4.0 x 10^{-6} kg CH_4/kg of anti-foam (Refs. 2 and 14 to 16).

(tt) Sulphuric acid (93% concentration) consumption rate of 380,016 kg/a, or 0.30 kg/t of clean sugar beet (Ref. 2) and a methane requirement of 2.7 x 10^{-4} ± 3.0 x 10^{-4} kg CH_4/kg for sulphuric acid (Ref. 13).

(uu) Surplus electricity of 29.9 MW for 8,064 hr/a resulting in 868,009 GJ/a of electricity exported for sale, equivalent to 694 MJ/t of clean sugar beet, and a methane requirement of 4.034 x 10^{-4} kg CH_4/MJ for displaced grid electricity supplies in the UK in 1996 (Ref. 11) .

(vv) LimeX production rate of 45 kg/t of clean sugar beet (Ref. 2) and a methane requirement 3.9 x 10^{-6} kg CH_4/kg for lime (Ref. 7).

(ww) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 85.7% to bioethanol.

(xx) Direct methane emissions of 29 g CH_4/t of straw fuel feed from the combined heat and power plant (Ref. 21) and straw fuel feed requirement of 2.03 t/t bioethanol and with heat and electricity measured on an equivalent basis, to washing, shredding and diffusion (25%), to purification, concentration, fermentation, distillation and dehydration (75%), and allocation between bioethanol, pulp and vinasses (66.8%), and between bioethanol and vinasses (85.7%) resulting in a total allocation to bioethanol of (25% x 66.8%)+ (75% x 85.7%) = 81%.

(yy) Primary energy input of 950,000 GJ for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £38.0 m (Ref. 2) and an estimated total methane requirement of 1.192×10^{-7} kg CH_4/MJ of primary energy input to plant construction (Ref. 16).

(zz) Primary energy input of 2,588,400 GJ for construction of a straw-fired combined heat and power plant with a 67t/hr steam output and a 36 MW rated electricity output, based pro rata on data for a straw-fired combined heat and power plant with a 13.0 MW rated heat output and a 5.0 MW rated electricity output (Ref. 21), with 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. 16), assuming 85.7% contribution to bioethanol by price of co-products.

(ab) Methane output of annual plant maintenance assumed to be 1.5% of methane output from plant construction (Ref. 2).

(ac) Ash sent for spreading as a fertiliser on fields at an average round trip distance of 80 km (Ref. 21) 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. 12).

(ad) Ash output of 5.5% of straw fuel feed (Ref. 21) and straw requirement of 2.03 t/t of bioethanol

(ae) Average round trip distance of 450 km (Ref. 19) 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. 12).

References

1. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 28 April 2003.

2. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 2 May 2003.

3. Private communication with D. Darby of British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication with G. Punter of British Sugar plc., Peterborough, United Kingdom, 8 May 2003.

5. "British Sugar Field Crop Survey 2001"

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Report No. 20/1, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003, for the Department for the Environment, Food and Rural Affairs, www.defra.

7. "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.

8. "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.

9. "Pesticide Use Survey Reports" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. British Sugar Internal Survey 2001

11. "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.

12. "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.

13. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

14. "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.

15. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

16. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

17. "Carbon and Energy Balances for a Range of Biofuel Options" by M. A. Elsayed, R. Matthews and N. D. Mortimer, B/B6/00784/REP, Energy Technology Support Unit, Harwell, United Kingdom, March 2003, www.shu.ac.uk/rru/projects/biofuels/biofuels.html.

18. "Handbook of Industrial Energy Analysis" by I. Boustead and G. Hancock, Ellis Horwood, Chichester, United Kingdom, 1979.

19. "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.

20. "Assessment of Net Emissions of Greenhouse Gases from Ethanol-Blended Gasolines in Canada: Lignocellulosic Feedstocks" R-2000-2, Levelton Engineering Ltd., Richmond, Canada, December 1998.

21. "Energy and Carbon Analysis of Using Straw as a Fuel" by J. F. Grant, R. Hetherington, R. E. Horne and N. D. Mortimer, Report ETSU B/M4/00487/01, Energy Technology Support Unit, Harwell, United Kingdom, 1995.

22. Private communication with G. Jungmeier, Joanneum Research, Austria, 15 January 2003.

Spreadsheet for Nitrous Oxide Outputs from Bioethanol Production from Sugar Beet using a Straw-fired Combined Heat and Power Plant with a Steam Turbine (Model 8)

Functional Unit:	Bioethanol at point of distribution derived from sugar beet using natural gas-fired combined heat and power with a gas turbine during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on a market price for 13.296 tonnes of sugar beet on the farm of £22.00/t (Ref. 1) and an effective price for 1.507 tonnes of sugar beet tops (dry matter) of £10.0/t, based on an average market price of £2.00/t (wet basis) with a 80% moisture content (Ref. 2), substitution of 0.669 tonnes of soil from washing by soil from main sources, substitution of 0.049 tonnes of stones from washing by stones from quarrying, an effective average price for 14.560 tonnes of thin juice (15% solids and 88% sugar purity) of £16.2/t, derived from a price for thick juice (67% solids and 92% sugar purity) of £72.48/t (Ref. 3), and an effective average price for 25.996 tonnes of pulp (97% moisture content) of £2.56/t, derived from an average market price for animal feed pellets (15% moisture content) of £72.50/t (Ref. 2), substitution of 0.566 tonnes of LimeX by agricultural lime, and an assumed price for bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solids and 66.5% sugar purity) of £122.15/t, based on the price of thick juice (Ref. 4).

Contribution	Per Unit	Nitrous Oxide Output (kg N_2O)						Notes
		Direct		Indirect		Total		
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	*ha.a*	*0.371*	*±0.125*	*1.514*	*±0.253*	*1.885*	*±0.283*	(a)
- P Fertiliser	*ha.a*	-	-	*0.004*	*±0.001*	*0.004*	*±0.001*	(b, c)
- K Fertiliser	*ha.a*	-	-	*0.001*	-	*0.001*	-	(c, d)
- Pesticides	*ha.a*	-	-	*0.004*	*±0.001*	*0.004*	*±0.001*	(c, e)
- Herbicide	*ha.a*	-	-	*0.001*	-	*0.001*	-	(c, f)
- Insecticide	*ha.a*	-	-	-	-	-	-	(c, g)
- Seed	*ha.a*	-	-	*0.004*	*±0.001*	*0.004*	*±0.001*	(c, h)
- Diesel Fuel	*ha.a*	*0.005*	*±0.001*	-	-	*0.005*	*±0.001*	(c, i)
Reference System:								
- Diesel Fuel	*ha.a*	*- 0.001*	-	-	-	*- 0.001*	-	(c, j)
Sub-Totals	*ha.a*	*0.375*	*±0.125*	*1.528*	*±0.253*	*1.903*	*±0.283*	
	t be	**0.061**	**±0.020**	**0.248**	**±0.041**	**0.309**	**±0.046**	(k)
Transport:								
- Diesel Fuel	*t ssb*	-	-	-	-	-	-	(l)
	t be	**-**	**-**	**-**	**-**	**-**	**-**	(m)
Straw Baling:								
- N Fertiliser	*ha.a*	*0.213*	*±0.033*	*0.872*	*±0.131*	*1.085*	*±0.135*	(n)
- P Fertiliser	*ha.a*	-	-	-	-	-	-	(c, o)
- K Fertiliser	*ha.a*	-	-	-	-	-	-	(c, p)
- Diesel Fuel	*ha.a*	-	-	-	-	-	-	(c, q)
- Machinery	*ha.a*	-	-	-	-	-	-	(c, r)
- Twine	*ha.a*	-	-	-	-	-	-	(c, s)
- Maintenance	*ha.a*	-	-	-	-	-	-	(c, t)
Sub-Totals	*ha.a*	*0.213*	*±0.033*	*0.872*	*±0.125*	*1.085*	*±0.135*	
	t be	**0.112**	**±0.017**	**0.460**	**±0.066**	**0.572**	**±0.071**	(u - w)
Straw Transport:								
- Diesel Fuel	*t bws*	-	-	-	-	-	-	(x)
	t be	**-**	**-**	**-**	**-**	**-**	**-**	(u, v, y)
Straw Storage:								
- Diesel Fuel	*t bws*	-	-	-	-	-	-	(c, z)
- Sheeting	*t bws*	-	-	-	-	-	-	(c, aa)
- Machinery	*t bws*	-	-	-	-	-	-	(c, bb)
- Maintenance	*t bws*	-	-	-	-	-	-	(c, cc)
Sub-Totals	*t bws*	-	-	-	-	-	-	
	t be	**-**	**-**	**-**	**-**	**-**	**-**	(u, v, y)
Washing, Shredding and Diffusion:								
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	(c, dd)
- Gypsum	*t csb*	-	-	-	-	-	-	(c, e)
- Hydrochloric Acid	*t csb*	-	-	-	-	-	-	(c, ff)
- Formaldehyde	*t csb*	-	-	-	-	-	-	(c, gg)
- Biocide	*t csb*	-	-	-	-	-	-	(c, hh)
- Foam Oil	*t csb*	-	-	-	-	-	-	(c, ii)
Credits:								
- Soil	*t csb*	-	-	-	-	-	-	(c, jj)
- Stones	*t csb*	-	-	-	-	-	-	(c, kk)
Sub-Totals	*t csb*	-	-	-	-	-	-	
	t be	**-**	**-**	**-**	**-**	**-**	**-**	(ll)
Purific., Conc., Fermentation, Distillation and Dehydration:								
- Sulphur	*t csb*	-	-	-	-	-	-	(c, mm)
- Soda	*t csb*	-	-	-	-	-	-	(c, nn)
- Anti-Scalant	*t csb*	-	-	-	-	-	-	(c, oo)
- EDTA	*t csb*	-	-	-	-	-	-	(c, pp)
- Limestone	*t csb*	-	-	-	-	-	-	(c, qq)
- Coke	*t csb*	-	-	-	-	-	-	(c, rr)
- Anti-Foam	*t csb*	-	-	-	-	-	-	(c, ss)
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	(c, tt)
Credit:								
- Electricity	*t csb*	*- 0.012*	*±0.002*	-	-	*- 0.012*	*±0.002*	(c, uu)
- LimeX	*t csb*	-	-	*- 0.001*	-	*- 0.001*	-	(c, vv)
Sub-Totals	*t csb*	*- 0.012*	*±0.002*	*- 0.001*	-	*- 0.013*	*±0.002*	
	t be	**- 0.129**	**±0.022**	**- 0.011**	**-**	**- 0.140**	**±0.022**	(ww)
Direct Emissions	**t be**	**0.127**	**±0.019**	**-**	**-**	**0.127**	**±0.019**	(xx)
Plant Construction	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(yy - zz)
Plant Maintenance	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(yy - ab)
Ash Disposal	*t ash*	-	-	-	-	-	-	(ac)
	t be	**-**	**-**	**-**	**-**	**-**	**-**	(ad)
Distribution	**t be**	**-**	**-**	**-**	**-**	**-**	**-**	(ae)
Totals	**t be**	**0.171**	**±0.039**	**0.697**	**±0.078**	**0.868**	**±0.087**	

Biofuel Specifications

Density of bioethanol	= 0.79 kg/l
Net calorific value of bioethanol	= 26.72 MJ/kg
Gross calorific value of bioethanol	= 29.74 MJ/kg

Abbreviations

ha.a	= hectare year
t csb	= tonne of clean sugar beet
t ssb	= tonne of soiled sugar beet
t be	= tonne of bioethanol
t bws	= tonne of baled wheat straw
t ash	= tonne of ash

Notes

(a) Nitrogen fertiliser application rate of 103.0 kg N/ha.a (Ref. 5) and a direct nitrous oxide requirement of 0.0036 kg N_2O/kg N (Ref. 5), an indirect nitrous oxide requirement of 0.0147 kg N_2O/kg N (Ref. 7) and a total nitrous oxide requirement for ammonium nitrate of 0.0183 kg N_2O/kg N (Ref. 6).

(b) Assuming an error bar of ±15% based on similar analyses (Ref. 8).

(c) Phosphate fertiliser application rates of 38.0 kg P/ha.a (Ref. 5), or 87.0 kg P_2O_5/ ha.a and a total nitrous oxide requirement for phosphate fertiliser of 4.2×10^{-5} kg N_2O/kg P_2O_5 (Ref. 7).

(d) Potash fertiliser application rate of 104.0 kg K/ha.a (Ref. 5), or 125.3 kg K_2O/ha.a and a total nitrous oxide requirement for potash fertiliser of 9.4×10^{-6} kg N_2O/ kg K_2O (Ref. 7).

(e) Pesticide application rate of 2.90 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.51×10^{-3} kg N_2O/kg (Ref. 7).

(f) Herbicide application rate of 0.40 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.51×10^{-3} kg N_2O/kg (Ref. 7).

(g) Insecticide application rate of 0.24 kg/ha.a (Ref. 9) and a total methane requirement for general pesticides, herbicides and fungicides of 1.51×10^{-3} kg N_2O/kg (Ref. 7).

(h) Sowing rate of 3.8 kg/ha.a, consisting of 1.2 kg/ha.a of seed and 2.6 kg/ha.a pelletising material (Ref. 10), and a total methane requirement of 0.001 kg N_2O /kg of seed (Ref. 7).

(i) Diesel fuel consumption of 8,870 MJ/ha.a used by agricultural machinery for ploughing, sowing, spreading fertilisers, pesticides, herbicides and insecticides, and harvesting (Ref. 2) and a direct nitrous oxide requirement of 5.64×10^{-7} kg N_2O/MJ, an indirect nitrous oxide requirement of 2.60×10^{-8} kg N_2/MJ and a total nitrous oxide requirement of 5.90×10^{-7} kg N_2O/MJ for diesel fuel in the UK in 1996 (Ref. 11).

(j) Reference system consisting of fallow set-aside with a diesel fuel consumption of 922 MJ/ha.a for mowing (Ref. 7) and a direct nitrous oxide requirement of 5.64×10^{-7} kg N_2O/MJ, an indirect nitrous oxide requirement of 2.60×10^{-8} kg N_2/MJ and a total nitrous oxide requirement of 5.90×10^{-7} kg N_2O/MJ for diesel fuel in the UK in 1996 (Ref. 11).

(k) Land requirement of 0.255 ha.a/t of bioethanol, partitioning between13.296 t of sugar beet at farm with a price of £22/t (Ref. 1) and 1.507 t sugar beet tops (dry matter) with an effective price of £10.00/t, based on an average market price of £2.00/t (wet basis) 80% moisture content (Ref. 2), and partitioning between 14.560 t of thin juice with an effective price of £16.2/t and an effective average price for 25.996 t of pulp with a moisture content of 97% of £2.56/t, derived from an average price for animal feed pellets with a moisture content of 15% of £72.50/t (Ref. 2), and an assumed price of bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solid and 66.5% sugar purity), based on the price of thick juice, giving an allocation of 95.1% x 78.0% x 85.7% = 63.6% to bioethanol.

(l) Average round trip distance of 94 km (Ref. 2) by bulk road carrier transport with a direct nitrous oxide requirement of $4.6 \times 10^{-7} \pm 1.7 \times 10^{-8}$ kg N_2O/t-km, an indirect nitrous oxide requirement of $2.1 \times 10^{-8} \pm 8 \times 10^{-10}$ kg N_2O/t-km and a total nitrous oxide requirement of $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8}$ kg N_2O/t-km (Ref. 12).

(m) Soiled sugar beet requirement of 13.296 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(n) Ammonium nitrate fertiliser application rate of 59.31 kg N /ha.a to replace straw removal, based on Canadian data (Ref. 21) adjusted pro rata to an average wheat straw yield of 3.5 t/ha.a (Ref. 1) with 2.28 t straw collected for fuel from 0.651 ha.a/t bioethanol, and a direct nitrous oxide requirement of 0.0036 kg N_2O/kg N (Ref. 5), an indirect nitrous oxide requirement of 0.0147 kg N_2O/kg N (Ref. 6) and a total nitrous oxide requirement for ammonium nitrate of 0.0183 kg N_2O/kg N (Ref. 6).

(o) Phosphate fertiliser application rate of 24.54 kg P_2O_5/ ha.a to replace straw removal, based on Canadian data (Ref. 21) adjusted pro rata to an average wheat straw yield of 3.5 t/ha.a (Ref. 1) with 2.28 t straw collected for fuel from 0.651 ha.a/t bioethanol, and a total nitrous oxide requirement for phosphate fertiliser of 4.2 x 10^{-5} kg N_2O/kg P_2O_5 (Ref. 7).

(p) Potash fertiliser application rate of 123.8 kg K_2O/ha.a to replace straw removal, based on Canadian data (Ref. 21) adjusted pro rata to an average wheat straw yield of 3.5 t/ha.a (Ref. 1) with 2.28 t straw collected for fuel from 0.651 ha.a/t bioethanol, a total nitrous oxide requirement for potash fertiliser of 9.4 x 10^{-6} kg N_2O/ kg K_2O (Ref. 7).

(q) Diesel fuel consumption for baling of 232 MJ/ha.a and loading in the field of 138 MJ/ha.a, based on data for straw fuel recovery (Ref. 21) adjusted for collection of 2.28 t straw from 0.651 ha.a/t bioethanol, 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_2O/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. 11).

(r) Primary energy input to manufacture of tractor for baling of 52 MJ/ha.a, Hesston baler of 312 MJ/ha.a and telescopic handler for loading in field of 41 MJ/ha.a, based on data for straw fuel recovery (Ref. 22) adjusted for collection of 2.28 t straw from 0.651 ha.a/t bioethanol and an estimated total nitrous oxide requirement of 1.866 x 10^{-9} kg N_2O/ MJ primary energy input to manufacturing (Ref. 16).

(s) Primary energy input to manufacture of baling twine of 94.3 MJ/ha.a, based on data for straw fuel recovery (Ref. 21) adjusted for collection of 2.28 t straw from 0.651 ha.a/t bioethanol and an estimated total nitrous oxide requirement of 1.866 x 10^{-9} kg N_2O/ MJ primary energy input to manufacturing (Ref. 16).

(t) Primary energy input to maintenance and repair of tractor for baling of 13.25 MJ/ha.a, of Hesston baler of 147 MJ/ha.a and of telescopic handler for loading in the field of 14.1MJ/ha.a, based on data for straw fuel recovery (Ref. 21) adjusted for collection of 2.28 t straw from 0.651 ha.a/t bioethanol and an estimated total nitrous oxide requirement of 1.866 x 10^{-9} kg N_2O/ MJ primary energy input to manufacturing (Ref. 18).

(u) Straw-fired combined heat and power plant based on a steam turbine with an overall efficiency of 85% and a load factor of 91%, consuming 202,827 t of straw (at 15% moisture content and 14.8 MJ/kg calorific value) to provide 67 t/hr or 186,126 MJ/hr of steam (matched to bioethanol plant requirements) and 36 MW (6.1 MW for bioethanol plant and 29.9 MW surplus) of electricity equal to 130,288 MJ/hr (Ref. 2). This provides total heat supplies of 1,193 MJ/t of clean sugar beet and total electricity supplies of 835 MJ/t of clean sugar beet (consisting of 141 MJ/t of clean sugar beet for bioethanol processing and 964 MJ/t of clean sugar beet of surplus for sale). Assuming 11% losses during baling and transport, 227,640 t of straw are required. Heat and electricity supplied by a straw-fired combined heat and power plant for washing, shredding and diffusion which requires 14 t/hr of steam, assumed to be 50% of total steam requirements of sugar plant (Ref. 2), equivalent to 186,126 x 14/67 = 38,892 MJ/hr, and an electricity consumption rate for washing, shredding and diffusion of 3.5 MW (Ref. 2). Heat and electricity supplied by a straw-fired combined heat and power plant for a steam consumption rate for purification of 1 t/hr and for fermentation, distillation and dehydration of 38 t/hr (Ref. 2), resulting in a total steam consumption rate of 39 t/hr or equivalent to 186,126 x 39/67 = 108,342 MJ/hr, and an electricity consumption rate for diffusion of 1.4 MW and for fermentation, distillation and dehydration of 1.2 MW (Ref. 2).

(v) Total clean sugar beet input of 1,257,774 t/a and a working time of 24 hr x 7 days x 48 weeks = 8,064 hr/a (Ref. 2), giving a clean sugar beet input rate of 156 t/hr.

(w) Land requirement of 0.651 ha.a/t bioethanol and partitioning, based on relative energy, with heat and electricity measured on an equivalent basis, to washing, shredding and diffusion (25%), to purification, concentration, fermentation, distillation and dehydration (75%), and allocation between bioethanol, pulp and vinasses (66.8%), and between bioethanol and vinasses (85.7%) resulting in a total allocation to bioethanol of (25% x 66.8%)+ (75% x 85.7%) = 81%.

(x) Average round trip distance of 80 km (Ref. 21) 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. 12).

(y) Baled straw requirement of 2.25 t/t bioethanol and partitioning, based on relative energy, with heat and electricity measured on an equivalent basis, to washing, shredding and diffusion (25%), to purification, concentration, fermentation, distillation and dehydration (75%), and allocation between bioethanol, pulp and vinasses (66.8%), and between bioethanol and vinasses (85.7%) resulting in a total allocation to bioethanol of (25% x 66.8%)+ (75% x 85.7%) = 81%.

(z) Diesel fuel consumption for baled straw handling in storage of 65.8 MJ/t of baled wheat straw (Ref. 21), 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_2O/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. 11).

(aa) Based on 2 tonnes of polyethylene sheeting used to protect each storage stack of 1,000 tonnes of baled wheat straw, with a life of 1 year and a direct energy requirement of 47 MJ/kg and a feedstock energy requirement of 46 MJ/kg for low density polyethylene (Ref. 21) and an estimated total nitrous oxide requirement of 1.866 x 10^{-9} kg N_2O/ MJ primary energy input to manufacturing (Ref. 16).

(bb) Primary energy input for manufacture of telescopic handler of 21.0 MJ/t of baled wheat straw (Ref. 21) and an estimated total nitrous oxide requirement of 1.866 x 10^{-9} kg N_2O/ MJ primary energy input to manufacturing (Ref. 16).

(cc) Primary energy input to maintenance and repair of telescopic handler of 7.2 MJ/t of baled wheat straw (Ref. 21) and an estimated total nitrous oxide requirement of 1.866 x 10^{-9} kg N_2O/ MJ primary energy input to manufacturing (Ref. 16).

(dd) Sulphuric acid (93% concentration) consumption rate of 0.18 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of 2.7 x 10^{-7} ± 3.0 x 10^{-7} kg N_2O/kg for sulphuric acid (Ref. 13).

(ee) Gypsum (calcium sulphate) consumption rate of 1.06 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of 5.9 x 10^{-7} kg N_2O/kg for gypsum (Ref. 13).

(ff) Hydrochloric acid (100% concentration) consumption rate of 0.025 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of 3.0 x 10^{-4} kg N_2O/kg for hydrochloric acid (Ref. 13)

(gg) Formaldehyde consumption rate of 0.15 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of 6.0 x 10^{-9} kg N_2O/kg for formaldehyde (Refs. 2 and 14 to 16).

(hh) Biocide consumption rate of 0.024 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of 5.0 x 10^{-9} kg N_2O/kg for biocide (Refs. 2 and 14 to 16).

(ii) Foam oil consumption rate of 0.03 kg/t of clean sugar beet (Ref. 2) and, assuming foam oil is similar to refined rapeseed oil, a nitrous oxide requirement of 1.79 x 10^{-3} ± 2.20 x 10^{-4} kg N_2O/kg of refined rapeseed oil (Ref. 17).

(jj) Soil recovery rate of 5.32% of clean sugar beet (Ref. 2), or 53.2 kg/t of clean sugar beet, and, assuming soil production is similar to sand extraction, a nitrous oxide requirement of 4.2 x 10^{-8} kg N_2O/kg for sand (Ref. 18).

(kk) Stone recovery rate of 0.39% of clean sugar beet (Ref. 2), or 3.9 kg/t of clean sugar beet, and, assuming stone production is similar to sand extraction, a nitrous oxide requirement of 4.2 x 10^{-8} kg N_2O/kg for sand (Ref. 18).

(ll) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(mm) Sulphur (as SO_2) consumption rate of 0.13 kg/t of clean sugar beet and a nitrous oxide requirement of 6.6 x 10^{-6} ± 1.8 x 10^{-6} kg N_2O/kg for sulphur (Ref. 13).

(nn) Soda (sodium carbonate) consumption rate of 0.05 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of 1.8 x 10^{-5} ± 0.5 x 10^{-6} kg N_2O/kg for soda (Ref. 13).

(oo) Anti-scalant consumption rate of 0.04 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of 6.0 x 10^{-8} kg N_2O/kg for anti-scalant (Refs. 2 and 14 to 16).

(pp) EDTA consumption rate of 0.055 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of 2.0 x 10^{-8} kg N_2O/kg for EDTA (Refs. 2 and 14 to 16).

(qq) Limestone consumption rate of 2.3% of clean sugar beet (Ref. 2), or 23 kg/t of clean sugar beet, and a nitrous oxide requirement of 3.5 x 10^{-7} kg N_2O/kg for limestone (Ref. 18).

(rr) Coke consumption rate of 0.18% of clean sugar beet (Ref. 2), or 1.8 kg/t of clean sugar beet, and a direct nitrous oxide requirement of 4.0 x 10^{-9} x 28.1 = 1.1 x 10^{-7} kg N_2O/kg and an indirect nitrous oxide requirement of 1.3 x 10^{-6} kg N_2O/kg for coke in the UK in 1996 (Ref. 11).

(ss) Anti-foam consumption rate of 253,344 kg/a (Ref. 2), or 0.20 kg/t of clean sugar beet, and, assuming similarity with anti-scalant, a nitrous oxide requirement of 6.0 x 10^{-8} kg N_2O/kg of anti-foam (Refs. 2 and 14 to 16).

(tt) Sulphuric acid (93% concentration) consumption rate of 380,016 kg/a, or 0.30 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement of 2.0 x 10^{-7} ± 3.0 x 10^{-7} kg N_2O/kg for sulphuric acid (Ref. 13).

(uu) Surplus electricity of 29.9 MW for 8,064 hr/a resulting in 868,009 GJ/a of electricity exported for sale, equivalent to 694 MJ/t of clean sugar beet, and a nitrous oxide requirement of 5.6 x 10^{-6} kg N_2O/MJ for displaced grid electricity supplies in the UK in 1996 (Ref. 11).

(vv) LimeX production rate of 45 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement 1.6 x 10^{-5} kg N_2O/kg for lime (Ref. 7).

(ww) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 85.7% to bioethanol.

(xx) Direct nitrous oxide emissions of 73 g N_2O/t of straw fuel feed from the combined heat and power plant (Ref. 23) and straw fuel feed requirement of 2.03 t/t bioethanol and with heat and electricity measured on an equivalent basis, to washing, shredding and diffusion (25%), to purification, concentration, fermentation, distillation and dehydration (75%), and allocation between bioethanol, pulp and vinasses (66.8%), and between bioethanol and vinasses (85.7%) resulting in a total allocation to bioethanol of (25% x 66.8%)+ (75% x 85.7%) = 81%.

(yy) Primary energy input of 950,000 GJ for construction of a bioethanol plant, with a capacity of a 100,000 t/a and a 20 year life, based on a total capital cost of £38.0 m (Ref. 2) and an estimated total nitrous oxide requirement of 1.866×10^{-9} kg N_2O/MJ of primary energy input to plant construction (Ref. 16).

(zz) Primary energy input of 2,588,400 GJ for construction of a straw-fired combined heat and power plant with a 67t/hr steam output and a 36 MW rated electricity output, based pro rata on data for a straw-fired combined heat and power plant with a 13.0 MW rated heat output and a 5.0 MW rated electricity output (Ref. 21), with a 25 year life and an estimated total nitrous oxide requirement of 1.866×10^{-9} kg N_2O/MJ primary energy input to construction (Ref. 16), assuming 85.7% contribution to bioethanol by price of co-products.

(ab) Nitrous oxide output of annual plant maintenance assumed to be 1.5% of primary energy input to plant construction (Ref. 2).

(ac) Ash sent for spreading as a fertiliser on fields at an average round trip distance of 80 km (Ref. 21) by bulk road carrier transport with a direct nitrous oxide requirement of $4.6 \times 10^{-7} \pm 1.7 \times 10^{-8}$ kg N_2O/t-km, an indirect nitrous oxide requirement of $2.1 \times 10^{-8} \pm 8 \times 10^{-10}$ kg N_2O/t-km and a total methane requirement of $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8}$ kg N_2O/t-km (Ref. 12).

(ad) Ash output of 5.5% of straw fuel feed (Ref. 21) and straw requirement of 2.03 t/t of bioethanol.

(ae) Average round trip distance of 450 km (Ref. 19) by bulk road carrier transport with a direct nitrous oxide requirement of $4.6 \times 10^{-7} \pm 1.7 \times 10^{-8}$ kg N_2O/t-km, an indirect nitrous oxide requirement of $2.1 \times 10^{-8} \pm 8 \times 10^{-10}$ kg N_2O/t-km and a total nitrous oxide requirement of $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8}$ kg N_2O/t-km (Ref. 11).

References

1. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 28 April 2003.

2. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 2 May 2003.

3. Private communication with D. Darby of British Sugar plc., Peterborough, United Kingdom, 14 August 2002.

4. Private communication with G. Punter of British Sugar plc., Peterborough, United Kingdom, 8 May 2003.

5. "British Sugar Field Crop Survey 2001"

6. "Evaluation of the Comparative Energy, Global Warming and Social Costs and Benefits of Biodiesel" by N. D. Mortimer, P. Cormack, M. A. Elsayed and R. E. Horne, Report No. 20/1, Resources Research Unit, Sheffield Hallam University, United Kingdom, January 2003, for the Department for the Environment, Food and Rural Affairs, www.defra.

7. "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.

8. "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.

9. "Pesticide Use Survey Reports" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.

10. British Sugar Internal Survey 2001

11. "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.

12. "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.

13. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, Open University, Milton Keynes, United Kingdom, December 1977.

14. "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.

15. Producer price indices for other chemicals n.e.c., www.statistics.gov.uk, accessed 7 February 2003.

16. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.

17. "Carbon and Energy Balances for a Range of Biofuel Options" by M. A. Elsayed, R. Matthews and N. D. Mortimer, B/B6/00784/REP, Energy Technology Support Unit, Harwell, United Kingdom, March 2003, www.shu.ac.uk/rru/projects/biofuels/biofuels.html.

18. "Handbook of Industrial Energy Analysis" by I. Boustead and G. Hancock, Ellis Horwood, Chichester, United Kingdom, 1979.

19. "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.

Spreadsheet for Total Greenhouse Gas Outputs from Bioethanol Production from Sugar Beet using a Straw-fired Combined Heat and Power Plant with a SteamTurbine (Model 8)

Functional Unit:	Bioethanol at point of distribution derived from sugar beet using straw-fired combined heat and power with a steam turbine during processing
Final Unit of Measurement:	1 tonne of bioethanol
Relevant Location:	United Kingdom
Relevant Period:	2002
Allocation Procedures:	Based on a market price for 13.296 tonnes of sugar beet on the farm of £22.00/t (Ref. 1) and an effective price for 1.507 tonnes of sugar beet tops (dry matter) of £10.0/t, based on an average market price of £2.00/t (wet basis) with a 80% moisture content (Ref. 2), substitution of 0.669 tonnes of soil from washing by soil from main sources, substitution of 0.049 tonnes of stones from washing by stones from quarrying, an effective average price for 14.560 tonnes of thin juice (15% solids and 88% sugar purity) of £16.2/t, derived from a price for thick juice (67% solids and 92% sugar purity) of £72.48/t (Ref. 3), and an effective average price for 25.996 tonnes of pulp (97% moisture content) of £2.56/t, derived from an average market price for animal feed pellets (15% moisture content) of £72.50/t (Ref. 2), substitution of 0.566 tonnes of LimeX by agricultural lime, and an assumed price for bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solids and 66.5% sugar purity) of £122.15/t, based on the price of thick juice (Ref. 4).

Contribution	Per Unit	Total Greenhouse Gas Output (kg eq CO_2)						Notes
		Direct		Indirect		Total		
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	*ha.a*	*119*	*±40*	*690*	*±86*	*809*	*±95*	(a)
- P Fertiliser	*ha.a*	-	-	*62*	*±9*	*62*	*±9*	(a)
- K Fertiliser	*ha.a*	-	-	*57*	*±9*	*57*	*±9*	(a)
- Pesticides	*ha.a*	-	-	*15*	*±2*	*15*	*±2*	(a)
- Herbicide	*ha.a*	-	-	*2*	-	*2*	-	(a)
- Insecticide	*ha.a*	-	-	*1*	-	*1*	-	(a)
- Seed	*ha.a*	-	-	*8*	*±1*	*8*	*±1*	(a)
- Diesel Fuel	*ha.a*	*610*	*±96*	*76*	*±33*	*686*	*±102*	(a)
Reference System:								
- Diesel Fuel	*ha.a*	*- 63*	*±10*	*- 7*	*±3*	*- 70*	*±10*	(a)
Sub-Totals	*ha.a*	*666*	*±104*	*904*	*±93*	*1,570*	*±140*	
	t be	**108**	**±17**	**147**	**±15**	**255**	**±23**	(b)
Transport:								
- Diesel Fuel	*t ssb*	*5*	-	*2*	-	*7*	-	(a)
	t be	**44**	**-**	**18**	**-**	**62**	**-**	(c)
Straw Baling:								
- N Fertiliser	*ha.a*	*68*	*±11*	*397*	*±45*	*465*	*±46*	(a)
- P Fertiliser	*ha.a*	-	-	*17*	*±3*	*17*	*±3*	(a)
- K Fertiliser	*ha.a*	-	-	*56*	*±8*	*56*	*±8*	(a)
- Diesel Fuel	*ha.a*	*23*	*±3*	*3*	-	*26*	-	(a)
- Machinery	*ha.a*	-	-	*19*	*±3*	*19*	*±3*	(a)
- Twine	*ha.a*	-	-	*7*	*±1*	*7*	*±1*	(a)
- Maintenance	*ha.a*	-	-	*8*	*±1*	*8*	*±1*	(a)
Sub-Totals	*ha.a*	*89*	*±11*	*507*	*±46*	*596*	*±47*	
	t be	**47**	**±6**	**267**	**±24**	**314**	**±25**	(d)
Straw Transport:								
- Diesel Fuel	*t bws*	*4*	-	*1*	-	*5*	-	(a)
	t be	**7**	**-**	**2**	**-**	**9**	**-**	(d)
Straw Storage:								
- Diesel Fuel	*t bws*	*5*	*±1*	*1*	-	*6*	*±1*	(a)
- Sheeting	*t bws*	-	-	*12*	*±2*	*12*	*±2*	(a)
- Machinery	*t bws*	-	-	*1*	-	*1*	-	(a)
- Maintenance	*t bws*	-	-	-	-	-	-	(a)
Sub-Totals	*t bws*	*5*	*±1*	*14*	*±2*	*19*	*±2*	
	t be	**9**	**±2**	**26**	**±4**	**35**	**±4**	(d)
Wash., Shred. and Diffusion:								
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	(a)
- Gypsum	*t csb*	-	-	-	-	-	-	(a)
- Hydrochloric Acid	*t csb*	-	-	-	-	-	-	(a)
- Formaldehyde	*t csb*	-	-	-	-	-	-	(a)
- Biocide	*t csb*	-	-	-	-	-	-	(a)
- Foam Oil	*t csb*	-	-	-	-	-	-	(a)
Credits:								
- Soil	*t csb*	-	-	-	-	-	-	(a)
- Stones	*t csb*	-	-	-	-	-	-	(a)
Sub-Totals	*t csb*	-	-	-	-	-	-	
	t be	**-**	**-**	**-**	**-**	**-**	**-**	(e)
Purific., Conc., Fermentation, Distillation and Dehydration:								
- Sulphur	*t csb*	-	-	-	-	-	-	(a)
- Soda	*t csb*	-	-	-	-	-	-	(a)
- Anti-Scalant	*t csb*	-	-	-	-	-	-	(a)
- EDTA	*t csb*	-	-	-	-	-	-	(a)
- Limestone	*t csb*	-	-	-	-	-	-	(a)
- Coke	*t csb*	-	-	-	-	-	-	(a)
- Anti-Foam	*t csb*	*5*	*±1*	*1*	-	*6*	*±1*	(a)
- Sulphuric Acid	*t csb*	-	-	-	-	-	-	(a)
Credit:								
- Electricity	*t csb*	*- 346*	**±48**	-	-	*- 346*	*±48*	(a)
- LimeX	*t csb*	-	-	*- 8*	*±1*	*- 8*	*±1*	(a)
Sub-Totals	*t csb*	*- 341*	*±48*	*- 7*	*±1*	*- 348*	*±48*	
	t be	**- 3,676**	**±517**	**- 75**	**±11**	**- 3,751**	**±517**	(f)
Direct Emissions		**41**	**±6**	**-**	**-**	**41**	**±6**	(f)
Plant Construction	**t be**	**-**	**-**	**69**	**±8**	**69**	**±8**	(a)
Plant Maintenance	**t be**	**-**	**-**	**24**	**±3**	**24**	**±3**	(a)
Ash Disposal	*t ash*	*4*	-	-	-	*4*	-	(a)
	t be	**-**	**-**	**-**	**-**	**-**	**-**	(a)
Distribution	**t be**	**25**	**±1**	**7**	**±1**	**32**	**±1**	(a)
Totals	**t be**	**- 3,395**	**±517**	**423**	**±32**	**- 2,910**	**±518**	

Biofuel Specifications

Density of bioethanol	= 0.79 kg/l
Net calorific value of bioethanol	= 26.72 MJ/kg
Gross calorific value of bioethanol	= 29.74 MJ/kg

Abbreviations

ha.a	= hectare year
t csb	= tonne of clean sugar beet
t ssb	= tonne of soiled sugar beet
t be	= tonne of bioethanol

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 0.255 ha.a/t of bioethanol, partitioning between13.296 t of sugar beet at farm with a price of £22/t (Ref. 1) and 1.507 t sugar beet tops (dry matter) with an effective price of £10.00/t, based on an average market price of £2.00/t (wet basis) 80% moisture content (Ref. 2), and partitioning between 14.560 t of thin juice with an effective price of £16.2/t and an effective average price for 25.996 t of pulp with a moisture content of 97% of £2.56/t, derived from an average price for animal feed pellets with a moisture content of 15% of £72.50/t (Ref. 2), and an assumed price of bioethanol of £529.00/t (Ref. 3) and an effective price for 0.720 tonnes of vinasses (55% solid and 66.5% sugar purity), based on the price of thick juice, giving an allocation of 95.1% x 78.0% x 85.7% = 63.6% to bioethanol.

(c) Soiled sugar beet requirement of 13.296 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol.

(d) Baled straw requirement of 2.25 t/t bioethanol and partitioning, based on relative energy, with heat and electricity measured on an equivalent basis, to washing, shredding and diffusion (25%), to purification, concentration, fermentation, distillation and dehydration (75%), and allocation between bioethanol, pulp and vinasses (66.8%), and between bioethanol and vinasses (85.7%) resulting in a total allocation to bioethanol of (25% x 66.8%)+ (75% x 85.7%) = 81%.

(e) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 78.0% x 85.7% = 66.8% to bioethanol

(f) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 85.7% to bioethanol.