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#### 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 grain and sugar beet (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.

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# 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<sub>2</sub> 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 1Agreed Models for the Production of Bioethanol from Wheat Grain and<br/>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 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<sub>2</sub> emissions, such as the manufacture of cement and nitrogen fertiliser, must be taken into account. Whether any CO<sub>2</sub> 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<sub>2</sub> released must be included. Additionally, the carbon in fossil fuels used as feedstocks in chemical processes may be released as CO<sub>2</sub> emissions as a result of chemical reactions. This is an important consideration for the production of nitrogen fertiliser from natural gas. Similarly, direct N<sub>2</sub>O 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<sub>2</sub> and total GHG emissions, in kg, are quoted in whole numbers, whilst results for CH<sub>4</sub> and N<sub>2</sub>O 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 coand 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<sub>2</sub>, 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 <sup>(a)</sup>	0.794 <sup>(b)</sup>
Net Calorific Value (MJ/kg)	43.99 <sup>(c)</sup>	26.70 <sup>(d)</sup>
Gross Calorific Value (MJ/kg)	47.10 <sup>(a)</sup>	29.74 <sup>(e)</sup>

Notes

(a) From Ref. 7.

(b) From Ref. 8.

(c) From Ref. 9. (d) From Ref. 10.

(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<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O) and as a total value measured as equivalent carbon dioxide (eq. CO<sub>2</sub>) derived using quoted global warming potentials (see Section 2.2). These GHG requirements include both direct (petrol combustion) and indirect (petrol production) emissions.

Fuel	Energy Requirement <sup>(a)</sup> (MJ/MJ)	Carbon Requirement <sup>(b)</sup> (kg CO <sub>2</sub> /MJ)	Methane Requirement <sup>(c)</sup> (g CH <sub>4</sub> /MJ)	Nitrous Oxide Requirement <sup>(d)</sup> (g N <sub>2</sub> O/MJ)	Total GHG Requirement <sup>(e)</sup> (kg eq. CO <sub>2</sub> /MJ)
Unleaded Petrol from Crude Oil	1.19	0.081	0.022	0.000028	0.081

#### Table 3 **Baseline Results for Unleaded Petrol**

Notes

Primary energy input per unit delivered energy output, based on the net calorific value of petrol. (a) Specified production and combustion emissions per unit delivered energy output, based on the net calorific

(b) value of petrol.

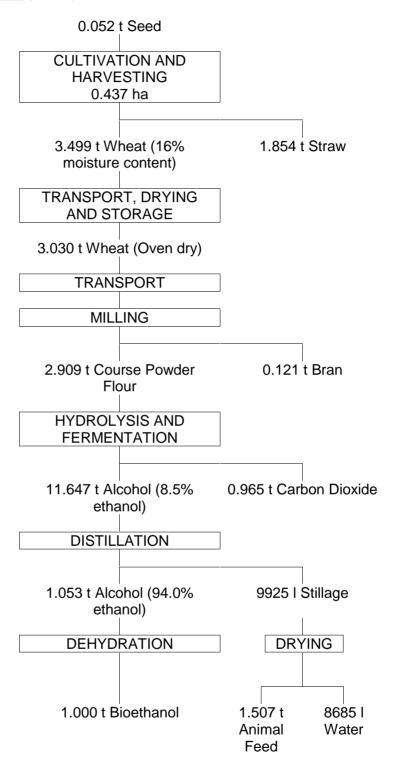
Specified production emissions per unit delivered energy output, based on the net calorific value of petrol, (c) excluding direct methane emissions during combustion due to variations in vehicle engine performance.

(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

Assuming 24.5 g eq.  $CO_2/g$  CH<sub>4</sub> and 320 g eq.  $CO_2/g$  N<sub>2</sub>O. (e)

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 <u>Baseline Flow Chart for the Production of Bioethanol from Wheat</u> <u>Grain in the UK</u> (Ref. 3)



# Table 4Baseline Results for Bioethanol Production from Wheat Grain in the<br/>UK (Ref. 3)

Fuel	Energy Requirement <sup>(a)</sup> (MJ/MJ)	Carbon Requirement <sup>(a)</sup> (kg CO <sub>2</sub> /MJ)	Methane Requirement <sup>(a)</sup> (g CH₄/MJ)	Nitrous Oxide Requirement <sup>(a)</sup> (g N <sub>2</sub> O/MJ)	Total GHG Requirement <sup>(a)</sup> (kg eq. CO <sub>2</sub> /MJ)
Bioethanol from Wheat Grain	0.464 ± 0.032	0.024 ± 0.002	0.028 ± 0.003 <sup>(b)</sup>	0.012 ± 0.001 <sup>(b)</sup>	0.029 ± 0.002 <sup>(c)</sup>

<u>Note</u>

(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.

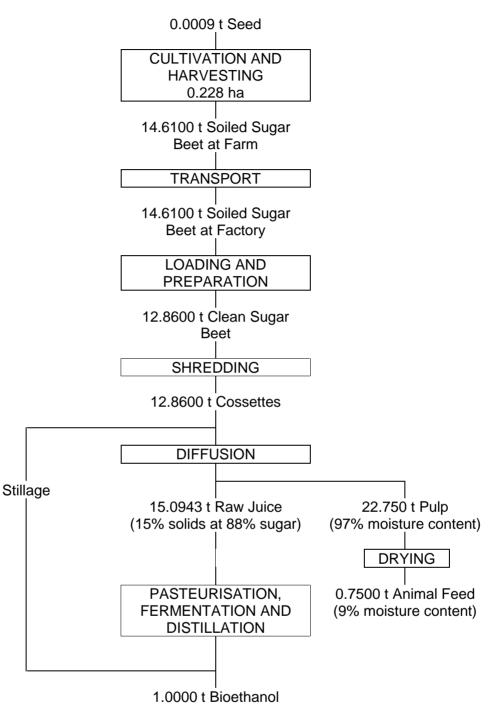
(d) Excluding the carbon dioxide equivalent of direct methane and nitrous oxide emissions during the combustion of bioethanol.

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

O a staile stile s	Duine a mu	O a sila a si	Mathana	Nitra o Outria	Tatal OLIO
Contribution	Primary	Carbon	Methane	Nitrous Oxide	Total GHG
	Energy	Dioxide	Emissions	Emissions	Emissions
	Inputs	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<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O) 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





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 <sup>(a)</sup> (MJ/MJ)	Carbon Requirement <sup>(a)</sup> (kg CO <sub>2</sub> /MJ)	Methane Requirement <sup>(a)</sup> (g CH₄/MJ)	Nitrous Oxide Requirement <sup>(a)</sup> (g N <sub>2</sub> O/MJ)	Total GHG Requirement <sup>(a)</sup> (kg eq. CO <sub>2</sub> /MJ)
Bioethanol from Sugar Beet	0.496 ± 0.044	0.034 ± 0.003	0.013 ± 0.001 <sup>(b)</sup>	0.018 ± 0.002 <sup>(c)</sup>	$0.040 \pm 0.003^{(d)}$

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.

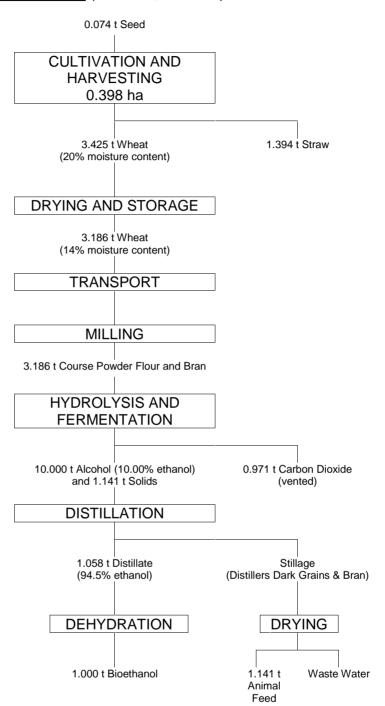
Table 7	Breakdown of Contributions to Baseline Results for Bioethanol
	Production from Sugar Beet in the UK (Ref. 3)

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)



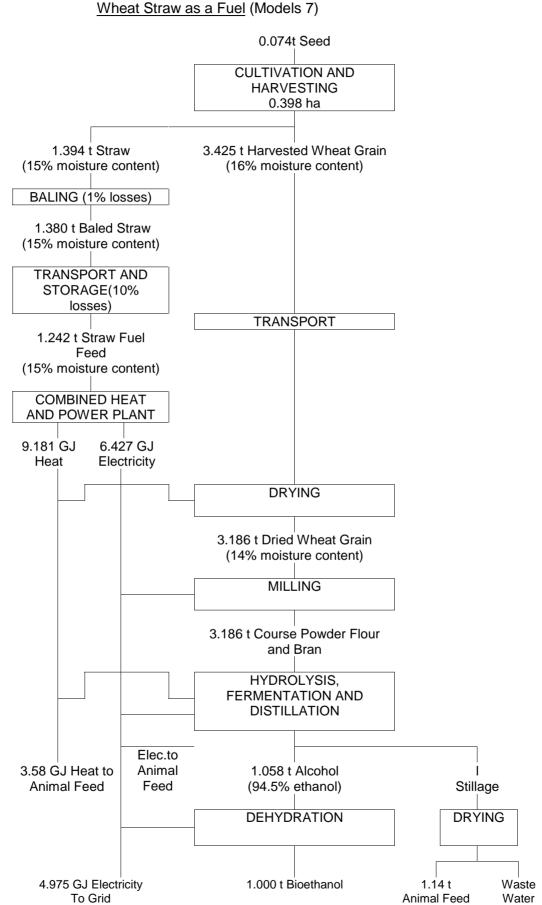


Figure 4 Flow Chart for the Production of Bioethanol from Wheat Grain using Wheat Straw as a Fuel (Models 7)

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 byproducts 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

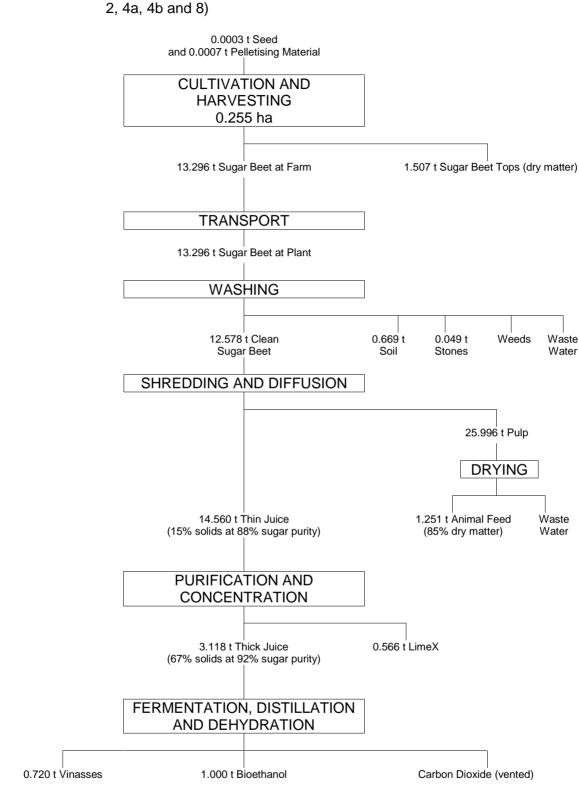
find a separate market as a material. The average round trip distance between the farm and the bioethanol production plant is taken to be 186 km. A natural gas-fired combined heat and power plant, with a gas turbine and an overall thermal efficiency of 85%, is matched to the steam and hot water requirements 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.



#### 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 vield 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 <sup>(a)</sup> (MJ/MJ)	Carbon Requirement <sup>(a)</sup> (kg CO <sub>2</sub> /MJ)	Methane Requirement <sup>(a)</sup> (g CH₄/MJ)	Nitrous Oxide Requirement <sup>(a)</sup> (g N <sub>2</sub> O/MJ)	Greenhouse Gas Requirement <sup>(a)</sup> (kg eq CO <sub>2</sub> /MJ)
Natural Gas-fired Boiler and Grid Electricity (Model 1)	$\textbf{0.644} \pm \textbf{0.041}$	$0.031\pm0.002$	$0.042 \pm 0.003^{(b)}$	$0.039 \pm 0.005^{(c)}$	$0.044 \pm 0.002^{(\text{d})}$
Natural Gas-fired Combined Heat and Power Plant with Steam Turbine (Model 3)	$0.597 \pm 0.042$	0.031 ± 0.002	$0.040 \pm 0.004^{(b)}$	$0.039 \pm 0.005^{(c)}$	$0.044 \pm 0.003^{(\text{d})}$
Natural Gas-fired Combined Heat and Power Plant with Gas Turbine (Model 3a)	0.404± 0.040	$0.021\pm0.002$	$0.009 \pm 0.004^{(b)}$	$0.039 \pm 0.005^{(c)}$	$0.033 \pm 0.003^{(\text{d})}$
Straw-fired Combined Heat and Power Plant with Steam Turbine (Model 7)	-0.070 ± 0.190	-0.002 ± 0.001	$\textbf{-0.046} \pm 0.002^{(b)}$	$0.055 \pm 0.005^{\text{(c)}}$	$0.014 \pm 0.002^{(\text{d})}$

#### Note

Based on the net calorific value of bioethanol.

(a) (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 <sup>(a)</sup> (MJ/MJ)	Carbon Requirement <sup>(a)</sup> (kg CO <sub>2</sub> /MJ)	Methane Requirement <sup>(a)</sup> (g CH₄/MJ)	Nitrous Oxide Requirement <sup>(a)</sup> (g N <sub>2</sub> O/MJ)	Greenhouse Gas Requirement <sup>(a)</sup> (kg eq CO <sub>2</sub> /MJ)
Natural Gas-fired Boiler and Grid Electricity (Model 2)	$0.828\pm0.086$	$0.041\pm0.003$	$0.074 \pm 0.006^{\text{(b)}}$	$0.011 \pm 0.002^{(c)}$	$0.047 \pm 0.003^{(\text{d})}$
Natural Gas-fired Combined Heat and Power Plant with Steam Turbine (Model 4a)	$0.678\pm0.064$	$0.034\pm0.003$	$0.055 \pm 0.006^{\text{(b)}}$	$0.011 \pm 0.002^{(c)}$	$0.039 \pm 0.003^{(d)}$
Natural Gas-fired Combined Heat and Power Plant with Gas Turbine (Model 4b)	0.360 ± 0.130	$\textbf{0.019} \pm \textbf{0.006}$	$0.007 \pm 0.004^{\text{(b)}}$	$0.010 \pm 0.002^{(c)}$	$0.022\pm0.003^{(d)}$
Straw-fired Combined Heat and Power Plant with Steam Turbine (Model 8)	-0.521 ± 0.130	-0.111 ± 0.020	$\text{-}0.337 \pm 0.052^{(b)}$	$0.032 \pm 0.003^{(c)}$	$\textbf{-0.109} \pm 0.019^{(d)}$

Note

(a) Based on the net calorific value of bioethanol.

Excluding direct methane emissions from the combustion of bioethanol. (b)

Excluding direct nitrous oxide emissions from the combustion of bioethanol. (C)

Excluding direct methane and nitrous oxide emissions from the combustion of bioethanol. (d)

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<sub>2</sub> and total GHG emissions associated with the options for producing bioethanol. In order of prominence, results improve from a conventional arrangement with a natural gasfired 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<sub>2</sub> emissions specifically, these bioethanol production options can be considered to be truly "carbon neutral" or "carbon beneficial" which means that CO<sub>2</sub> credits exceed all the associated CO<sub>2</sub> emissions of the entire process chain. Total CH<sub>4</sub> 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<sub>2</sub>O 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 Saving	s <sup>(a)</sup>	
	Primary Energy	Carbon Dioxide	Methane	Nitrous Oxide	Total Greenhouse Gases
	(%)	(%)	(%)	(%)	(%)
<b>Bioethanol from Wheat Grain:</b> Natural Gas- fired Boiler and Grid Electricity (Model 1)	46	62	- 91	- 139,186	46
<b>Bioethanol from Wheat Grain</b> : Natural Gas- fired Combined Heat and Power Plant with Steam Turbine (Model 3)	50	62	- 82	- 139,186	46
<b>Bioethanol from Wheat Grain</b> : Natural Gas- fired Combined Heat and Power Plant with Gas Turbine (Model 3a)	66	74	59	- 139,186	59
<b>Bioethanol from Wheat Grain</b> : Straw-fired Combined Heat and Power Plant with Steam Turbine (Model 7)	106	102	309	- 196,329	83
<b>Bioethanol from Sugar Beet:</b> Natural Gas- fired Boiler and Grid Electricity (Model 2)	30	49	- 236	- 39,186	42
<b>Bioethanol from Sugar Beet:</b> Natural Gas- fired Combined Heat and Power Plant with Steam Turbine (Model 4a)	43	58	- 150	- 39,186	52
<b>Bioethanol from Sugar Beet:</b> Natural Gas- fired Combined Heat and Power Plant with Gas Turbine (Model 4b)	70	77	68	- 35,614	73
<b>Bioethanol from Sugar Beet:</b> 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<sub>4</sub> and N<sub>2</sub>O 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<sub>2</sub> 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<sub>4</sub> 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<sub>4</sub> emissions are associated with the production of unleaded petrol, mainly in crude oil extraction activities, compared with CH<sub>4</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> emissions and total GHG emissions.

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#### **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)

- Diesel Fuel Totals	t be t be	369 9,398	±14 ±967	129 6,379	±16 ±524	- 1,439	- ±57	498 17,216	±21 ±1,103	(ee)
Distribution:		0.00		400	140			400	104	
Maintenance	t be	-	-	162	±24	-	-	162	±24	(c, dd)
Construction Plant	t be	-	-	541	±81	-	-	541	±81	(c, cc)
Plant	L DE	23	±1		±10	-	-	10	±12	ິມມ
Dehydration: - Electricity	t be	25	±7	53	±10	-	-	78	±12	(c, q, aa bb)
Sub-Totals	t de t be	7,035 <b>6,282</b>	±1,031 <b>±921</b>	3,035 <b>2,710</b>	±430 <b>±384</b>	-	-	10,070 <b>8,992</b>	±1,118 <b>±998</b>	(z)
- Calcium Chlor.			-	_	±1	-	-	_	±1	(c, y)
- Enzyme AA	t de t de	-	-	43 6	±6	-	-	43 6	±6	(c, x)
- Enzyme AMG	t de	-	-	110	±16	-	-	110	±16	(c, w)
- Sulphuric Acid	t de	-	-	66	±74	-	-	66	±74	(c, v)
- Diam. Phosph.	t de	-	-	55	±8	-	-	55	±8	(c, u)
- Caustic Śoda	t de	-	-	836	±125	-	-	836	±125	(c, t)
- Electricity	t de	580	±153	1,209	<u>+</u> 221	-	-	1,789	±268	(c, q – s
and Distillation: - Natural Gas	t de	6,455	±1,020	710	±338	-	-	7,165	±1,075	(c, q - s
Hydrolysis, Fermentation										
Milling,	t be	409	±16	143	±19	-	-	552	±25	(p)
Transport: - Diesel Fuel	t dwg	152	±6	53	±7	-	-	205	±9	(o)
	t hwg t be	977	±53 ±153	37 107	±78 ±52	-	-	1,084	±56 ±162	(c, m) (n)
Drying: - Diesel Fuel	thuc	338	±53	37	±18			375	±56	(c, m)
Sub-Totals	ha.a <b>t be</b>	<i>4,568</i> <b>1,336</b>	±880 <b>±257</b>	8,660 <b>2,534</b>	±1,168 <b>±342</b>	4,920 <b>1,439</b>	±196 <b>±57</b>	18,148 <b>5,309</b>	±1,477 <b>±432</b>	(I)
- Diesel Fuel	ha.a	- 922	±146	- 101	±48	-	-	-1,023	±154	(c, k)
System:										
Reference		,								(-) <b>)</b>
- Diesel Fuel	ha.a	5,490	±868	604	±288	-	-	6,094	±914	(c, j)
- Seed	ha.a	-	-	2,498	±375	-	-	2,498	±375	(c, i)
- Fungicide	ha.a	-	-	274	±41	-	-	274	±00	(c, g) (c, h)
- Insecticide	ha.a	-	-	219	±33	-	-	219	±33	(c, r) (c, g)
- Herbicide	ha.a	-	-	27	±4	-	-	27	±4	(c, c) (c, f)
- Pesticide	ha.a	-	-	548	±82	-	-	548	±82	(c, d) (c, e)
- K Fertiliser	ha.a		-	515	±223	-	-	515	±223	(b, c) (c, d)
- N Fertiliser	ha.a ha.a	-	-	2,592 1,484	±1,036 ±223	4,920 -	±196	7,512 1,484	±1,054 ±223	(a) (b, c)
Harvesting: - N Fertiliser	h			2 500	11.000	4 000	1100	7 540	14 054	(-)
Cultivation and	. <u> </u>									
	Unit	Value	ect Range	Value	rect Range	Value	stock Range	Value	tal Range	Notes
Contribution	Per Unit	Die	oot	ا- ما		y Energy I		<b>.</b>	tol	Note -
	1	giving a 8 and 1.000			l at £494/t	(Ref. 4), g	iving a 84.			
		and 3.425	tonnes of	harvested	wheat gra	in with 20°	% moisture	e content a	t £69/t (Re	ef. 2),
Allocation Proced	ures:	Based on average market prices, assuming 1.394 tonnes of wheat straw a							v at £25/t (	Ref. 1)
Relevant Period:	•	2002								
Relevant Location		United Kingdom								
Final Unit of Maar		grid electricity during processing t: 1 tonne of bioethanol								
Final Unit of Meas	urement.				•					

**Biofuel Specifications** 

Density of bioethanol Net calorific value of bioethanol Gross calorific value of bioethanol

#### **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<sub>2</sub>O/ha.a assuming 1.205 kg K<sub>2</sub>O/kg K, and a total energy requirement for potash fertiliser of 9.3 MJ/ kg K<sub>2</sub>O (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).
- (I) 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).

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

Functional Unit: :	grid ele	ctricity durin	of distributio		m wheat usir	ng a natural	gas-fired bo	iler and
Final Unit of Measurem	ent: 1 tonne	e of bioethar	nol					
Relevant Location:	United	Kingdom						
Relevant Period:	2002							
Allocation Procedures:	and 3.4 giving a	25 tonnes o 87.1% allo	market price f harvested v cation to bioe f bioethanol	vheat grain v ethanol, and	vith 20% moi 1.141 tonnes	sture conten s of animal fe	nt at £69/t (R eed at £80/t	ef. 2), (Ref. 3)
Contribution	Per			Carbon Di	ioxide Outpu	t (kg CO <sub>2</sub> )		
	Unit	Di	rect	Indi	irect	To	otal	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, g) (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:	na.a	0//	200		120	72 1	200	(0, j)
- Diesel Fuel	ha.a	- 63	±10	- 7	±3	- 70	±11	(c, k)
	na.a	- 05	10	- /	±5	- 70	±//	(C, K)
Sub-Totals	ha.a	314	±61	565	±57	879	±83	
Sub-Totals	t be	92	±18	165	±17	257	±25	(I)
Draina	l De	52	10	105	11/	231	125	(1)
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:								
<ul> <li>Natural Gas</li> </ul>	t de	270	±41	9	±8	279	±42	(c,q - s)
- Electricity	t de	-	-	87	±13	87	±13	(c,q-s)
- Caustic Šoda	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)
			1					/
Sub-Totals	t de	270	±41	157	±17	427	±45	
	t be	241	±37	140	±15	381	±40	(z)
Dehydration:					-		-	(c, q, aa
- Electricity	t be	-	-	4	±1	4	±1	(0, q, uu bb)
Plant Construction	t be	-	-	27	±4	27	±4	(C, CC)
Plant Maintenance	t be	_		8	±4	8	±4	(c, cc) (c, dd)
Distribution:	L DE	-	-	0	± 1	0	± 1	(c, uu)
- Diesel Fuel	t be	25	±1	7	±1	32	±1	(ee)
	L NG	451	_ <u> </u>	1	<b>1</b>	32		(ee)

#### **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

t hwg

t dwg

hectare year
tonne of harvested wheat grain
tonne of dried wheat grain
tonne of distillate ethanol (94.5% alcohol) t de

t be = tonne of bioethanol

#### <u>Notes</u>

- (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<sub>2</sub>/kg N (Ref. 6).
- (b) Phosphate fertiliser application rates of 41 kg P/ha.a (Ref. 5), or 93.9 kg P<sub>2</sub>O<sub>5</sub>/ ha.a assuming 2.290 kg P<sub>2</sub>O<sub>5</sub>/kg P, and a total carbon requirement for phosphate fertiliser of 0.700 kg CO<sub>2</sub>/kg P<sub>2</sub>O<sub>5</sub> (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<sub>2</sub>O/ha.a assuming 1.205 kg K<sub>2</sub>O/kg K, and a total carbon requirement for potash fertiliser of 0.453 kg CO<sub>2</sub>/ kg K<sub>2</sub>O (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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/kg (Ref. 7).
- Sowing rate of 185 kg/ha.a (Ref. 10) and a total carbon requirement of 0.547 kg CO<sub>2</sub>/kg of seed based on a ratio of 0.0405 kg CO<sub>2</sub>/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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0081 kg CO<sub>2</sub>/MJ and a total carbon requirement of 0.0767 kg CO<sub>2</sub>/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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0081 kg CO<sub>2</sub>/MJ and a total carbon requirement of 0.0767 kg CO<sub>2</sub>/MJ for diesel fuel in the UK in 1996 (Ref. 12).
- (I) 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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0081 kg CO<sub>2</sub>/MJ and a total carbon requirement of 0.0767 kg CO<sub>2</sub>/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<sub>2</sub>/t-km, an indirect carbon requirement of 0.0161 ± 0.0017 kg CO<sub>2</sub>/tkm and a total carbon requirement of 0.0723 ± 0.0027 kg CO<sub>2</sub>/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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0017 kg CO<sub>2</sub>/MJ and a total carbon requirement of 0.0539 kg CO<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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  $0.13 \pm 0.16$  kg CO<sub>2</sub>/ 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<sub>2</sub>/ 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<sub>2</sub>/ 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<sub>2</sub>/ 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<sub>2</sub> 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<sub>2</sub>/£ (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<sub>2</sub>/t-km, an indirect carbon requirement of 0.0161 ± 0.0017 kg CO<sub>2</sub>/t-km and a total carbon requirement of 0.0723 ± 0.0027 kg CO<sub>2</sub>/t-km (Ref. 13).

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

Functional Unit: :		anol at point ctricity durin		n derived fro	m wheat usir	ng a natural	gas-fired boi	ler and
Final Unit of Measuren				•				
Relevant Location:	United	Kingdom						
Relevant Period:	2002	0						
Allocation Procedures:	Based	on average i	market price	s, assuming	1.394 tonnes	s of wheat st	raw at £25/t	(Ref. 1)
				vheat grain w				
	giving a	a 87.1% alloo	cation to bioe	ethanol, and	1.141 tonnes	of animal fe	ed at £80/t (	Ref. 3)
	and 1.0	000 tonnes of	f bioethanol	at £494/t (Re	f. 4), giving a	a 84.4% alloo	cation to bio	ethanol.
Contribution	Per				e Output (ko			
	Unit	Dir	ect	Indi	rect	To	otal	Notes
		Value	Range	Value	Range	Value	Range	-
Cultivation and					-			
Harvesting:								
- N Fertiliser	ha.a	-	-	0.666	±0.111	0.666	±0.111	(a)
<ul> <li>P Fertiliser</li> </ul>	ha.a	-	-	0.002	-	0.002	-	(b, c)
<ul> <li>K Fertiliser</li> </ul>	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)
<ul> <li>Diesel Fuel</li> </ul>	ha.a	0.003	-	0.112	±0.017	0.115	±0.017	(c, j)
Reference System:								
<ul> <li>Diesel Fuel</li> </ul>	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	(I)
Drying:								
- Diesel Fuel	t hwg	0.001	-	0.007	±0.001	0.008	±0.001	(c, m)
<b>-</b> .	t be	0.003	-	0.020	±0.003	0.023	±0.003	(n)
Transport:	6.4			0.000		0.000		(-)
- Diesel Fuel	t dwg	-	-	0.003	-	0.003	-	(0)
M'll's so the dealers is	t be		-	0.008	-	0.008	-	(p)
Milling, Hydrolysis,								
Fermentation and								
Distillation:	t de	0.019	±0.016	0.550	±0.085	0.578	±0.087	(0,0,0)
- Natural Gas	t de	0.019	±0.076	0.559				(c,q - s)
<ul> <li>Electricity</li> <li>Caustic Soda</li> </ul>	t de	-	-	0.235 0.136	±0.035	0.235 0.136	±0.035	(c,q - s)
- Diam. Phosph.	t de	-	-	0.130	±0.020	0.130	±0.020	(c, t)
- Sulphuric Acid	t de	_	-	0.007	- ±0.008	0.007	- ±0.008	(c, u)
- Enzyme AMG	t de	-	-	0.007	±0.008	0.007	±0.008	(C, V) (C, W)
- Enzyme AA	t de	-	-	-	-	-	-	(C, W) (C, X)
- Calcium Chlor.	t de	-	-	_	-	-	-	(c, x) (c, y)
	i ue	-	-	-		-	-	(c, y)
Sub-Totals	t de	0.019	±0.016	0.937	±0.094	0.956	±0.096	
	t be	0.013	±0.014	0.837	±0.094 ±0.084	0.854	±0.090	(z)
Dehydration:		0.017	_0.014	0.007	10.004	0.004	10.000	(c, q,
- Electricity	t be	-	_	0.010	±0.002	0.010	±0.002	(c, q, aa, bb)
Plant Construction	t be		-	-		-	±0.002	
Plant Construction Plant Maintenance		-	-		-			(c, cc)
	t be	-	-	-	-	-	-	(c, dd)
Distribution:	4 6 4			0.000		0.000		(aa)
- Diesel Fuel	t be	-	-	0.008	-	0.008	-	(ee)
Totals	t be	0.021	±0.014	1.106	±0.090	1.127	±0.092	1

#### **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

t hwg

t dwg

hectare year
tonne of harvested wheat grain
tonne of dried wheat grain
tonne of distillate ethanol (94.5% alcohol) t de

t be = tonne of bioethanol

- (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<sub>4</sub>/kg N (Ref. 6).
- (b) Phosphate fertiliser application rates of 41 kg P/ha.a (Ref. 5), or 93.9 kg P<sub>2</sub>O<sub>5</sub>/ ha.a assuming 2.290 kg P<sub>2</sub>O<sub>5</sub>/kg P, and a total methane requirement for phosphate fertiliser of 2.3 x 10<sup>-5</sup> kg CH<sub>4</sub>/kg P<sub>2</sub>O<sub>5</sub> (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<sub>2</sub>O/ha.a assuming 1.205 kg K<sub>2</sub>O/kg K, and a total methane requirement for potash fertiliser of 2.1 x 10<sup>-5</sup> kg CH<sub>4</sub>/ kg K<sub>2</sub>O (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  $1.8 \times 10^{-4}$  kg CH<sub>4</sub>/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 x 10<sup>-4</sup> kg CH<sub>4</sub>/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  $1.8 \times 10^{-4}$  kg CH<sub>4</sub>/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 x 10<sup>-4</sup> kg CH<sub>4</sub>/kg (Ref. 7).
- (i) Sowing rate of 185 kg/ha.a (Ref. 10) and a total methane requirement of 0 kg CH<sub>4</sub>/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 x 10<sup>-7</sup> kg CH<sub>4</sub>/MJ, an indirect methane requirement of 2.04 x 10<sup>-5</sup> kg CH<sub>4</sub>/MJ and a total methane requirement of 2.1 x 10<sup>-5</sup> kg CH<sub>4</sub>/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 x 10<sup>-7</sup> kg CH<sub>4</sub>/MJ, an indirect methane requirement of 2.04 x 10<sup>-5</sup> kg CH<sub>4</sub>/MJ and a total methane requirement of 2.1 x 10<sup>-5</sup> kg CH<sub>4</sub>/MJ for diesel fuel in the UK in 1996 (Ref. 12).
- (I) 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 x  $10^{-6}$  kg CH<sub>4</sub>/MJ, an indirect methane requirement of 2.04 x  $10^{-5}$  kg CH<sub>4</sub>/MJ and a total methane requirement of 2.3 x  $10^{-5}$  kg CH<sub>4</sub>/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<sub>4</sub>/t-km, an indirect methane requirement of  $1.672 \times 10^{-5} \pm 6.3 \times 10^{-7}$  kg CH<sub>4</sub>/t-km and a total methane requirement of  $1.721 \times 10^{-5} \pm 6.5 \times 10^{-7}$  kg CH<sub>4</sub>/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  $3.70 \times 10^{-6}$  kg CH<sub>4</sub>/MJ, an indirect methane requirement of  $1.083 \times 10^{-4}$  kg CH<sub>4</sub>/MJ and a total methane requirement of  $1.12 \times 10^{-4}$  kg CH<sub>4</sub>/MJ for natural gas in the UK in 1996 (Ref. 12), and electricity obtained from the grid with an indirect methane requirement of  $4.043 \times 10^{-4}$  kg CH<sub>4</sub>/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  $3.25 \times 10^{-3}$  kg CH<sub>4</sub>/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<sup>-6</sup> kg CH<sub>4</sub>/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<sub>4</sub>/ 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<sub>4</sub>/ 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  $4 \times 10^{-6}$  kg CH<sub>4</sub>/ 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  $2 \times 10^{-4}$  kg CO<sub>2</sub>/ 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  $\pounds$ 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<sup>-7</sup> kg CH<sub>4</sub>/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<sub>4</sub>/t-km, an indirect methane requirement of  $1.672 \times 10^{-5} \pm 6.3 \times 10^{-7}$  kg CH<sub>4</sub>/t-km and a total methane requirement of  $1.721 \times 10^{-5} \pm 6.5 \times 10^{-7}$  kg CH<sub>4</sub>/t-km (Ref. 13).

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

Functional Unit: :			of distribution		m wheat usir	ng a natural g	gas-fired boi	ler and
Final Unit of Measureme								
Relevant Location:		Kingdom						
Relevant Period:	2002	angaom						
Allocation Procedures:		n average n	narket prices	assuming 1	394 tonnes	of wheat str	aw at £25/t (	Ref 1)
Allocation r roccaures.			f harvested w					
			cation to bioe					
			f bioethanol a					
Contribution	Per				xide Output			
Contribution	Unit	Dir	ect		rect		otal	Notes
	Onic	Value	Range	Value	Range	Value	Range	110103
Cultivation and		value	Range	value	Range	value	Range	
Harvesting:								
- N Fertiliser	ha.a	0.666	±0.100	2.720	±0.408	3.386	±0.420	(a, b)
- P Fertiliser	ha.a	0.000	±0.100	0.004	±0.408 ±0.001	0.004	±0.420 ±0.001	· · · /
- K Fertiliser	ha.a	-	-	0.004 0.001	10.001	0.004 0.001	±0.001	(b, c) (b, d)
		-	-		-		-	(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	(I)
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	-	-	-	-	-	-	(b, q, uu bb)
Plant Construction	t be	-	-	-	-	-	-	(b, cc)
Plant Maintenance	t be	-	-		-	-	-	(b, cc) (b, dd)
Distribution:	I DE	-	-	-		-	-	(0, 00)
- Diesel Fuel	t be	_	_	-	_	-	- I	(ee)
	1.00		-	-	-	-	-	1001

# **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)

= tonne of bioethanol t be

- (a) Nitrogen fertiliser application rate of 185 N/ha.a (Ref. 5) and a direct nitrous oxide requirement of 0.0036 kg N<sub>2</sub>O/kg N (Ref. 5), an indirect nitrous oxide requirement of 0.0147 kg N<sub>2</sub>O/kg N (Ref. 6) and a total nitrous oxide requirement for ammonium nitrate of 0.0183 kg N<sub>2</sub>O/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<sub>2</sub>O<sub>5</sub>/ ha.a assuming 2.290 kg P<sub>2</sub>O<sub>5</sub>/kg P, and a total nitrous oxide requirement for phosphate fertiliser of 4.2 x 10<sup>-5</sup> kg N<sub>2</sub>O/kg P<sub>2</sub>O<sub>5</sub> (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<sup>-6</sup> 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  $1.51 \times 10^{-3}$  kg N<sub>2</sub>O/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<sup>-3</sup> kg N<sub>2</sub>O/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  $1.51 \times 10^{-3}$  kg N<sub>2</sub>O/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  $1.51 \times 10^{-3}$  kg N<sub>2</sub>O/kg (Ref. 8).
- (i) Sowing rate of 185 kg/ha.a (Ref. 10) and a total nitrous oxide requirement of 0.001 kg N<sub>2</sub>O/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  $5.64 \times 10^{-7}$  kg N<sub>2</sub>O/MJ, an indirect nitrous oxide requirement of  $2.60 \times 10^{-8}$  kg N<sub>2</sub>/MJ and a total nitrous oxide requirement of  $5.90 \times 10^{-7}$  kg N<sub>2</sub>O/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<sup>-7</sup> kg N<sub>2</sub>O/MJ, an indirect nitrous oxide requirement of 2.60 x 10<sup>-8</sup> kg N<sub>2</sub>/MJ and a total nitrous oxide requirement of 5.90 x 10<sup>-7</sup> kg N<sub>2</sub>O/MJ for diesel fuel in the UK in 1996 (Ref. 12).
- (I) 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  $5.64 \times 10^{-7}$  kg N<sub>2</sub>O/MJ, an indirect nitrous oxide requirement of  $2.60 \times 10^{-8}$  kg N<sub>2</sub>/MJ and a total nitrous oxide requirement of  $5.90 \times 10^{-7}$  kg N<sub>2</sub>O/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<sub>2</sub>O/t-km, an indirect nitrous oxide requirement of  $2.1 \times 10^{-8} \pm 8 \times 10^{-10}$  kg N<sub>2</sub>O/t-km and a total nitrous oxide requirement of  $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8}$  kg N<sub>2</sub>O/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  $8.9 \times 10^{-8}$  kg N<sub>2</sub>O/MJ, an indirect nitrous oxide requirement of  $1.1 \times 10^{-8}$  kg N<sub>2</sub>O/MJ and a total nitrous oxide requirement of  $1.0 \times 10^{-7}$  kg N<sub>2</sub>O/MJ for natural gas in the UK in 1996 (Ref. 12), and electricity obtained from the grid with an indirect nitrous oxide requirement of  $5.577 \times 10^{-6}$  kg N<sub>2</sub>O/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<sub>4</sub>/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<sup>-6</sup> kg CH₄/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 CH<sub>4</sub>/ 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<sub>4</sub>/ 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  $6 \times 10^{-8}$  kg CH<sub>4</sub>/ 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<sub>2</sub>/ 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<sup>-9</sup> kg N<sub>2</sub>O/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<sub>2</sub>O/t-km, an indirect nitrous oxide requirement of  $2.1 \times 10^{-8} \pm 8 \times 10^{-10}$  kg N<sub>2</sub>O/t-km and a total nitrous oxide requirement of  $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8}$  kg N<sub>2</sub>O/t-km (Ref. 13).

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

Functional Unit: :			of distribution		om wheat us	ing a natura	al gas-fired bo	oiler and
Final Unit of Measuren	nent: 1 tonne	e of bioethan	ol					
Relevant Location:		Kingdom						
Relevant Period:	2002							
Allocation Procedures:		on average i	market price	s assuming	1 394 tonne	s of wheat	straw at £25/t	(Ref 1)
	and 3.4 giving a and 1.0	25 tonnes of 87.1% alloc	f harvested v cation to bioe f bioethanol	vheat grain wethanol, and fat £494/t (Re	vith 20% moi 1.141 tonnes f. 4), giving a	sture conte s of animal a 84.4% all	ent at £69/t (F feed at £80/t ocation to bic	tef. 2), (Ref. 3)
Contribution	Per		Tota	l Greenhous	e Gas Outpι	ut (kg eq Co	<b>O</b> <sub>2</sub> )	
	Unit	Dir	rect	Indi	rect	7	Fotal	Notes
		Value	Range	Value	Range	Value	Range	
Cultivation and			Ŭ				Ŭ	
Harvesting:								
- N Fertiliser	ha.a	213	±32	1,239	±140	1,452	±144	(a)
- P Fertiliser	ha.a	215		67	±140 ±10	67	±10	(a)
- K Fertiliser	ha.a	-	_	25	±4	25	±10	(a) (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:								X-7
- Diesel Fuel	t hwg	23	±4	3	-	26	±4	(a)
Dieserraei	t be	66	±12	9	-	75	±12	(c)
Transport:	1.50		_12	U		10	-1-	(0)
- Diesel Fuel	t dwg	10		3		13		(a)
- Diesei Fuei	•	27	±1	8	-	35	±1	(d)
Million and the share has to	t be	21	<b>1</b>	0	-		±1	(u)
Milling, Hydrolysis, Fermentation and								
Distillation:								
- Natural Gas	t de	270	±41	23	±8	293	±42	(a)
- Electricity	t de	-	-	94	±13	94	±13	(a)
<ul> <li>Caustic Soda</li> </ul>	t de	-	-	50	±7	50	±7	(a)
<ul> <li>Diam. Phosph.</li> </ul>	t de	-	-	2	-	2	-	(a)
<ul> <li>Sulphuric Acid</li> </ul>	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)
								l `´
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	-11	(a)
			-				±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	1

# **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

= hectare year = tonne of harvested wheat grain ha.a

t hwg

= tonne of dried wheat grain = tonne of distillate ethanol (94.5% alcohol) t dwg

t de t be = tonne of bioethanol

- (a) Summation of results from previous spreadsheets with conversion using a global warming potential for methane of 24.5 kg eq CO<sub>2</sub>/kg CH<sub>4</sub> and a global warming potential for nitrous oxide of 320 kg eq CO<sub>2</sub>/kg N<sub>2</sub>O.
- (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.

- 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 <u>www.hgca.com/c-stats</u> 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:		Bioethand							-fired com	pined heat
Final Unit of Meas	surement		f bioethanc			<u></u>				
Relevant Location		United Kir								
Relevant Period:		2002	gaom							
Allocation Proced	ures.		average m	arket nric	es, assum	ina 1 394 i	onnes of v	wheat stray	∧ at £25/t	(Ref 1)
Allocation rioccu	urcs.	and 3.425								
		giving a 87								
		and 1.000								
Contribution	Per			bioctriario		y Energy I				
Contribution	Unit	Dir	ect	Ind	irect		stock	Тс	otal	Notes
	Onic	Value	Range	Value	Range	Value	Range	Value	Range	NOICES
Cultivation and		value	Range	value	Range	value	Range	value	Range	
Harvesting:										
•	haa			2 502	11.026	4 020	1106	7 5 1 0	11051	
- 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:										
<ul> <li>Diesel Fuel</li> </ul>	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	(I)
Drying:										
<ul> <li>Diesel Fuel</li> </ul>	t hwg	338	±53	37	±18	-	-	375	±56	(c, m)
	t be	977	±153	107	±52	-	-	1,084	±162	(n)
Transport:										
<ul> <li>Diesel Fuel</li> </ul>	t dwg	152	±6	53	±7	-	-	205	±9	(o)
	t be	409	±16	143	±19	-	-	552	±25	(p)
Milling,										
Hydrolysis,										
Fermentation										
and Distillation:										
<ul> <li>Natural Gas</li> </ul>	t de	6,836	±1,080	752	±358	-	-	7,588	±1,138	(c, q - s)
<ul> <li>Caustic Soda</li> </ul>	t de	-	-	836	±125	-	-	836	±125	(c, t)
- Diam. Phosph.	t de	-	-	55	±8	-	-	55	±8	(c, u)
<ul> <li>Sulphuric Acid</li> </ul>	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:										(c, q, aa,
- Natural Gas	t be	30	±5	3	±2	-	-	33	±5	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<sub>2</sub>O/ha.a assuming 1.205 kg K<sub>2</sub>O/kg K, and a total energy requirement for potash fertiliser of 9.3 MJ/ kg K<sub>2</sub>O (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).
- (I) 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).

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- 9. "Pesticide Use Survey" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.
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- 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.
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# 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: :					m wheat usir luring proces		as-fired com	pined heat
Final Unit of Measurem			ol					
Relevant Location:	United	Kingdom						
Relevant Period:	2002							
Allocation Procedures:	and 3.4 giving a	25 tonnes of a 87.1% alloc	f harvested v cation to bioe	vheat grain v thanol, and	1.394 tonnes vith 20% mois 1.141 tonnes ef. 4), giving a	sture conten of animal fe	it at £69/t (R eed at £80/t (	ef. 2), (Ref. 3)
Contribution	Per			Carbon Di	ioxide Output	t (kg CO <sub>2</sub> )		
	Unit	Dir	ect	Indi	irect	To	otal	Notes
		Value	Range	Value	Range	Value	Range	
Cultivation and			J -				J. J.	
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	±10 ±4	25	±10 ±4	(c, d)
- Pesticide	ha.a	-	-	25 10	±4 ±1	25 10	±4 ±1	(c, u) (c, e)
- Herbicide	ha.a	-	-	10	±/	10	±/	,
		-	-	- 4		- 4		(c, f)
- Insecticide	ha.a	-	-	-	±1		±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	(1)
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:								
<ul> <li>Natural Gas</li> </ul>	t de	357	±54	12	±10	369	±55	(c,q - s)
<ul> <li>Caustic Soda</li> </ul>	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:								(c, q, aa,
- Natural Gas	t be	2	-	-	-	2	-	(c, q, aa, bb)
Plant Construction	t be	-	-	27	±4	27	±4	(C, CC)
Plant Maintenance	t be	-	-	- 27	±4 ±1	8	±4 ±1	
	i ne	-	-	0	ΞI	0	±1	(c, dd)
Distribution: - Diesel Fuel	t be	25	±1	7	±1	32	±1	(ee)
Totals	t be	531	<u> </u>	289		52		

#### **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 t dwg

- tonne of harvested wheat grain
  tonne of dried wheat grain
  tonne of distillate ethanol (94.5% alcohol) t de
- t be = tonne of bioethanol

- (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<sub>2</sub>/kg N (Ref. 6).
- (b) Phosphate fertiliser application rates of 41 kg P/ha.a (Ref. 5), or 93.9 kg P<sub>2</sub>O<sub>5</sub>/ ha.a assuming 2.290 kg P<sub>2</sub>O<sub>5</sub>/kg P, and a total carbon requirement for phosphate fertiliser of 0.700 kg CO<sub>2</sub>/kg P<sub>2</sub>O<sub>5</sub> (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<sub>2</sub>O/ha.a assuming 1.205 kg K<sub>2</sub>O/kg K, and a total carbon requirement for potash fertiliser of 0.453 kg CO<sub>2</sub>/ kg K<sub>2</sub>O (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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/kg (Ref. 7).
- Sowing rate of 185 kg/ha.a (Ref. 10) and a total carbon requirement of 0.547 kg CO<sub>2</sub>/kg of seed based on a ratio of 0.0405 kg CO<sub>2</sub>/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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0081 kg CO<sub>2</sub>/MJ and a total carbon requirement of 0.0767 kg CO<sub>2</sub>/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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0081 kg CO<sub>2</sub>/MJ and a total carbon requirement of 0.0767 kg CO<sub>2</sub>/MJ for diesel fuel in the UK in 1996 (Ref. 12).
- (I) 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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0081 kg CO<sub>2</sub>/MJ and a total carbon requirement of 0.0767 kg CO<sub>2</sub>/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<sub>2</sub>/t-km, an indirect carbon requirement of 0.0161 ± 0.0017 kg CO<sub>2</sub>/tkm and a total carbon requirement of 0.0723 ± 0.0027 kg CO<sub>2</sub>/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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0017 kg CO<sub>2</sub>/MJ and a total carbon requirement of 0.0539 kg CO<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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  $0.13 \pm 0.16$  kg CO<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/ 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<sub>2</sub>/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<sub>2</sub> 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<sub>2</sub>/£ (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<sub>2</sub>/t-km, an indirect carbon requirement of 0.0161 ± 0.0017 kg CO<sub>2</sub>/t-km and a total carbon requirement of 0.0723 ± 0.0027 kg CO<sub>2</sub>/t-km (Ref. 13).

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# 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: :				n derived from a steam turb			s-fired com	bined
Final Unit of Measuren					51	J		
Relevant Location:		Kingdom						
Relevant Period:	2002							
Allocation Procedures:		on average i	market price	s, assuming	1.394 tonnes	s of wheat st	raw at £25/t	(Ref 1)
,	and 3.4 giving a	25 tonnes of 87.1% alloc	harvested v ation to bioe	wheat grain wethanol, and at £494/t (Re	<i>i</i> ith 20% moi 1.141 tonnes	sture conten of animal fe	t at £69/t (R ed at £80/t (	ef. 2), (Ref. 3)
Contribution		ou tonnes of	Divenanon					
Contribution	Per Unit		ect		e Output (kg rect		otal	Notes
	Offic	Value		-		Value		notes
Cultivation and		value	Range	Value	Range	value	Range	
Cultivation and								
Harvesting: - N Fertiliser	h			0.000	±0.111	0.000	10 111	(-)
- N Fertiliser	ha.a	-	-	0.666	±0.111	0.666 0.002	±0.111	(a)
- K Fertiliser	ha.a	-	-	0.002	-	0.002	-	(b, c)
- K Fertiliser - Pesticide	ha.a ha.a	-	-	0.001	-	0.001	-	(c, d)
- Pesticide - Herbicide		-	-	-	-	-	-	(c, e)
- Herbicide - Insecticide	ha.a	-	-	-	-	-	-	(c, f)
- Insecticide - Fungicide	ha.a ha.a	-	-	-	-	-	-	(c, g)
- Fungicide - Seed	ha.a	-	-	-	-	-	-	(c, h)
- Diesel Fuel	ha.a	0.003	-	0.112	- ±0.017	0.115	±0.017	(c, i)
	IId.d	0.003	-	0.112	±0.017	0.115	10.017	(c, j)
Reference System: - Diesel Fuel	ha.a	- 0.001		- 0.019		- 0.020	±0.003	
- Diesel Fuel	na.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	
Oub Totals	t be	0.002	-	0.223	±0.033	0.224	±0.033	(I)
Drying:		0.001		01220	201000	0.22	_0.000	(1)
- 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	(0, 11) (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	0.025	±0.021	0.140		0.136	±0.775 ±0.020	
- Diam. Phosph.	t de t de	-	-	0.130	±0.020	0.136	±0.020	(c, t) (c, u)
- Sulphuric Acid	t de	-	-	0.007	- ±0.008	0.007	- ±0.008	(C, U) (C, V)
- Enzyme AMG	t de	-	-	0.007	-	-		(C, V) (C, W)
- Enzyme AA	t de	_	-	_	-	-	-	(C, W) (C, X)
- Calcium Chlor.	t de	-	-		-	-		(c, x) (c, y)
	100	-	_	_		_	_	(C, y)
Sub-Totals	t de	0.025	±0.021	0.883	±0.115	0.908	±0.117	
	t be	0.020	±0.019	0.788	±0.103	0.810	±0.104	(z)
Dehydration:								(c, q,
- Natural Gas	t be	-	-	0.003	-	0.003	-	(0, q, aa, bb)
Plant Construction	t be	-	-	-	-	-	-	(C, CC)
Plant Maintenance	t be	-	-	-	-	-	-	(c, dd)
Distribution:							-	(0, 00)
- 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
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t hwg

t dwg

= tonne of harvested wheat grain
= tonne of dried wheat grain
= tonne of distillate ethanol (94.5% alcohol)
= tonne of bioethanol t de t be

- (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<sub>4</sub>/kg N (Ref. 6).
- (b) Phosphate fertiliser application rates of 41 kg P/ha.a (Ref. 5), or 93.9 kg P<sub>2</sub>O<sub>5</sub>/ ha.a assuming 2.290 kg P<sub>2</sub>O<sub>5</sub>/kg P, and a total methane requirement for phosphate fertiliser of 2.3 x 10<sup>-5</sup> kg CH<sub>4</sub>/kg P<sub>2</sub>O<sub>5</sub> (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<sub>2</sub>O/ha.a assuming 1.205 kg K<sub>2</sub>O/kg K, and a total methane requirement for potash fertiliser of 2.1 x 10<sup>-5</sup> kg CH<sub>4</sub>/ kg K<sub>2</sub>O (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  $1.8 \times 10^{-4}$  kg CH<sub>4</sub>/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  $1.8 \times 10^{-4}$  kg CH<sub>4</sub>/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  $1.8 \times 10^{-4}$  kg CH<sub>4</sub>/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 x 10<sup>-4</sup> kg CH<sub>4</sub>/kg (Ref. 7).
- (i) Sowing rate of 185 kg/ha.a (Ref. 10) and a total methane requirement of 0 kg CH<sub>4</sub>/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 x 10<sup>-7</sup> kg CH<sub>4</sub>/MJ, an indirect methane requirement of 2.04 x 10<sup>-5</sup> kg CH<sub>4</sub>/MJ and a total methane requirement of 2.1 x 10<sup>-5</sup> kg CH<sub>4</sub>/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 x 10<sup>-7</sup> kg CH<sub>4</sub>/MJ, an indirect methane requirement of 2.04 x 10<sup>-5</sup> kg CH<sub>4</sub>/MJ and a total methane requirement of 2.1 x 10<sup>-5</sup> kg CH<sub>4</sub>/MJ for diesel fuel in the UK in 1996 (Ref. 12).
- (I) 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 x  $10^{-6}$  kg CH<sub>4</sub>/MJ, an indirect methane requirement of 2.04 x  $10^{-5}$  kg CH<sub>4</sub>/MJ and a total methane requirement of 2.3 x  $10^{-5}$  kg CH<sub>4</sub>/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<sub>4</sub>/t-km, an indirect methane requirement of  $1.672 \times 10^{-5} \pm 6.3 \times 10^{-7}$  kg CH<sub>4</sub>/t-km and a total methane requirement of  $1.721 \times 10^{-5} \pm 6.5 \times 10^{-7}$  kg CH<sub>4</sub>/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 x 10<sup>-6</sup> kg CH<sub>4</sub>/MJ, an indirect methane requirement of 1.083 x 10<sup>-6</sup> kg CH<sub>4</sub>/MJ and a total methane requirement of 1.12 x 10<sup>-4</sup> kg CH<sub>4</sub>/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  $3.25 \times 10^{-3}$  kg CH<sub>4</sub>/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<sup>-6</sup> kg CH<sub>4</sub>/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<sub>4</sub>/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<sub>4</sub>/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  $4 \times 10^{-6}$  kg CH<sub>4</sub>/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  $2 \times 10^{-4}$  kg CH<sub>4</sub>/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  $\pounds$ 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<sup>-7</sup> kg CH<sub>4</sub>/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<sub>4</sub>/t-km, an indirect methane requirement of  $1.672 \times 10^{-5} \pm 6.3 \times 10^{-7}$  kg CH<sub>4</sub>/t-km and a total methane requirement of  $1.721 \times 10^{-5} \pm 6.5 \times 10^{-7}$  kg CH<sub>4</sub>/t-km (Ref. 13).

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

Functional Unit: :			of distributior on with a stea				s-fired comb	bined heat
Final Unit of Measureme					annig procee	enig		
Relevant Location:		Kingdom						
Relevant Period:	2002	J						
Allocation Procedures:	Based of	on average r	narket prices	. assumina 1	.394 tonnes	of wheat str	aw at £25/t (	Ref. 1)
			f harvested w					
			cation to bioe					
			f bioethanol a					
Contribution	Per				Dxide Output			
Company	Unit	Dir	rect		rect		otal	Notes
		Value	Range	Value	Range	Value	Range	
Cultivation and		Value	range	Value	range	Value	runge	
Harvesting:								
- N Fertiliser	ha.a	0.666	±0.100	2.720	±0.408	3.386	±0.420	(a, b)
- P Fertiliser	ha.a	0.000	10.100	0.004	±0.001	0.004	±0.001	(a, b) (b, c)
- K Fertiliser	ha.a	-	-	0.004	10.001	0.004	10.007	(b, c) (b, d)
- R Pertiliser	na.a ha.a	-	-	0.001	-	0.001	-	
- Pesticide - Herbicide		-	-	0.003	-		-	(b, e)
	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	(I)
Drying:								
<ul> <li>Diesel Fuel</li> </ul>	t hwg	-	-	-	-	-	-	(b, m)
	t be	-	-	-	-	-	-	(n)
Transport:								
- Diesel Fuel	t dwg	-	-	-	-	-	-	(o)
	t be	-	-	-	-	-	-	(p)
Milling, Hydrolysis,								
Fermentation and								
Distillation:								
<ul> <li>Natural Gas</li> </ul>	t de	0.001	-	-	-	0.001	-	(b,q - s)
<ul> <li>Caustic Soda</li> </ul>	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 Tatala	t de	0.001				0.001	_	(-)
Sub-Totals	t be	0.001 0.001	-	-	-	0.001 0.001	-	(z)
Dehydration:	t dwg	-	-	-	-	-	-	(b, q, aa
- Natural Gas	t be	-	-	-	-	-	-	(b, q, db)
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
---------------------

= tonne of harvested wheat grain t hwg

t dwg

tonne of dried wheat grain
tonne of distillate ethanol (94.5% alcohol)
tonne of bioethanol t de t be

- (a) Nitrogen fertiliser application rate of 185 N/ha.a (Ref. 5) and a direct nitrous oxide requirement of 0.0036 kg N<sub>2</sub>O/kg N (Ref. 5), an indirect nitrous oxide requirement of 0.0147 kg N<sub>2</sub>O/kg N (Ref. 6) and a total nitrous oxide requirement for ammonium nitrate of 0.0183 kg N<sub>2</sub>O/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<sub>2</sub>O<sub>5</sub>/ ha.a assuming 2.290 kg P<sub>2</sub>O<sub>5</sub>/kg P, and a total nitrous oxide requirement for phosphate fertiliser of 4.2 x 10<sup>-5</sup> kg N<sub>2</sub>O/kg P<sub>2</sub>O<sub>5</sub> (Ref. 8).
- (d) Potash fertiliser application rate of 46 kg K/ha.a (Ref. 5), or 55.4 kg K<sub>2</sub>O/ha.a assuming 1.205 kg K<sub>2</sub>O/kg K, and a total nitrous oxide requirement for potash fertiliser of 9.4 x 10<sup>-6</sup> kg N<sub>2</sub>O/ kg K<sub>2</sub>O (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  $1.51 \times 10^{-3}$  kg N<sub>2</sub>O/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<sup>-3</sup> kg N<sub>2</sub>O/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  $1.51 \times 10^{-3}$  kg N<sub>2</sub>O/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  $1.51 \times 10^{-3}$  kg N<sub>2</sub>O/kg (Ref. 8).
- (i) Sowing rate of 185 kg/ha.a (Ref. 10) and a total nitrous oxide requirement of 0.001 kg N<sub>2</sub>O/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  $5.64 \times 10^{-7}$  kg N<sub>2</sub>O/MJ, an indirect nitrous oxide requirement of  $2.60 \times 10^{-8}$  kg N<sub>2</sub>/MJ and a total nitrous oxide requirement of  $5.90 \times 10^{-7}$  kg N<sub>2</sub>O/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<sup>-7</sup> kg N<sub>2</sub>O/MJ, an indirect nitrous oxide requirement of 2.60 x 10<sup>-8</sup> kg N<sub>2</sub>/MJ and a total nitrous oxide requirement of 5.90 x 10<sup>-7</sup> kg N<sub>2</sub>O/MJ for diesel fuel in the UK in 1996 (Ref. 12).
- (I) 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  $5.64 \times 10^{-7}$  kg N<sub>2</sub>O/MJ, an indirect nitrous oxide requirement of  $2.60 \times 10^{-8}$  kg N<sub>2</sub>/MJ and a total nitrous oxide requirement of  $5.90 \times 10^{-7}$  kg N<sub>2</sub>O/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<sub>2</sub>O/t-km, an indirect nitrous oxide requirement of  $2.1 \times 10^{-8} \pm 8 \times 10^{-10}$  kg N<sub>2</sub>O/t-km and a total nitrous oxide requirement of  $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8}$  kg N<sub>2</sub>O/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 x 10<sup>-8</sup> kg N<sub>2</sub>O/MJ, an indirect nitrous oxide requirement of 1.1 x 10<sup>-8</sup> kg N<sub>2</sub>O/MJ and a total nitrous oxide requirement of 1.0 x 10<sup>-7</sup> kg N<sub>2</sub>O/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<sub>2</sub>O/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<sup>-6</sup> kg N<sub>2</sub>O/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  $2 \times 10^{-7} \pm 3 \times 10^{-7} \text{ kg N}_2\text{O/kg}$  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 N<sub>2</sub>O/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<sup>-8</sup> kg N<sub>2</sub>O/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<sup>-7</sup> kg N<sub>2</sub>O/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 x 10<sup>-9</sup> kg N<sub>2</sub>O/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<sub>2</sub>O/t-km, an indirect nitrous oxide requirement of  $2.1 \times 10^{-8} \pm 8 \times 10^{-10}$  kg N<sub>2</sub>O/t-km and a total nitrous oxide requirement of  $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8}$  kg N<sub>2</sub>O/t-km (Ref. 13).

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- 2. Annual average ex-farm price of feed wheat, United Kingdom, 2000/02 from <u>www.hgca.com/c-stats</u> accessed 3 February 2003.
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# 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: :			of distribution				gas-fired con	nbined
Final Unit of Measurem		e of bioethar			ionio ading	p.00000g		
Relevant Location:		Kingdom						
Relevant Period:	2002							
Allocation Procedures:		on average	market price	nuimina e	1 304 tonne	s of wheat	straw at £25/1	(Ref 1)
	and 3.4 giving a and 1.0	25 tonnes o 87.1% allo	f harvested v cation to bioe f bioethanol	vheat grain v ethanol, and at £494/t (Re	vith 20% mo 1.141 tonne: ef. 4), giving	isture conte s of animal a 84.4% al	ent at £69/t (F feed at £80/t location to bio	Ref. 2), (Ref. 3)
Contribution	Per		Tota	I Greenhous	se Gas Outp	ut (kg eq C	O <sub>2</sub> )	
	Unit	Dii	ect	Ind	irect		Total	Notes
		Value	Range	Value	Range	Value	Range	
Cultivation and					U		- J.	
Harvesting:								
- N Fertiliser	ha.a	213	±32	1.239	±140	1.452	±144	(a)
- P Fertiliser	ha.a	215		67	±10	67	±10	(a)
- K Fertiliser	ha.a	_		25	±10 ±4	25	±10 ±4	(a) (a)
- Pesticide	ha.a	-	-	25 11	±4 ±1	11	±4 ±1	
- Herbicide		-	-	11	±/		±1	(a)
	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:								
<ul> <li>Natural Gas</li> </ul>	t de	358	±55	30	±10	388	±55	(a)
<ul> <li>Caustic Soda</li> </ul>	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:						1		(a)
- Natural Gas	t be	2	-	-	-	2	-	(4)
Plant Construction	t be	_	_	27	±4	27	±4	(2)
		-	-					(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	(00)

### **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 t dwg

- = tonne of harvested wheat grain
  = tonne of dried wheat grain
  = tonne of distillate ethanol (94.5% alcohol) t de
- 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<sub>2</sub>/kg CH<sub>4</sub> and a global warming potential for nitrous oxide of 320 kg eq CO<sub>2</sub>/kg N<sub>2</sub>O.
- (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.

- 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 <u>www.hgca.com/c-stats</u> 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**

# <u>Spreadsheet for Primary Energy Inputs to Bioethanol Production from Wheat</u> (Model 3a)

Functional Unit:		Bioethanol power gene				rom beet	using natu	ral gas-fired	l combined	neat and
Final Unit of Meas	urement:			•						
<b>Relevant Location</b>	:	United King	Idom							
Relevant Period:		2002								
Allocation Proced	uroe:		vorago ma	rkot prico		a 12 579	t cloop cur	gar beet 394	toppos of y	vhoat
Allocation Floced	ules.									
		straw at £25								
		£69/t (Ref. 2								a at £80/t
		(Ref. 3) and	11.000 ton	nes of bio	ethanol at	£494/t (Re	et. 4), givir	ng a 84.4% a	allocation to	
		bioethanol.								
Contribution	Per				Prima		Input (MJ)			
	Unit	Dire	ect	Ind	irect	Feed	lstock	То	tal	Notes
		Value	Range	Value	Range	Value	Range	Value	Range	1
Cultivation and									. ien ige	
Harvesting:	4.4.4			0.500	±1,036	4 000	1400	7 540	14.054	(-)
- N Fertiliser	ha.a	-	-	2,592		4,920	±196	7,512	±1,054	(a)
<ul> <li>P Fertiliser</li> </ul>	ha.a	-	-	1,484	±223	-	-	1,484	±223	(b, c)
<ul> <li>K Fertiliser</li> </ul>	ha.a	-	-	515	±77	-	-	515	±77	(c, d)
<ul> <li>Pesticide</li> </ul>	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	na.a	5,430	1000	004	1200	-	_	0,034		(C, J)
System:										
<ul> <li>Diesel Fuel</li> </ul>	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	(I)
Drying:										
<ul> <li>Diesel Fuel</li> </ul>	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,										(P)
Hydrolysis,										
Fermentation										
and Distillation:	4 -1-	0.075	14.004	750	1440			7 004	14.007	()
- 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)
<ul> <li>Diam. Phosph.</li> </ul>	t de	-	-	55	±8	-	-	55	±8	(c, u)
<ul> <li>Sulphuric Acid</li> </ul>	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:	, ne	0,400	-320	1,731	103	-		0,101	±333	. ,
	4 6 6	20	±E	2				22	+ E	(c, q, aa
- Natural Gas	t be	30	±5	3	-	-	-	33	± 5	bb)
Surplus	t be	-5,574	-	-	-	-	-	-5,574	-	(cc)
Electricity										
Plant										
Construction	t be	-	-	541	±81	-	-	541	±81	(c, dd)
										(,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,
Plant	1	1	1	400	+24			162	±24	(c, ee)
Plant Maintenance	t be	-	-	162	±24	-	-	102		
Maintenance	t be	-	-	162	±24	-	-	102	±27	(0, 00)
	t be t be	- 369	- ±14	162	±16	-	-	498	±24	(0, 00) (ff)

**Biofuel Specifications** 

Density of bioethanol= 0.79 kg/lNet calorific value of bioethanol= 26.72 MJ/kgGross 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<sub>2</sub>O/ha.a assuming 1.205 kg K<sub>2</sub>O/kg K, and a total energy requirement for potash fertiliser of 9.3 MJ/ kg K<sub>2</sub>O (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).
- (I) 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).

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- 2. Annual average ex-farm price of feed wheat, United Kingdom, 2000/02 from <u>www.hgca.com/c-stats</u> accessed 3 February 2003.
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- 5. "British Survey of Fertiliser Practice 1999", Fertiliser Manufacturers' Association.
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- 9. "Pesticide Use Survey" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.
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- 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.
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- 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., <u>www.statistics.gov.uk</u>, 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: :			of distributio		m wheat usi	ng natural ga	as-fired com	bined heat
Final Unit of Measurem	nent: 1 tonne	e of bioethan	nol					
Relevant Location:	United	Kingdom						
Relevant Period:	2002							
Allocation Procedures:	Based	on average	market price	s, assuming	1.394 tonnes	s of wheat st	raw at £25/t	(Ref. 1)
	and 3.4 giving a and 1.0	25 tonnes o 87.1% allo	f harvested v cation to bioe	vheat grain v ethanol, and at £494/t (Re	with 20% moi 1.141 tonnes of. 4), giving a	isture conter s of animal fe a 84.4% allo	nt at £69/t (R eed at £80/t	ef. 2), (Ref. 3)
Contribution	Per			1	ioxide Outpu	<u> </u>		
	Unit		rect		irect		otal	Notes
		Value	Range	Value	Range	Value	Range	
Cultivation and								
Harvesting:								
<ul> <li>N Fertiliser</li> </ul>	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	-	- 1	66	±10	66	±10	(c, i)
- Diesel Fuel	ha.a	377	±60	44	±20	421	±63	(c, j)
Reference System:	na.a	0//	200		120	-12-1	200	(0, j)
- Diesel Fuel	ha.a	- 63	±10	- 7	±3	- 70	±11	(c, k)
- Diesei Fuei	IId.d	- 03	±10	- /	13	- 70	±//	(C, K)
Sub-Totals	haa	214	161	ECE	1.57	070	1.00	
Sub-Totals	ha.a	314	±61	565	±57	879	±83	(1)
<u> </u>	t be	92	±18	165	±17	257	±25	(I)
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:								
<ul> <li>Natural Gas</li> </ul>	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:		-	-					(c, q, aa,
- Natural Gas	t be	2	-	-	-	2	-	(0, q, uu, bb)
Surplus Electricity	t be	-272	-	-	-	-272	-	(cc)
Plant Construction	t be		- -	- 27	- ±4	-272	- ±4	(cc) (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

- (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<sub>2</sub>/kg N (Ref. 6).
- (b) Phosphate fertiliser application rates of 41 kg P/ha.a (Ref. 5), or 93.9 kg P<sub>2</sub>O<sub>5</sub>/ ha.a assuming 2.290 kg P<sub>2</sub>O<sub>5</sub>/kg P, and a total carbon requirement for phosphate fertiliser of 0.700 kg CO<sub>2</sub>/kg P<sub>2</sub>O<sub>5</sub> (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<sub>2</sub>O/ha.a assuming 1.205 kg K<sub>2</sub>O/kg K, and a total carbon requirement for potash fertiliser of 0.453 kg CO<sub>2</sub>/ kg K<sub>2</sub>O (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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/kg (Ref. 7).
- Sowing rate of 185 kg/ha.a (Ref. 10) and a total carbon requirement of 0.547 kg CO<sub>2</sub>/kg of seed based on a ratio of 0.0405 kg CO<sub>2</sub>/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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0081 kg CO<sub>2</sub>/MJ and a total carbon requirement of 0.0767 kg CO<sub>2</sub>/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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0081 kg CO<sub>2</sub>/MJ and a total carbon requirement of 0.0767 kg CO<sub>2</sub>/MJ for diesel fuel in the UK in 1996 (Ref. 12).
- (I) 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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0081 kg CO<sub>2</sub>/MJ and a total carbon requirement of 0.0767 kg CO<sub>2</sub>/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<sub>2</sub>/t-km, an indirect carbon requirement of 0.0161 ± 0.0017 kg CO<sub>2</sub>/tkm and a total carbon requirement of 0.0723 ± 0.0027 kg CO<sub>2</sub>/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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0017 kg CO<sub>2</sub>/MJ and a total carbon requirement of 0.0539 kg CO<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/ 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<sub>2</sub>/ 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<sub>2</sub>/ 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<sub>2</sub>/ 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<sub>2</sub>/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  $CO_2/\pounds$  (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<sub>2</sub>/t-km, an indirect carbon requirement of 0.0161 ± 0.0017 kg CO<sub>2</sub>/tkm and a total carbon requirement of 0.0723 ± 0.0027 kg CO<sub>2</sub>/t-km (Ref. 13).

- 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 <u>www.hgca.com/c-stats</u> accessed 3 February 2003.
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- 10. "Farm Management Pocket Handbook" by J. Nix, Wye College, University of London, United Kingdom, 2002.
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# Spreadsheet for Methane Outputs from Bioethanol Production from Wheat (Model 3a)

Functional Unit: :				n derived fro		ng natural ga	s-fired com	bined
Final Unit of Measurer		e of bioethan		<u>.g p. e e e e e e e e e e e e e e e e e e </u>	2			
Relevant Location:		Kingdom	-					
Relevant Period:	2002	<u>9</u>						
Allocation Procedures:		on average	market price	s, assuming	1.394 tonnes	s of wheat st	raw at £25/t	(Ref 1)
				vheat grain w				
				thanol, and				
				at £494/t (Re				
Contribution	Per				e Output (ko			
	Unit	Dir	ect		rect		otal	Notes
		Value	Range	Value	Range	Value	Range	
Cultivation and							ge	
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	(I)
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:								
<ul> <li>Natural Gas</li> </ul>	t de	0.025	±0.021	0.745	±0.112	0.770	±0.114	(c,q - s)
<ul> <li>Caustic Soda</li> </ul>	t de	-	-	0.136	±0.020	0.136	±0.020	(c, t)
- Diam. Phosph.	t de	-	-	-	-	-	-	(c, u)
<ul> <li>Sulphuric Acid</li> </ul>	t de	-	-	0.007	±0.008	0.007	±0.008	(c, v)
- Enzyme AMG	t de	-	-	-	-	-	-	(c, w)
- Enzyme AA	t de	-	-	-	-	-	-	(c, x)
<ul> <li>Calcium Chlor.</li> </ul>	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:								(c, q,
- Natural Gas	t be	-	-	0.004	-	0.004	-	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	1

# **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

#### <u>Notes</u>

- (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<sub>4</sub>/kg N (Ref. 6).
- (b) Phosphate fertiliser application rates of 41 kg P/ha.a (Ref. 5), or 93.9 kg P<sub>2</sub>O<sub>5</sub>/ ha.a assuming 2.290 kg P<sub>2</sub>O<sub>5</sub>/kg P, and a total methane requirement for phosphate fertiliser of 2.3 x 10<sup>-5</sup> kg CH<sub>4</sub>/kg P<sub>2</sub>O<sub>5</sub> (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 x 10<sup>-5</sup> kg CH<sub>4</sub>/ 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  $1.8 \times 10^{-4}$  kg CH<sub>4</sub>/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 x 10<sup>-4</sup> kg CH<sub>4</sub>/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  $1.8 \times 10^{-4}$  kg CH<sub>4</sub>/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 x 10<sup>-4</sup> kg CH<sub>4</sub>/kg (Ref. 7).
- (i) Sowing rate of 185 kg/ha.a (Ref. 10) and a total methane requirement of 0 kg CH<sub>4</sub>/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 x 10<sup>-7</sup> kg CH<sub>4</sub>/MJ, an indirect methane requirement of 2.04 x 10<sup>-5</sup> kg CH<sub>4</sub>/MJ and a total methane requirement of 2.1 x 10<sup>-5</sup> kg CH<sub>4</sub>/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 x 10<sup>-7</sup> kg CH<sub>4</sub>/MJ, an indirect methane requirement of 2.04 x 10<sup>-5</sup> kg CH<sub>4</sub>/MJ and a total methane requirement of 2.1 x 10<sup>-5</sup> kg CH<sub>4</sub>/MJ for diesel fuel in the UK in 1996 (Ref. 12).
- (I) 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 x  $10^{-6}$  kg CH<sub>4</sub>/MJ, an indirect methane requirement of 2.04 x  $10^{-5}$  kg CH<sub>4</sub>/MJ and a total methane requirement of 2.3 x  $10^{-5}$  kg CH<sub>4</sub>/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<sub>4</sub>/t-km, an indirect methane requirement of  $1.672 \times 10^{-5} \pm 6.3 \times 10^{-7}$  kg CH<sub>4</sub>/t-km and a total methane requirement of  $1.721 \times 10^{-5} \pm 6.5 \times 10^{-7}$  kg CH<sub>4</sub>/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  $3.70 \times 10^{-6}$  kg CH<sub>4</sub>/MJ, an indirect methane requirement of  $1.083 \times 10^{-4}$  kg CH<sub>4</sub>/MJ and a total methane requirement of  $1.12 \times 10^{-4}$  kg CH<sub>4</sub>/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  $3.25 \times 10^{-3}$  kg CH<sub>4</sub>/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<sub>4</sub>/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<sub>4</sub>/ 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<sub>4</sub>/ 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  $4 \times 10^{-6}$  kg CH<sub>4</sub>/ 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<sub>2</sub>/ 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  $4.043 \times 10^{-4} \text{ kg CH}_4/\text{MJ}$  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  $\pounds$ 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<sup>-7</sup> kg CH<sub>4</sub>/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  $4.900 \times 10^{-7} \pm 2.000 \times 10^{-8}$  kg CH<sub>4</sub>/t-km, an indirect methane requirement of  $1.672 \times 10^{-5} \pm 6.3 \times 10^{-7}$  kg CH<sub>4</sub>/t-km and a total methane requirement of  $1.721 \times 10^{-5} \pm 6.5 \times 10^{-7}$  kg CH<sub>4</sub>/t-km (Ref. 13).

- 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 <u>www.hgca.com/c-stats</u> 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.
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- "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.
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# Spreadsheet for Nitrous Oxide Outputs from Bioethanol Production from Wheat (Model 3a)

Functional Unit: :			of distributio	on derived fro	om wheat			
Final Unit of Measureme			ol					
Relevant Location:		Kingdom						
Relevant Period:	2002							
Allocation Procedures:			market prices					
			harvested w					
			ation to bioe					
		00 tonnes of	f bioethanol a				cation to bioe	ethanol.
Contribution	Per				xide Output			
	Unit		ect		rect	-	otal	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	(I)
Drying:								
- Diesel Fuel	t hwg	-	-	-	-	-	-	(b, m)
	t be	-	-	-	-	-	-	(n)
Transport:								
- Diesel Fuel	t dwg	-	-	-	-	-	-	(o)
	t be	-	-	-	-	-	-	(p)
Milling, Hydrolysis,								
Fermentation and								
Distillation:								
<ul> <li>Natural Gas</li> </ul>	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	-	(4)
Dehydration:	t dwg	-	_		-	-	-	(b, q, aa
- Natural Gas	t be	-	-	-	-	_	-	(b, q, aa bb)
Surplus Electricity	tbe	-0.017	-	-	-	-0.017	-	(CC)
Plant Construction	tbe	-0.017	-			-0.017	-	(b, dd)
Plant Maintenance	tbe	-	-		-			· · · /
Distribution:	l ne	-	-	-	-	-	-	(b, ee)
- Diesel Fuel	t be	-	_	-	-	-	-	(ff)
Totals	tbe	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 yeartonne of harvested wheat grain

t hwg t dwg t de

= tonne of dried wheat grain = tonne of distillate ethanol (94.5% alcohol)

= tonne of bioethanol t be

#### <u>Notes</u>

- (a) Nitrogen fertiliser application rate of 185 N/ha.a (Ref. 5) and a direct nitrous oxide requirement of 0.0036 kg N<sub>2</sub>O/kg N (Ref. 5), an indirect nitrous oxide requirement of 0.0147 kg N<sub>2</sub>O/kg N (Ref. 6) and a total nitrous oxide requirement for ammonium nitrate of 0.0183 kg N<sub>2</sub>O/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<sub>2</sub>O<sub>5</sub>/ ha.a assuming 2.290 kg P<sub>2</sub>O<sub>5</sub>/kg P, and a total nitrous oxide requirement for phosphate fertiliser of 4.2 x 10<sup>-5</sup> kg N<sub>2</sub>O/kg P<sub>2</sub>O<sub>5</sub> (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<sup>-6</sup> 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  $1.51 \times 10^{-3}$  kg N<sub>2</sub>O/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<sup>-3</sup> kg N<sub>2</sub>O/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  $1.51 \times 10^{-3}$  kg N<sub>2</sub>O/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  $1.51 \times 10^{-3}$  kg N<sub>2</sub>O/kg (Ref. 8).
- (i) Sowing rate of 185 kg/ha.a (Ref. 10) and a total nitrous oxide requirement of 0.001 kg N<sub>2</sub>O/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  $5.64 \times 10^{-7}$  kg N<sub>2</sub>O/MJ, an indirect nitrous oxide requirement of  $2.60 \times 10^{-8}$  kg N<sub>2</sub>/MJ and a total nitrous oxide requirement of  $5.90 \times 10^{-7}$  kg N<sub>2</sub>O/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<sup>-7</sup> kg N<sub>2</sub>O/MJ, an indirect nitrous oxide requirement of 2.60 x 10<sup>-8</sup> kg N<sub>2</sub>/MJ and a total nitrous oxide requirement of 5.90 x 10<sup>-7</sup> kg N<sub>2</sub>O/MJ for diesel fuel in the UK in 1996 (Ref. 12).
- (I) 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  $5.64 \times 10^{-7}$  kg N<sub>2</sub>O/MJ, an indirect nitrous oxide requirement of  $2.60 \times 10^{-8}$  kg N<sub>2</sub>/MJ and a total nitrous oxide requirement of  $5.90 \times 10^{-7}$  kg N<sub>2</sub>O/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<sub>2</sub>O/t-km, an indirect nitrous oxide requirement of  $2.1 \times 10^{-8} \pm 8 \times 10^{-10}$  kg N<sub>2</sub>O/t-km and a total nitrous oxide requirement of  $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8}$  kg N<sub>2</sub>O/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 x 10<sup>-8</sup> kg N<sub>2</sub>O/MJ, an indirect nitrous oxide requirement of 1.1 x 10<sup>-8</sup> kg N<sub>2</sub>O/MJ and a total nitrous oxide requirement of 1.0 x 10<sup>-7</sup> kg N<sub>2</sub>O/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<sub>2</sub>O/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<sup>-6</sup> kg N<sub>2</sub>O/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  $2 \times 10^{-7} \pm 3 \times 10^{-7} \text{ kg N}_2\text{O}/\text{ kg for sulphuric acid (Ref. 15)}.$
- (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<sup>-8</sup> kg N<sub>2</sub>O/ 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  $6 \times 10^{-8}$  kg N<sub>2</sub>O / 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 kg N<sub>2</sub>O / 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  $5.577 \times 10^{-6} \text{ kg N}_2\text{O}$  /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 x 10<sup>-9</sup> kg N<sub>2</sub>O/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<sub>2</sub>O/t-km, an indirect nitrous oxide requirement of  $2.1 \times 10^{-8} \pm 8 \times 10^{-10}$  kg N<sub>2</sub>O/t-km and a total nitrous oxide requirement of  $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8}$  kg N<sub>2</sub>O/t-km (Ref. 13).

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

Functional Unit: :	Bioeth	anol at poin	t of distributio	on derived fro	om wheat			
Final Unit of Measureme	ent: 1 tonn	e of bioethar	nol					
Relevant Location:	United	Kingdom						
Relevant Period:	2002	-						
Allocation Procedures:	Based	on average	market price	s, assuming	1.394 tonnes	s of wheat s	straw at £25/	(Ref. 1)
			f harvested v					
			cation to bioe					
	and 1.0	000 tonnes o	f bioethanol	at £494/t (Re	ef. 4), giving a	a 84.4% allo	ocation to bio	èthanol.
Contribution	Per		Tota	I Greenhous	se Gas Outpu	ut (ka ea CC	D <sub>2</sub> )	
	Unit	Di	rect		irect		otal	Notes
		Value	Range	Value	Range	Value	Range	_
Cultivation and		, aldo	rtange	- Taile	rtange	1 4140	range	
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:	nala	0/0	_00		-20	120	_000	(4)
- Diesel Fuel	ha.a	- 63	±10	- 7	±3	- 70	±11	(a)
Dieserruer	na.u	00	10	,		10		(u)
Sub-Totals	ha.a	528	±68	1.517	±142	2.045	±158	
	t be	154	±20	444	±42	598	±46	(b)
Drying:	1.50							(0)
- Diesel Fuel	t hwg	23	±4	3	_	26	±4	(a)
	t be	66	±12	9	_	75	±12	(c)
Transport:	1.00	00	-12	<b>v</b>		10		(0)
- Diesel Fuel	t dwg	10	_	3	_	13	_	(a)
Dieserruer	t be	27	±1	8	_	35	±1	(d)
Milling, Hydrolysis,	1.00					00		(u)
Fermentation and								
Distillation:								
- Natural Gas	t de	360	±54	30	±10	390	±55	(a)
- Caustic Soda	t de	500		50	±70	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)
- Calcium Chior.	i ue	-	-	'	-	1	-	(a)
Sub-Totals	t de	360	±54	94	±13	454	±56	
	t be	300 321	±34 ±48	94 84	±13 ±12	404	±50 ±50	(e)
Dehydration:		521	±+0	04	±12	405	±30	(e) (a)
- Natural Gas	t be	2	-	-	-	2	-	(a)
	tbe	-298		-	-	-298	-	(0)
Surplus Electricity		-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

#### <u>Notes</u>

- (a) Summation of results from previous spreadsheets with conversion using a global warming potential for methane of 24.5 kg eq CO<sub>2</sub>/kg CH<sub>4</sub> and a global warming potential for nitrous oxide of 320 kg eq CO<sub>2</sub>/kg N<sub>2</sub>O.
- (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.

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## **APPENDIX D: Model 7**

# <u>Spreadsheet for Primary Energy Inputs to Bioethanol Production from Wheat Using</u> <u>Straw as Fuel</u> (Model 7)

Functional Unit:		Bioethanol at processing		button denv		sat using st	raw-meu con	nonica neat a	nu power ge	
Final Unit of Measur	omont:	1 tonne of bioe	othanal							
Relevant Location:	ement.	United Kingdo								
Relevant Period:		2002								
Allocation Procedure	es:	Based on aver harvested w	/heat grain w s of animal f	<i>i</i> ith 20% mc	isture conte	nt at £69/t (	(Ref. 2), givin		ocation to b	ioethanol, and
Contribution	Per				Prim	ary Energy	Input (MJ)			
	Unit	Dire		Indi			stock	Tota		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)
<ul> <li>Insecticide</li> </ul>	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 Reference System:	ha.a	5,490	±868	604	±288	-	-	6,094	±914	(c, j)
- Diesel Fuel	ha.a	-922	±146	- 101	±48	-	-	-1,023	±154	(c, k)
Sub-Totals	ha.a <b>t be</b>	4,568 <b>1,336</b>	±880 <b>±257</b>	8,660 <b>2,534</b>	±1,168 <b>±342</b>	<i>4,920</i> <b>1,439</b>	±196 <b>±57</b>	18,148 <b>5,309</b>	±1,477 <b>±432</b>	(I)
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	- 01	-	403	±60	(c, q)
- Twine - Maintenance	ha.a ha.a			- 175	- ±26	94	±14 -	94 175	±14 ±26	(c, r) (c, s)
		-	-	-		-	-			(0, 5)
Sub-Totals	ha.a <b>t be</b>	343 115	±51 <b>±17</b>	2971 <b>999</b>	±512 <b>±172</b>	1,671 <b>562</b>	±63 <b>±21</b>	4,985 <b>1,676</b>	±518 <b>±174</b>	(t)
Straw Transport: - Diesel Fuel	t bws t be	66 77	±2 <b>±1</b>	23 <b>27</b>	±3 <b>±2</b>	-	-	89 <b>104</b>	±4 <b>±2</b>	(u) (v)
Straw Storage:	t be			21	<u></u> 2	-		104	±2	(•)
- 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 t be	66 77	±10 <b>±5</b>	129 <b>150</b>	±15 <b>±8</b>	92 <b>107</b>	±14 <b>±8</b>	287 <b>334</b>	±23 <b>±12</b>	(v)
Wheat Transport:			-•					007		(*/
- Diesel Fuel	thwg <b>t</b>	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. - Sulphuric Acid	t de	-	-	55 66	±8 +74	-	-	55 66	±8 +74	(gg) (bb)
- Sulphuric Acid	t de t de	-	-	66 110	±74 ±16	-	-	66 110	±74 ±16	(hh) (ii)
- Enzyme AA	t de	-	-	43	±10 ±6	-	-	43	±10 ±6	(ii) (jj)
- Calcium Chlor.	t de	-	-	43 6	±1	-	-	43 6	±1	(jj) (kk)
Sub-Totals	t de t be	-	-	1116 <b>1,044</b>	±146 <b>±130</b>	-	-	1116 <b>1,044</b>	±146 <b>±130</b>	(11)
Dehydration:	t be	-	-	-	-	-	-	-	-	(c)(mm)(nn)
		-12,945						10.045		
Surplus Electric.	t be		-	- 1,044	-	-	-	-12,945	-	(00)
Plant Construct. Plant Mainten.	t be	32	-	,	-	-	-	1,076 430	±156	(pp)-(rr)
	t be t ash	-		430	- ±3	-	-	<b>430</b> 89	±65 +4	(SS) (#)
Ash Disposal:	t asn t be	66 3	±2 -	23 1	±3 -	-	-	89 <b>4</b>	±4 -	(tt) (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	()

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

- (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<sub>2</sub>O/ha.a assuming 1.205 kg K<sub>2</sub>O/kg K, and a total energy requirement for potash fertiliser of 9.3 MJ/ kg K<sub>2</sub>O (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).
- (I) 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<sub>2</sub>O<sub>5</sub>/ 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<sub>2</sub>O<sub>5</sub> (Ref. 7).
- (o) Potash fertiliser application rate of 123.8 kg K<sub>2</sub>O/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<sub>2</sub>O (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).

- (II) 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 i) and total electricity supplies of 6,427 MJ/t of bioethanol (consisting of 515 MJ/t of bioethanol for milling, hydrolysis, fermentation and distillation, 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).

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

Functional Unit: :		on during pro		inved from W	ieat using hat	urai gas-tireo	a combined h	eat and powe
Final Unit of Measurement:		of bioethanol	cessing					
Relevant Location:	United K							
Relevant Period:	2002	inguom						
Allocation Procedures:			rkat pricas as		4 tonnes of wh	naat straw at	£25/t (Ref. 1	) and 3 /25
Anocation Procedures.	tonnes o to bioeth	of harvested w anol, and 1.1	heat grain wit	h 20% moisti animal feed a	ure content at t £80/t (Ref. 3	£69/t (Ref. 2	), giving a 87	.1% allocation
Contribution	Per	(ci. 4), giving	a 04.470 alloc		Dioxide Outpu	it (ka CO <sub>2</sub> )		
Contribution	Unit	Dire	ect	Indir		Tot	al	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) (C, I)
· Diesel Fuel	ha.a	377	±60	44	±20	421	±63	(c, j)
Reference System: - Diesel Fuel	ha.a	- 63	±00 ±10	- 7	±3	- 70	±00	(c, j) (c, k)
Sub-Totals		314	±61		±57	879	±83	(0, 1)
	ha.a <b>t be</b>	92	±07 ±18	565 <b>165</b>	±37 ±17	257	±03 ±25	(I)
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 <b>t be</b>	23 8	±3 <b>±1</b>	223 <b>75</b>	±18 <b>±6</b>	246 <b>83</b>	±19 <b>±6</b>	(t)
Straw Transport:	l De	0		13	10	00	10	(1)
- 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, y) (c, z)
		-				10		(0, 2)
Sub-Totals	t bws t be	5 6	±1 <b>±1</b>	14 16	±2 <b>±2</b>	19 <b>22</b>	±2 <b>±2</b>	(v)
Wheat Transport:	1.1-			_				
- 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: · Caustic Soda	t de	_	_	47	±7	47	±7	(dd) (ee) (ff)
Diam. Phosph.	t de	_	_	47	±′	47	±′	(II) (gg)
Sulphuric Acid	t de t de	_	_	2 4	±4	2 4	±4	(gg) (hh)
Enzyme AMG	t de t de	-	_	4 5	±4 ±1	4 5	±4 ±1	• • •
Enzyme AA	t de t de	-		2	±1	2	±1	(ii) (ii)
Calcium Chlor.	t de t de	-		2	-	2	-	(jj) (kk)
		-	-		-		-	(KK)
Sub-Totals	t de t be	-	-	61 <b>54</b>	±8 <b>±7</b>	61 <b>54</b>	±8 <b>±7</b>	(II)
Dehydration:	t be	-	-	-	-	-	-	(c)(mm)(nn)
Surplus Electricity	t be	-630	-	-	-	-630	-	(00)
Plant Construction	t be	-	-	55	±	55	±8	(pp)-(rr)
Plant Maintenance	t be	-	-	19	±	19	±3	(ss)
Ash Disposal:	t ash	- 4	-	-	-	4	- 10	(tt) (uu)
	t be	-	-	-	-	-	-	(ii) (uu)
Distribution: Diesel Fuel	t be	25	±1	7	±1	32	±1	(vv)
Totals	t be	- 464	±18	401	±21	-63	±28	× /

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

- (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<sub>2</sub>/kg N (Ref. 6).
- (b) Phosphate fertiliser application rates of 41 kg P/ha.a (Ref. 5), or 93.9 kg P<sub>2</sub>O<sub>5</sub>/ ha.a assuming 2.290 kg P<sub>2</sub>O<sub>5</sub>/kg P, and a total carbon requirement for phosphate fertiliser of 0.700 kg CO<sub>2</sub>/kg P<sub>2</sub>O<sub>5</sub> (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<sub>2</sub>O/ha.a assuming 1.205 kg K<sub>2</sub>O/kg K, and a total carbon requirement for potash fertiliser of 0.453 kg CO<sub>2</sub>/ kg K<sub>2</sub>O (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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/kg (Ref. 7).
- Sowing rate of 185 kg/ha.a (Ref. 10) and a total carbon requirement of 0.547 kg CO<sub>2</sub>/kg of seed based on a ratio of 0.0405 kg CO<sub>2</sub>/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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0081 kg CO<sub>2</sub>/MJ and a total carbon requirement of 0.0767 kg CO<sub>2</sub>/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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0081 kg CO<sub>2</sub>/MJ and a total carbon requirement of 0.0767 kg CO<sub>2</sub>/MJ for diesel fuel in the UK in 1996 (Ref. 12).
- (I) 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<sub>2</sub>/MJ N for ammonium nitrate (Ref. 6).
- (n) Phosphate fertiliser application rate of 24.54 kg P<sub>2</sub>O<sub>5</sub>/ 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<sub>2</sub>O<sub>5</sub> (Ref. 7).
- (o) Potash fertiliser application rate of 123.8 kg K<sub>2</sub>O/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 CO<sub>2</sub>/ kg K<sub>2</sub>O (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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0081 kg CO<sub>2</sub>/MJ and a total carbon requirement of 0.0767 kg CO<sub>2</sub>/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<sub>2</sub>/ha.a, Hesston baler of 14.4 kg CO<sub>2</sub>/ha.a and telescopic handler for loading in field of 1.9 kg CO<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/ha.a, of Hesston baler of 6.8 kg CO<sub>2</sub>/ha.a and of telescopic handler for loading in the field of 0.65 kg CO<sub>2</sub>/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<sub>2</sub>/t-km, an indirect carbon requirement of 0.0161 ± 0.0017 kg CO<sub>2</sub>/t-km and a total carbon requirement of 0.0723 ± 0.0027 kg CO<sub>2</sub>/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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0081 kg CO<sub>2</sub>/MJ and a total carbon requirement of 0.0767 kg CO<sub>2</sub>/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<sub>2</sub>/kg for low density polyethylene (Ref. 22).
- (y) Carbon dioxide output from manufacture of telescopic handler of 1.0 kg CO<sub>2</sub>/t of baled wheat straw (Ref. 22).
- (z) Carbon dioxide output from maintenance and repair of telescopic handler of 0.3 kg CO<sub>2</sub>/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<sub>2</sub>/t-km, an indirect carbon requirement of 0.0161 ± 0.0017 kg CO<sub>2</sub>/tkm and a total carbon requirement of 0.0723 ± 0.0027 kg CO<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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  $0.13 \pm 0.16$  kg CO<sub>2</sub>/ 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<sub>2</sub>/ 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<sub>2</sub>/ 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<sub>2</sub>/ kg for calcium chloride (Ref. 19).
- (II) 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<sub>2</sub>/ 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<sub>2</sub> 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<sub>2</sub>/£ (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 j and total electricity supplies of 6,427 MJ/t of bioethanol (consisting of 515 MJ/t of bioethanol for milling, hydrolysis, fermentation and distillation, and distillation, 25 MJ/t of bioethanol (consisting of 515 MJ/t of bioethanol for milling, hydrolysis, fermentation and distillation, 25 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<sub>2</sub> 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<sub>2</sub>/t-km, an indirect carbon requirement of 0.0161 ± 0.0017 kg CO<sub>2</sub>/t-km and a total carbon requirement of 0.0723 ± 0.0027 kg CO<sub>2</sub>/tkm (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<sub>2</sub>/t-km, an indirect carbon requirement of 0.0161 ± 0.0017 kg CO<sub>2</sub>/t-km and a total carbon requirement of 0.0723 ± 0.0027 kg CO<sub>2</sub>/t-km (Ref. 13).

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# Spreadsheet for Methane Outputs from Bioethanol Production from Wheat Using Straw as Fuel (Model 7)

Functional Unit: :		nol at point of ion during pro		derived from w	heat using na	atural gas-fire	d combined h	neat and power	
Final Unit of Measurement:			cessing						
Relevant Location:		1 tonne of bioethanol United Kingdom							
Relevant Period:	2002	linguonn							
Allocation Procedures:		n average ma	arket prices	assuming 1.30	A toppes of y	whoat straw a	+ £25/t (Dof	1) and 3 425	
Anocation r rocedures.	tonnes to bioet		vheat grain w 41 tonnes of	vith 20% mois f animal feed a	ture content a at £80/t (Ref.	at £69/t (Ref. 2	2), giving a 8	7.1% allocation	
Contribution	Per	, g			hane Output	(ka CH₄)			
	Unit	Dire		Indi	rect	Tc	otal	Notes	
		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, b)	
- 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	0.002	-	0.223	±0.033	0.224	±0.033	(I)	
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)	
o: o:	t be	-	-	0.001	-	0.001	-	(v)	
Straw Storage:	4 6			0.001		0.001		(2.11)	
- Diesel Fuel - Sheeting	t bws t bws	-	-	0.001	-	0.001	-	(c,w)	
- Machinery	t bws	-	-	-	-	-	-	(c, x)	
- Maintenance	t bws	-	-	-	-	-	-	(c, y) (c, z)	
	1.0003	-	-	-	-	-	-	(0, 2)	
Sub-Totals	t bws	-	-	0.001	-	0.001	-		
M/h = = t Tree reserves	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								(dd) (aa)	
Distillation: - Caustic Soda	t de			0.136	±0.020	0.136	±0.020	(dd) (ee)	
- Diam. Phosph.	t de t de	-	-	0.130	±0.020	0.130	±0.020	(ff)	
- Sulphuric Acid	t de t de	-	-	0.007	- ±0.008	- 0.007	- ±0.008	(gg) (hh)	
- Enzyme AMG	t de	_	-	-	-	-	-	(iii)	
- Enzyme AA	t de	_	-	_	_	_	_	(ii) (jj)	
- Calcium Chlor.	t de	-	-	-	-	-	-	(kk)	
Sub Totols	t al a			0.440	+0.000	0.4.40	0.000		
Sub-Totals	t de <b>t be</b>	-	-	0.143 <b>0.128</b>	±0.022 ±0.019	0.143 <b>0.128</b>	0.022 <b>±0.019</b>	(II)	
Dehydration:	tbe	-	-	-	-	-	-	(c) (mm) (nn	
Direct Emissions	tbe	0.030	-	-	-	0.030	-	(00)	
Surplus Electricity	tbe	-1.698	-	-	-	-1.698	-	(pp)	
Plant Construction	tbe	-1.050	-	-	-	-1.050	-	(qq)-(ss)	
Plant Maintenance	tbe	-	-	-	-	-	-	(qq)-(33) (tt)	
Ash Disposal	tash	-	-	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		

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

- (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<sub>4</sub>/kg N (Ref. 6).
- (b) Phosphate fertiliser application rates of 41 kg P/ha.a (Ref. 5), or 93.9 kg P<sub>2</sub>O<sub>5</sub>/ ha.a assuming 2.290 kg P<sub>2</sub>O<sub>5</sub>/kg P, and a total methane requirement for phosphate fertiliser of 2.3 x 10<sup>-5</sup> kg CH<sub>4</sub>/kg P<sub>2</sub>O<sub>5</sub> (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<sub>2</sub>O/ha.a assuming 1.205 kg K<sub>2</sub>O/kg K, and a total methane requirement for potash fertiliser of 2.1 x 10<sup>5</sup> kg CH<sub>4</sub>/ kg K<sub>2</sub>O (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 x 10<sup>-4</sup> kg CH<sub>4</sub>/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 x 10<sup>-4</sup> kg CH<sub>4</sub>/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  $1.8 \times 10^{-4}$  kg CH<sub>4</sub>/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 x 10<sup>-4</sup> kg CH<sub>4</sub>/kg (Ref. 7).
- (i) Sowing rate of 185 kg/ha.a (Ref. 10) and a total methane requirement of 0 kg CH<sub>4</sub>/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 x 10<sup>-7</sup> kg CH<sub>4</sub>/MJ, an indirect methane requirement of 2.04 x 10<sup>-5</sup> kg CH<sub>4</sub>/MJ and a total methane requirement of 2.1 x 10<sup>-5</sup> kg CH<sub>4</sub>/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 x 10<sup>-7</sup> kg CH<sub>4</sub>/MJ, an indirect methane requirement of 2.04 x 10<sup>-5</sup> kg CH<sub>4</sub>/MJ and a total methane requirement of 2.1 x 10<sup>-5</sup> kg CH<sub>4</sub>/MJ for diesel fuel in the UK in 1996 (Ref. 12).
- (I) 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 x  $10^{-3} \pm 0.6 \times 10^{-3}$  kg CH<sub>4</sub>/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 x 10<sup>-5</sup> kg CH<sub>4</sub>/kg P<sub>2</sub>O<sub>5</sub> (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 x  $10^{-5}$  kg CH<sub>4</sub>/ kg K<sub>2</sub>O (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  $6.0 \times 10^{-7}$  kg CH<sub>4</sub>/ MJ, an indirect methane requirement of  $2.04 \times 10^{-5}$  kg CH<sub>4</sub>/ MJ and a total methane requirement of  $2.1 \times 10^{-5}$  kg CH<sub>4</sub>/ 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<sup>-7</sup> kg CH<sub>4</sub>/ 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  $1.192 \times 10^{-7}$  kg CH<sub>4</sub>/ 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<sup>-7</sup> kg CH<sub>4</sub>/ 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  $4.900 \times 10^{-7} \pm 2.000 \times 10^{-8}$  kg CH<sub>4</sub>/t-km, an indirect methane requirement of  $1.672 \times 10^{-5} \pm 6.3 \times 10^{-7}$  kg CH<sub>4</sub>/t-km and a total methane requirement of  $1.721 \times 10^{-5} \pm 6.5 \times 10^{-7}$  kg CH<sub>4</sub>/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  $6.0 \times 10^{-7}$  kg CH<sub>4</sub>/ MJ, an indirect methane requirement of  $2.04 \times 10^{-5}$  kg CH<sub>4</sub>/ MJ and a total methane requirement of  $2.1 \times 10^{-5}$  kg CH<sub>4</sub>/ 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<sup>-7</sup> kg CH<sub>4</sub>/ 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<sup>-7</sup> kg CH₄/ 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<sup>-7</sup> kg CH<sub>4</sub>/ 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  $4.900 \times 10^{-7} \pm 2.000 \times 10^{-8}$  kg CH<sub>4</sub>/t-km, an indirect methane requirement of  $1.672 \times 10^{-5} \pm 6.3 \times 10^{-7}$  kg CH<sub>4</sub>/t-km and a total methane requirement of  $1.721 \times 10^{-5} \pm 6.5 \times 10^{-7}$  kg CH<sub>4</sub>/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  $3.25 \times 10^{-3}$  kg CH<sub>4</sub>/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<sup>-6</sup> kg CH<sub>4</sub>/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  $2.7 \times 10^{-4} \pm 3.0 \times 10^{-4}$  kg CH<sub>4</sub>/ 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<sub>4</sub>/ 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  $4 \times 10^{-6}$  kg CH<sub>4</sub>/ 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  $2 \times 10^{-4}$  kg CH<sub>4</sub>/ kg for calcium chloride (Ref. 19).
- (II) 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<sub>4</sub>/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  $4.034 \times 10^{-4} \text{ kg CH}_4$ / 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<sup>-7</sup> kg CH<sub>4</sub>/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 j and total electricity supplies of 6,427 MJ/t of bioethanol (consisting of 515 MJ/t of bioethanol for milling, hydrolysis, fermentation and distillation, 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<sup>-7</sup> kg CH<sub>4</sub>/MJ primary energy input to construction (Ref. 18), assuming 84.4% contribution to bioethanol by price of coproducts
- (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  $4.900 \times 10^{-7} \pm 2.000 \times 10^{-8}$  kg CH<sub>4</sub>/t-km, an indirect methane requirement of  $1.672 \times 10^{-5} \pm 6.3 \times 10^{-7}$  kg CH<sub>4</sub>/t-km and a total methane requirement of  $1.721 \times 10^{-5} \pm 6.5 \times 10^{-7}$  kg CH<sub>4</sub>/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  $4.900 \times 10^{-7} \pm 2.000 \times 10^{-8}$  kg CH<sub>4</sub>/t-km, an indirect methane requirement of  $1.672 \times 10^{-5} \pm 6.3 \times 10^{-7}$  kg CH<sub>4</sub>/t-km and a total methane requirement of  $1.721 \times 10^{-5} \pm 6.5 \times 10^{-7}$  kg CH<sub>4</sub>/t-km (Ref. 13).

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# Spreadsheet for Nitrous Oxide Outputs from Bioethanol Production from Wheat Using Straw as Fuel (Model 7)

Functional Unit: :	Bioethan	ol at point of	distribution de	erived from w	heat			
Final Unit of Measureme		of bioethanol						
Relevant Location:	United k	Kingdom						
Relevant Period:	2002							
Allocation Procedures:		on average ma						
	to bioet	hanol, and 1. <sup>4</sup>	141 tonnes of	animal feed	at £80/t (Ref.			7.1% allocation ethanol at
Contribution	Per Unit	Ref. 4), giving a 84.4% allocation to bioethanol. Nitrous Oxide Output (kg N <sub>2</sub> O) Direct Indirect Total						
		Value	Range	Value	Range	Value	Range	
Cultivation and			-		-			
Harvesting:								
<ul> <li>N Fertiliser</li> </ul>	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 - Herbicide	ha.a	-	-	0.003	-	0.003	-	(b, e)
- Insecticide	ha.a ha.a	-	-	- 0.001	-	- 0.001	-	(b, f) (b, g)
- Fungicide	ha.a	_	_	0.007	-	0.007	-	(b, g) (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:								(-)1)
- Diesel Fuel	ha.a	- 0.001	-	-		- 0.001	-	(b, k)
Sub-Totals	ha.a <b>t be</b>	0.668 <b>0.195</b>	±0.100 ±0.029	2.916 <b>0.853</b>	±0.409 <b>±0.120</b>	3.584 <b>1.048</b>	±0.421 <b>±0.123</b>	(I)
Straw Baling:	1.00	0.100	-0.025	0.000	20.120	1.040	20.120	(7)
- 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 <b>t be</b>	0.213 <b>0.072</b>	±0.033 <b>±0.011</b>	0.872 <b>0.293</b>	±0.125 <b>±0.044</b>	1.085 <b>0.365</b>	±0.135 <b>±0.045</b>	(t)
Straw Transport:	l De	0.072	10.011	0.235	10.044	0.303	10.045	(1)
- Diesel Fuel	t bws	-	-	-	-	-	-	(u)
	t be	-	-	-	-	-	-	(v)
Straw Storage:								
- Diesel Fuel	t bws	-	-	-	-	-	-	(c,w)
<ul> <li>Sheeting</li> </ul>	t bws	-	-	-	-	-	-	(c, x)
- Machinery	t bws	-	-	-	-	-	-	(c, y)
- Maintenance	t bws	-	-	-	-	-	-	(c, z)
Sub-Totals	t bws	-	-	-	-	-	-	(.)
Wheat Transport:	t be	-	-	-	-	-	-	(v)
wheat transport.	t hwg t be	-	-	-		-	-	(aa) (bb)
Wheat Drying:	tbe	-	-		-	-	-	(bb) (cc)
Milling, Hydrolysis,	1.00		-		_		_	
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 - Calcium Chlor.	t de t de	-	-	-	-	-	-	(jj) (kk)
- Calcium Chior.	t de	-	-	-	-	-	-	(kk)
Sub-Totals	t de <b>t be</b>	-	-	-	-	-	-	/11)
Dehydration:	tbe	-	-	-	-	-	-	(II) (c) (mm) (nn
Direct Emissions	tbe	0.077	-		-	0.077	-	(00)
Surplus Electricity	tbe	- 0.023			-	- 0.023	-	(00) (pp)
Plant Construction	tbe	- 0.025			-	- 0.025	-	(pp) (qq)-(ss)
Plant Maintenance	tbe	-	-		-	-	-	(qq)-(ss) (tt)
Ash Disposal	1.76	-		-	-	-	-	(uu)
	t be							(uu) (vv)
		1	1		1		1	1
Distribution: - Diesel Fuel	t be	-	_	-	-	-	-	(ww)

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

- (a) Nitrogen fertiliser application rate of 185 N/ha.a (Ref. 5) and a direct nitrous oxide requirement of 0.0036 kg N<sub>2</sub>O/kg N (Ref. 5), an indirect nitrous oxide requirement of 0.0147 kg N<sub>2</sub>O/kg N (Ref. 6) and a total nitrous oxide requirement for ammonium nitrate of 0.0183 kg N<sub>2</sub>O/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<sup>-5</sup> 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<sup>-6</sup> 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  $1.51 \times 10^3$  kg N<sub>2</sub>O/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  $1.51 \times 10^{-3}$  kg N<sub>2</sub>O/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  $1.51 \times 10^{-3}$  kg N<sub>2</sub>O/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  $1.51 \times 10^{-3}$  kg N<sub>2</sub>O/kg (Ref. 8).
- (i) Sowing rate of 185 kg/ha.a (Ref. 10) and a total nitrous oxide requirement of 0.001 kg N<sub>2</sub>O/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<sup>-7</sup> kg N<sub>2</sub>O/MJ, an indirect nitrous oxide requirement of 2.60 x 10<sup>-8</sup> kg N<sub>2</sub>O/MJ and a total nitrous oxide requirement of 5.90 x 10<sup>-7</sup> kg N<sub>2</sub>O/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<sup>-7</sup> kg N<sub>2</sub>O/MJ, an indirect nitrous oxide requirement of 2.60 x 10<sup>-8</sup> kg N<sub>2</sub>O/MJ and a total nitrous oxide requirement of 5.90 x 10<sup>-7</sup> kg N<sub>2</sub>O/MJ for diesel fuel in the UK in 1996 (Ref. 12).
- (I) 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<sub>2</sub>O/kg N (Ref. 5), an indirect nitrous oxide requirement of 0.0147 kg N<sub>2</sub>O/kg N (Ref. 6) and a total nitrous oxide requirement for ammonium nitrate of 0.0183 kg N<sub>2</sub>O/kg N (Ref. 6).
- (n) Phosphate fertiliser application rate of 24.54 kg P<sub>2</sub>O<sub>5</sub>/ 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 x 10<sup>-5</sup> kg N<sub>2</sub>O/kg P<sub>2</sub>O<sub>5</sub> (Ref. 7).
- (o) Potash fertiliser application rate of 123.8 kg K<sub>2</sub>O/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 x 10<sup>6</sup> kg N<sub>2</sub>O/ kg K<sub>2</sub>O (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 x 10<sup>-7</sup> kg N<sub>2</sub>O/MJ, an indirect nitrous oxide requirement of 2.60 x 10<sup>-8</sup> kg N<sub>2</sub>O/MJ and a total nitrous oxide requirement of 5.90 x 10<sup>-7</sup> kg N<sub>2</sub>O/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 x 10<sup>-9</sup> kg N<sub>2</sub>O/ 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 x 10<sup>-9</sup> kg N₂O/ 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 x 10<sup>-9</sup> kg N<sub>2</sub>O/ 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<sub>2</sub>O/t-km, an indirect nitrous oxide requirement of  $2.1 \times 10^{-8} \pm 8 \times 10^{-10}$  kg N<sub>2</sub>O/t-km and a total nitrous oxide requirement of  $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8}$  kg N<sub>2</sub>O/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 x 10<sup>-7</sup> kg N<sub>2</sub>O/MJ, an indirect nitrous oxide requirement of 2.60 x 10<sup>-8</sup> kg N<sub>2</sub>O/MJ and a total nitrous oxide requirement of 5.90 x 10<sup>-7</sup> kg N<sub>2</sub>O/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 x 10<sup>9</sup> kg N<sub>2</sub>O/ 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 x 10<sup>-9</sup> kg N<sub>2</sub>O/ MJ primary energy input to manufacturing (Ref. 18).
- 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 x 10<sup>-9</sup> kg N<sub>2</sub>O/ 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<sub>2</sub>O/t-km, an indirect nitrous oxide requirement of  $2.1 \times 10^{-8} \pm 8 \times 10^{-10}$  kg N<sub>2</sub>O/t-km and a total nitrous oxide requirement of  $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8}$  kg N<sub>2</sub>O/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<sub>2</sub>O /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<sup>-6</sup> kg N<sub>2</sub>O/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  $2 \times 10^{-7} \pm 3 \times 10^{-7} \text{ kg N}_2\text{O}/\text{ kg for sulphuric acid (Ref. 15)}.$
- (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<sub>2</sub>O/ 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  $6 \times 10^{-8}$  kg N<sub>2</sub>O/ 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<sub>2</sub>O/ kg for (Ref. 19).
- (II) 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  $5.577 \times 10^{-6} \text{ kg N}_2\text{O}/\text{ MJ}$  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<sup>-9</sup> kg N<sub>2</sub>O /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 j and total electricity supplies of 6,427 MJ/t of bioethanol (consisting of 515 MJ/t of bioethanol for milling, hydrolysis, fermentation and distillation, 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<sup>9</sup> kg N<sub>2</sub>O/MJ primary energy input to construction (Ref. 18), assuming 84.4% contribution to bioethanol by price of coproducts
- (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  $4.6 \times 10^{-7} \pm 1.7 \times 10^{-8} \text{ kg N}_2\text{O/t-km}$ , an indirect nitrous oxide requirement of  $2.1 \times 10^{-8} \pm 8 \times 10^{-10} \text{ kg N}_2\text{O/t-km}$  and a total methane requirement of  $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8} \text{ kg N}_2\text{O/t-km}$  (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<sub>2</sub>O/t-km, an indirect nitrous oxide requirement of  $2.1 \times 10^{-8} \pm 8 \times 10^{-10}$  kg N<sub>2</sub>O/t-km and a total nitrous oxide requirement of  $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8}$  kg N<sub>2</sub>O/t-km (Ref. 13).

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# Greenhouse Gas Outputs from Bioethanol Production from Wheat Using Straw as Fuel (Model 7)

Functional Unit: :		ol at point of d	istribution de	rived from wh	leat						
Final Unit of Measureme											
Relevant Location:	United Ki	ngdom									
Relevant Period:	2002										
Allocation Procedures:	Based or	i average mark	ket prices, ass	suming 1.394	tonnes of wh	eat straw at £	25/t (Ref. 1)	and			
		onnes of harve									
	87.1% a	allocation to bio	bethanol, and	1.141 tonnes	s of animal fe	ed at £80/t (R	ef. 3) and 1.0	000			
	tonnes of bioethanol at £494/t (Ref. 4), giving a 84.4% allocation to bioethanol.										
Contribution	Per Total Greenhouse Gas Output (kg eq CO <sub>2</sub> )										
	Unit	Dire	ect	Total Notes							
		Value	Range	Value	Range	Value	Range				
Cultivation and					- <b>J</b>						
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:	na.a	570	100	47	120	425	105	(a)			
- Diesel Fuel	ha.a	- 63	±10	- 7	±3	- 70	±11	(a)			
	ila.d	- 03	±10	- /	ΞJ	- 70	±11	(a)			
Sub-Totals	ha a	528	±68	1 5 1 7	+112	2,045	+150				
Jub-101dlb	ha.a <b>t be</b>	528 154	±08 ±20	1,517 <b>444</b>	±142 <b>±42</b>	2,045 <b>598</b>	±158 <b>±46</b>	(b)			
Strow Boling:	i be	134	IZU	444	142	090	140 140	(a)			
Straw Baling:	h = -			007	. 45	405		(-)			
- 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)			
<ul> <li>Maintenance</li> </ul>	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:								X-7			
- Diesel Fuel	t hwg	10	±1	3	-	13	±1	(a)			
2.000.1 00.	t be	30	±3	9	-	39	±3	(e)			
Milling, Hydrolysis,				•				(0)			
Fermentation and											
Distillation:											
- Caustic Soda	t de		_	50	±7	50	±7	(a)			
- Diam. Phosph.	t de	-	_	2	±′	2	±1 -	(a) (a)			
- Sulphuric Acid	t de	-	-	2 4	- ±4	2 4	- ±4	(a) (a)			
- Enzyme AMG	t de		_	4 5	±4 ±1	4 5	±4 ±1	(a) (a)			
- Enzyme AA	t de		-	2	±1 -	2	±/ -	(a) (a)			
- Enzyme AA - Calcium Chlor.	t de t de		-	2	-	2	-	(a) (a)			
	i ue	-	-	1	-	1	-	(a)			
Sub-Totals	t de		_	64	±8	64	±8				
Sub-Totals	t be	-	-	57	±0 ±7	57	±0 ±7	$(\mathbf{a})$			
Dehydration:	t be	-	-	57	1	- 57	1	(e)			
				-	•						
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:				Τ							
- Diesel Fuel	t be	25	±1	7	±1	32	±1	(a)			
Totals	t be	-404	±21	778	±43	374	±49				

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<sub>2</sub>/kg CH<sub>4</sub> and a global warming potential for nitrous oxide of 320 kg eq CO<sub>2</sub>/kg N<sub>2</sub>O.
- (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.

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# 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)

LISUIDUUUU	L NG	16,248	±14 ±2,201	5,422	±10 ±619	- 444	- ±18	22,114		(11111)	
Plant Maintenance Distribution	t be t be	- 369	- ±14	142 129	±21 ±16	-	-	142 498	±21 ±21	(II) (mm)	
Plant Construction	t be	-	-	475	±71	-	-	475	±71	(kk)	
	t be	10,553	±1,408	1,789	±560		-	12,342	±1,519	(jj)	
Sub-Totals	t csb	979 10 552	±131	166	±52	-	-	1,145	±141	(::)	
- LimeX	t csb	-	-	- 94	±14	-	-	- 94	±14	(c, ii)	
Credit:				~ ~	<i>±1</i>			~ ~ ~	<i></i> '	. ,	
- Sulphuric Acid	t csb	-	-	1	±1 ±1	-	-	1	±1 ±1	(hh)	
- Anti-Foam	t csb	-	<i>±9</i> -	6	±5 +1	-	-	6	±10 +1	(c, ŋg)	
- Coke	t csb	- 51	- ±9	16	<u>+2</u>	-	-	67	<u>±2</u> +10	(c, ff)	
- EDTA - Limestone	t csb t csb	-	-	- 13	-	-	-	- 13	- 	(dd) (ee)	
- Anti-Scalant - EDTA	t csb t csb	-	-	1	-	-	-	1	-	(cc) (dd)	
- Soda	t csb	-	-	1	-	-	-	1	-	(bb)	
- Sulphur	t csb	-	-	1	-	-	-	1	-	(aa)	
- Electricity	t csb	60	±9	125	±19			185	<u>+</u> 21	(c, n, p,z)	
- Natural Gas	t csb	868	±130	96	<i>±</i> 46	-	-	964	±138	(c, n, p,z)	
Dehydration:											
Distillation and											
Fermentation,											
Concentration,											
Purification,											
	t be	3,353	±408	1,680	±214	-	-	5,033	±495	(y)	
Sub-Totals	t csb	399	±49	200	<i>±</i> 26	-	-	599	±59		
0.0100	1 000	-	-	-	-	-	-	-	-	(0, 1)	
- Soil - Stones	t csb t csb	-	-	- 4	± 1	-	-	- 4	± 1	(c, w) (c, x)	
Credits:	toch			4						(a)	
- Foam Oil	t csb	-	-	-	-	-	-	-	-	(v)	
- Biocide	t csb	-	-	-	-	-	-	-	-	(c, u)	
- Formaldehyde	t csb	-	-	-	-	-	-	-	-	(c, t)	
- Hydrochlor. Acid	t csb	-	-	1	-	-	-	1	-	(s)	
- Gypsum	t csb	-	-	1	-	-	-	1	-	(c, r)	
- Sulphuric Acid	t csb	-		-	-	-	-	-	-	(q)	
- Electricity	t csb	81	±12	168	±25			249	±28	(c, n-p)	
- Natural Gas	t csb	312	±47	34	±5	-	-	346	±52	(c, n-p)	
and Diffusion:											
Washing, Shredding	l be	004	121	240	121	-	-	924	130	(11)	
- Diesel Fuel	t ssb t be	77 684	±3 <b>±27</b>	27 <b>240</b>	±3 <b>±27</b>	-	-	104 <b>924</b>	±4 ±36	(l) (m)	
Transport: Diosol Fuol	tooh	77	+ 9	27	±0			104	+1	(1)	
Transport	t be	1,289	±229	967	±130	444	±18	2,700	±263	(k)	
Sub-Totals	ha.a	7,948	±1,410	5,964	±800	2,739	±109	16,651	±1,624	(1.)	
Sub Totolo	ha -	7040	1 1 1 1 1 0	E 064	1 000	0 700	+ 100	16 654	1 604		
- Diesel Fuel	ha.a	- 922	±146	- 101	±48	-	-	- 1,023	±154	(c, j)	
Reference System:	ha -	000	1440	404	1.40			1 000		(- !)	
- Diesel Fuel	ha.a	8,870	±1,402	976	±465	-	-	9,846	±1,477	(c, i)	
- Seed	ha.a	-	-	135	±20	-	-	135	±20	(c, h)	
- Insecticide	ha.a	-	-	66	±10	-	-	66	±10	(c, g)	
- Herbicide	ha.a	-	-	110	±16	-	-	110	±16	(c, f)	
- Pesticides	ha.a	-	-	795	±119	-	-	795	±119	(c, e)	
- K Fertiliser	ha.a	-	-	1,165	±175	-	-	1,165	±175	(c, d)	
- P Fertiliser	ha.a	-	-	1,375	±206	-	-	1,375	±206	(b, c)	
- N Fertiliser	ha.a	-	-	1,443	±577	2,739	±109	4, 182	±587	(a)	
Cult. and Harvest:											
		Value	Range	Value	Range	Value	Range	Value	Range		
	Unit	, , , , ,								Notes	
Contribution	Per Primary Energy Input (MJ)										
Contribution	Per	Direct Indirect Feedstock Total								Notes	
					00/t (Ref. 3)				nes of vinas	ses (55%	
					substitution						
					t, derived fro						
										.996 tonnes	
										price for thick	
					of stones fro						
										soil from main	
Allocation Procedures:					ry matter) of					effective pric	
Relevant Period:	200			40.000 +-			h - ( ( C	00.00// /D -	( <b>1</b> ) and an		
Relevant Location:		ted Kingdon	n								
Final Unit of Measurem		onne of bioe									
			41								

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

- (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<sub>2</sub>O/ha.a assuming 1.205 kg K<sub>2</sub>O/kg K, and a total energy requirement for potash fertiliser of 9.3 MJ/ kg K<sub>2</sub>O (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).
- 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.
- (I) 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  $11 \pm 1$  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 1.11 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<sub>2</sub>) 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  $2.4 \pm 2.7$  MJ/kg for sulphuric acid (Ref. 13).
- 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).
- (II) 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).

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- 2. Private communication with A. Nixon of British Sugar plc., Peterborough, United Kingdom, 2 May 2003.
- 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.
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- 9. "Pesticide Use Survey Reports" Ministry of Agriculture, Fisheries and Food, London, United Kingdom.
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# Spreadsheet for Carbon Dioxide Outputs from Bioethanol Production from Sugar Beet using a Natural Gas-fired Boiler and Grid Electricity (Model 2)

Functional Unit:		nol at point of		erived from s	ugar beet usi	ng natural ga	s-fired boiler a	ind grid	
Final Unit of Measurement		y during proce	essing						
Relevant Location:	United Ki								
		inguom							
Relevant Period:	2002		( 40,000 t			( 000 00/4 //		- ff time	
Allocation Procedures:				0		`	,	effective price	
		nnes of sugar							
								soil from main	
		bstitution of 0.							
		.560 tonnes of							
								5.996 tonnes o	
		noisture conte							
		ontent) of £72.5							
		rice for bioetha						sses (55%	
0		6.5% sugar p	urity) of £122.				4).		
Contribution	Per			Carbon Dioxide Output (kg CO2)           Indirect         Total					
	Unit	Direct					Notes		
		Value	Range	Value	Range	Value	Range		
Cult. and Harvest.:									
- N Fertiliser	ha.a	-	-	196	±28	196	<u>+</u> 28	(a)	
- P Fertiliser	ha.a	-	-	61	±9	61	±9	(b, c)	
- K Fertiliser	ha.a	_	_	57		57		(b, c) (c, d)	
- Pesticides	ha.a	Ē	-	14	<u>+9</u>	14	±9		
		-	-		<u>+</u> 2		<u>+</u> 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)	
	1				<u>_</u> 5		<i>±10</i>		
Sub-Totals	ha.a	545	<i>±</i> 97	403	145	948	407		
	t be	88	±16	65	±45	153	±107	(k)	
			ΞĪŪ		±7		±17	()	
Transport:									
- Diesel Fuel	t ssb	5	-	2	-	7	-	(I)	
	t be	44	-	18	-	62	-	(m)	
Washing, Shredding and									
Diffusion:									
- Natural Gas	t csb	16	(2	1	_	17	(2	(c, n, n)	
		10	±2		-		<u>±2</u>	(c, n - p)	
- Electricity	t csb	-	-	12	<u>+2</u>	12	<u>+</u> 2	(c, n - p)	
- Sulphuric Acid	t csb	-	-	-	-	-	-	(q)	
- Gypsum	t csb	-	-	-	-	-	-	(c, r)	
<ul> <li>Hydrochloric Acid</li> </ul>	t csb	-	-	-	-	-	-	(s)	
<ul> <li>Formaldehyde</li> </ul>	t csb	-	-	-	-	-	-	(c, t)	
- Biocide	t csb	-	-	-	-	-	-	(c, u)	
- Foam Oil	t csb	-	-	-	-	-	-	(v)	
Credits:									
- Soil	t csb	_	-	-	-	-	_	(c, w)	
- Stones	t csb	_	_	_	_	_	-	(C, W) (C, X)	
	1050	-	-	-	-	-	-	(0, X)	
Sub Tatala	4	10	_	10	_				
Sub-Totals	t csb	16	<u>+</u> 2	13	<u>+</u> 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	14	46	. 7	(c, n,p, z)	
		40	±7		±1		±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)	
	1050	-	-	- 0	±1	- 0	±1	(0, 11)	
Sub Totala	tash	E0	. –	2		50	. –		
Sub-Totals	t csb	50	±7	3	±2	53	±7	7:0	
	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	(II)	
Distribution	t be	25	±1	7	±1	32	±1	(mm)	
			±79	262		1,092	±85	· ···/	

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
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t csb	= te	onne	of	clean	sugar	bee
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- t ssb = tonne of soiled sugar beet
- t be = tonne of bioethanol

#### <u>Notes</u>

- (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<sub>2</sub>/kg N (Ref. 6).
- (b) Phosphate fertiliser application rates of 38.0 kg P/ha.a (Ref. 5), or 87.0 kg P<sub>2</sub>O<sub>5</sub>/ ha.a assuming 2.290 kg P<sub>2</sub>O<sub>5</sub>/kg P, and a total carbon requirement for phosphate fertiliser of 0.700 kg CO<sub>2</sub>/kg P<sub>2</sub>O<sub>5</sub> (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<sub>2</sub>O/ha.a assuming 1.205 kg K<sub>2</sub>O/kg K, and a total carbon requirement for potash fertiliser of 0.453 kg CO<sub>2</sub>/ kg K<sub>2</sub>O (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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub> /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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0081 kg CO<sub>2</sub>/MJ and a total carbon requirement of 0.0767 kg CO<sub>2</sub>/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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0081 kg CO<sub>2</sub>/MJ and a total carbon requirement of 0.0767 kg CO<sub>2</sub>/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 £29.00/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.
- (I) 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<sub>2</sub>/t-km, an indirect carbon requirement of 0.0161 ± 0.0017 kg CO<sub>2</sub>/tkm and a total carbon requirement of 0.0723 ± 0.0027 kg CO<sub>2</sub>/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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0017 kg CO<sub>2</sub>/MJ and a total carbon requirement of 0.0539 kg CO<sub>2</sub>/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<sub>2</sub>/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  $0.13 \pm 0.16$  kg CO<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sup>-3</sup> kg CO<sub>2</sub>/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<sup>-3</sup> kg CO<sub>2</sub>/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<sub>2</sub>) consumption rate of 0.13 kg/t of clean sugar beet and a carbon requirement of  $0.89 \pm 0.24$  kg CO<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/kg and an indirect carbon requirement of 0.37 kg CO<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub> 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<sub>2</sub>/£ (Ref. 14).
- (II) 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<sub>2</sub>/t-km, an indirect carbon requirement of 0.0161 ± 0.0017 kg CO<sub>2</sub>/t-km and a total carbon requirement of 0.0723 ± 0.0027 kg CO<sub>2</sub>/t-km (Ref. 11).

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# Spreadsheet for Methane Outputs from Bioethanol Production from Sugar Beet using a Natural Gas-fired Boiler and Grid Electricity (Model 2)

Stones $t csb$ $\cdot$	(y) (c,n,p,z) (c,n,p,z) (a) (bb) (cc) (dd) (ee) (c, ff) (c, gg) (hh) (c, ii) (jj) (kk) (ll) (mm)
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Sub-Totals t csb 0.001 ±0.001 0.067 ±0.007 0.068 ±0.007	60
Stones t csb	(c, x)
Soil t csb	(c, w)
Credits:	
Foam Oil t csb	(v)
Biocide t csb	(c, u)
Formaldehyde t csb	(C, t)
Hydrochloric Acid $t csb$	(C, T) (S)
complete Acid to the transformed for the tra	(q) (c, r)
Electricity $t csb$ $0.033 \pm 0.005$ $0.033 \pm 0.005$ Sulphuric Acid $t csb$	(c, n - p) (q)
	(c, n - p) (c, n - p)
Natural Gas $t  csb$ 0.001 $\pm 0.001$ 0.034 $\pm 0.005$ 0.035 $\pm 0.005$	(c, n - p)
Nashing, Shredding and Diffusion:	
t be 0.018 - 0.018 -	(m)
Diesel Fuel t ssb 0.002 - 0.002 -	(l) (m)
Fransport:	//\
10.001 <u>10.011</u> <u>10.011</u>	(19
t be 0.001 0.088 10.000 0.089 10.000	(k)
Sub-Totals ha.a 0.004 ±0.005 0.547 ±0.068 0.551 ±0.068	
	(0, ])
Diesel Fuel ha.a - 0.001 ±0.001 - 0.019 ±0.003 - 0.020 ±0.003	(c, j)
Reference System:	(-) /
Diesel Fuel         ha.a         0.005         ±0.005         0.181         ±0.027         0.186         ±0.028	(c, i)
Seed ha.a 0.008 ±0.001 0.008 ±0.001	(c, h)
Insecticide ha.a	(c, g)
Herbicide ha.a	(c, f)
Pesticides ha.a 0.001 - 0.001 -	(c, e)
K Fertiliser ha.a 0.003 - 0.003 -	(c, d)
P Fertiliser ha.a 0.002 - 0.002 -	(b, c)
N Fertiliser ha.a $0.371 \pm 0.062 = 0.371 \pm 0.062$	(a)
Cult. and Harvest.:	
Unit Direct Indirect Total Value Range Value Range Value Range	NOLES
	Notes
solids and 66.5% sugar purity) of £122.15/t, based on the price of thick juice (Ref. 4).           Contribution         Per         Methane Output (kg CH <sub>4</sub> )	

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
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t csb	= te	onne	of	clean	sugar	bee
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- t ssb = tonne of soiled sugar beet
- t be = tonne of bioethanol

- (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<sub>4</sub>/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 x 10<sup>-5</sup> kg CH<sub>4</sub>/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<sub>2</sub>O/ha.a assuming 1.205 kg K<sub>2</sub>O/kg K, and a total methane requirement for potash fertiliser of 2.1 x 10<sup>-5</sup> kg CH<sub>4</sub>/ kg K<sub>2</sub>O (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  $1.8 \times 10^{-4}$  kg CH<sub>4</sub>/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  $1.8 \times 10^{-4}$  kg CH<sub>4</sub>/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 x 10<sup>-4</sup> kg CH<sub>4</sub>/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<sub>4</sub> /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 x 10<sup>-7</sup> kg CH<sub>4</sub>/MJ, an indirect methane requirement of 2.04 x 10<sup>-5</sup> kg CH<sub>4</sub>/MJ and a total methane requirement of 2.1 x 10<sup>-5</sup> kg CH<sub>4</sub>/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 x 10<sup>-7</sup> kg CH<sub>4</sub>/MJ, an indirect methane requirement of 2.04 x 10<sup>-5</sup> kg CH<sub>4</sub>/MJ and a total methane requirement of 2.1 x 10<sup>-5</sup> kg CH<sub>4</sub>/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.
- Average round trip distance of 94 km (Ref. 2) by bulk road carrier transport with a direct methane requirement of 4.900 x 10<sup>-7</sup> ± 2.000 x 10<sup>-8</sup> kg CH<sub>4</sub>/t-km, an indirect methane requirement of 1.672 x 10<sup>-5</sup> ± 6.3 x 10<sup>-7</sup> kg CH<sub>4</sub>/t-km and a total methane requirement of 1.721 x 10<sup>-5</sup> ± 6.5 x 10<sup>-7</sup> kg CH<sub>4</sub>/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  $3.7 \times 10^{-6}$  kg CH<sub>4</sub>/MJ, an indirect methane requirement of  $1.1 \times 10^{-4}$  kg CH<sub>4</sub>/MJ and a total methane requirement of  $1.1 \times 10^{-4}$  kg CH<sub>4</sub>/MJ for natural gas in the UK in 1996 (Ref. 11), and electricity obtained from the grid with an indirect methane requirement of  $4.043 \times 10^{-4}$  kg CH<sub>4</sub>/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<sub>4</sub>/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  $2.1 \times 10^{-5}$  kg CH<sub>4</sub>/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  $0.01 \pm 0.001$  kg CH<sub>4</sub>/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  $\times 10^{-7}$  kg CH<sub>4</sub>/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  $3.0 \times 10^{-7}$  kg CH<sub>4</sub>/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 x 10<sup>-4</sup> ± 7.0 x 10<sup>-5</sup> kg CH<sub>4</sub>/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 x 10<sup>-6</sup> kg CH<sub>4</sub>/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 x 10<sup>6</sup> kg CH₄/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<sub>2</sub>) consumption rate of 0.13 kg/t of clean sugar beet and a methane requirement of 2.5 x  $10^{-5} \pm 7.0 \times 10^{-6}$  kg CH<sub>4</sub>/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<sub>4</sub>/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 x  $10^{-6}$  kg CH<sub>4</sub>/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 x 10<sup>-6</sup> kg CH₄/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  $2.1 \times 10^{-5}$  kg CH<sub>4</sub>/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<sub>4</sub>/kg and an indirect methane requirement of  $9.2 \times 10^{-3}$  kg CH<sub>4</sub>/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 x 10<sup>-6</sup> kg CH<sub>4</sub>/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<sub>4</sub>/kg for sulphuric acid (Ref. 13).
- (ii) LimeX production rate of 45 kg/t of clean sugar beet (Ref. 2) and a methane requirement  $3.9 \times 10^{-6}$  kg CH<sub>4</sub>/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  $1.192 \times 10^{-7}$  kg CH<sub>4</sub>/MJ of primary energy input to plant construction (Ref. 16).
- (II) 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  $4.900 \times 10^{-7} \pm 2.000 \times 10^{-8}$  kg CH<sub>4</sub>/t-km, an indirect methane requirement of  $1.672 \times 10^{-5} \pm 6.3 \times 10^{-7}$  kg CH<sub>4</sub>/t-km and a total methane requirement of  $1.721 \times 10^{-5} \pm 6.5 \times 10^{-7}$  kg CH<sub>4</sub>/t-km (Ref. 11).

- 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"
- "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.
- "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.
- "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., <u>www.statistics.gov.uk</u>, accessed 7 February 2003.
- 16. Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, HMSO, London, United Kingdom, 2000.
- "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.
- "Handbook of Industrial Energy Analysis" by I. Boustead and G. Hancock, Ellis Horwood, Chichester, United Kingdom, 1979.
- "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:		at point of during proc		lerived from s	ugar beet usi	ng natural ga	s-fired boiler	and grid
Final Unit of Measurement:	1 tonne of b		ะรรแบ่ง					
Relevant Location:	United King							
Relevant Period:	2002	uom						
		orkat price f	or 12 206 top	non of ourgor b	act on the form	n of 622.00/# /!	Dof 1) and an	offootivo
				nes of sugar b				
				s (dry matter) (				
				t (Ref. 2), subs				
				of this is is				
				es of thin juice				
				and 92% sugar				
				pisture content				
				ent) of £72.50/1 for bioethanol				
				5% sugar purit				
4		5565 (33 /0 5	ulus anu oo.	5 % sugai puni	y) 01 £ 122.13/		price of thick	Juice (itel.
				Nitracca	Outide Outer			
Contribution	Per				Oxide Outpu			
	Unit		rect		rect		otal	Notes
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:					Ŭ		Ŭ	
- N Fertiliser	ha.a	0.371	±0.125	1.514	±0.253	1.885	<i>±</i> 0.283	(a)
- P Fertiliser	ha.a	-	<u>_0.120</u>	0.004	±0.203	0.004	±0.203	(b, c)
- K Fertiliser	ha.a	-	-	0.004	<u>_0.001</u>	0.004	_0.001	(b, c) (c, d)
- R Fertiliser - Pesticides	ha.a	-	-	0.001	-	0.001	-	
- Pesticides - Herbicide		-	-		±0.001		±0.001	(c, e)
	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:		1						
- Diesel Fuel	ha.a	- 0.001	-	-	-	- 0.001	_	(c, j)
					_		-	· · ·
Sub-Totals	ha.a	0.375	±0.125	1.528	10.050	1.903	10.000	
	t be	0.061		0.248	±0.253	0.309	±0.283	(k)
		0.001	±0.020	0.240	±0.041	0.000	±0.046	(14)
Transport:								
- Diesel Fuel	t ssb	-	-	-	-	-	-	(1)
	t be	-	-	-	-	-	-	(m)
Washing, Shredding and								()
Diffusion:								
	1 aab							(
- 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)
<ul> <li>Hydrochloric Acid</li> </ul>	t csb	-	-	-	-	-	-	(s)
- Formaldehyde	t csb	-	-	-	-	-	-	(c, t)
- Biocide	t csb	-	-	-	-	-	-	(c, u)
- Foam Oil	t csb	-	-	-	-	-	-	(v)
Credits:	1000							(.,
- Soil	t csb	_	_	_	_	_	_	(c, w)
		-	-	-	-	-	-	
- Stones	t csb	-	-	-	-	-	-	(c, x)
$\mathbf{O}$ + $\mathbf{T}$ + 1		1						
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)
	t csb		-	-	-	-	-	
- Sulphur		-	-	-	-	-	-	(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)
LINEX	1 030	_	-	- 0.007	-	- 0.001	_	(0, 11)
Sub Totala	tach			0.004		0.004		
Sub-Totals	t csb	-	-	- 0.001	-	- 0.001	-	/m
	t be	-	-	- 0.011	-	- 0.011	-	(jj)
		1		-	-	-	-	(kk)
Plant Construction	t be	-	-	-	-	-	-	(((((
Plant Construction Plant Maintenance	t be t be	-	-	-	-	-	-	(II)

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
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t csb = tonne of clean sugar	beet
------------------------------	------

- t ssb = tonne of soiled sugar beet
- t be = tonne of bioethanol

- (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<sub>2</sub>O/kg N (Ref. 5), an indirect nitrous oxide requirement of 0.0147 kg N<sub>2</sub>O/kg N (Ref. 7) and a total nitrous oxide requirement for ammonium nitrate of 0.0183 kg N<sub>2</sub>O/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<sub>2</sub>O/ha.a and a total nitrous oxide requirement for potash fertiliser of 9.4 x 10<sup>-6</sup> kg N<sub>2</sub>O/ kg K<sub>2</sub>O (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  $1.51 \times 10^{-3}$  kg N<sub>2</sub>O/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<sup>-3</sup> kg N<sub>2</sub>O/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<sup>-3</sup> kg N₂O/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<sub>2</sub>O /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<sup>-7</sup> kg N<sub>2</sub>O/MJ, an indirect nitrous oxide requirement of 2.60 x 10<sup>-8</sup> kg N<sub>2</sub>/MJ and a total nitrous oxide requirement of 5.90 x 10<sup>-7</sup> kg N<sub>2</sub>O/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<sup>-7</sup> kg N<sub>2</sub>O/MJ, an indirect nitrous oxide requirement of 2.60 x 10<sup>-8</sup> kg N<sub>2</sub>/MJ and a total nitrous oxide requirement of 5.90 x 10<sup>-7</sup> kg N<sub>2</sub>O/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 £29.00/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.
- (I) 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<sub>2</sub>O/t-km, an indirect nitrous oxide requirement of  $2.1 \times 10^{-8} \pm 8 \times 10^{-10}$  kg N<sub>2</sub>O/t-km and a total nitrous oxide requirement of  $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8}$  kg N<sub>2</sub>O/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  $8.9 \times 10^{-8}$  kg N<sub>2</sub>O/MJ, an indirect nitrous oxide requirement of  $1.1 \times 10^{-8}$  kg N<sub>2</sub>O/MJ and a total nitrous oxide requirement of  $1.0 \times 10^{-7}$  kg N<sub>2</sub>O/MJ for natural gas in the UK in 1996 (Ref. 11), and electricity obtained from the grid with an indirect nitrous oxide requirement of  $5.577 \times 10^{-6}$  kg N<sub>2</sub>O/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<sub>2</sub>O/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  $5.9 \times 10^{-7}$  kg N<sub>2</sub>O/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  $3.0 \times 10^{-4}$  kg N<sub>2</sub>O/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  $6.0 \times 10^{-9}$  kg N<sub>2</sub>O/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 x  $10^{.9}$  kg N<sub>2</sub>O/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 x 10<sup>-3</sup> ± 2.20 x 10<sup>-4</sup> kg N<sub>2</sub>O/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 x 10<sup>-8</sup> kg N<sub>2</sub>O/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 x 10<sup>-8</sup> kg N<sub>2</sub>O/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<sub>2</sub>) consumption rate of 0.13 kg/t of clean sugar beet and a nitrous oxide requirement of 6.6 x  $10^{-6} \pm 1.8 \times 10^{-6}$  kg N<sub>2</sub>O/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<sub>2</sub>O/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  $6.0 \times 10^{-8}$  kg N<sub>2</sub>O/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 x  $10^{-8}$  kg N<sub>2</sub>O/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  $3.5 \times 10^{-7}$  kg N<sub>2</sub>O/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  $4.0 \times 10^{-9} \times 28.1 = 1.1 \times 10^{-7} \text{ kg } N_2 \text{O/kg}$  and an indirect nitrous oxide requirement of  $1.3 \times 10^{-6} \text{ kg } N_2 \text{O/kg}$  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 x 10<sup>-8</sup> kg N<sub>2</sub>O/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<sub>2</sub>O/kg for sulphuric acid (Ref. 13).
- LimeX production rate of 45 kg/t of clean sugar beet (Ref. 2) and a nitrous oxide requirement 1.6 x 10<sup>-5</sup> kg N<sub>2</sub>O/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 x 10<sup>-9</sup> kg N<sub>2</sub>O/MJ of primary energy input to plant construction (Ref. 16).
- (II) 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<sub>2</sub>O/t-km, an indirect nitrous oxide requirement of  $2.1 \times 10^{-8} \pm 8 \times 10^{-10}$  kg N<sub>2</sub>O/t-km and a total nitrous oxide requirement of  $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8}$  kg N<sub>2</sub>O/t-km (Ref. 11).

- 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"
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- 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.
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- 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., <u>www.statistics.gov.uk</u>, 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.
- "Handbook of Industrial Energy Analysis" by I. Boustead and G. Hancock, Ellis Horwood, Chichester, United Kingdom, 1979.
- "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:		anol at point o		derived from	sugar beet u	sing natural g	as-fired boiler	and grid
Final Unit of Measureme		of bioethanc						
Relevant Location:		Kingdom	/1					
		Ringuom						
Relevant Period:	2002							<i></i>
Allocation Procedures:							(Ref. 1) and a	
	price for 1	.507 tonnes o	f sugar beet to	ops (dry matter	) of £10.0/t, ba	ased on an ave	erage market p	rice of £2.00/t
	(wet basis	s) with a 80% r	noisture conte	ent (Ref. 2), su	bstitution of 0.0	669 tonnes of s	soil from washi	ng by soil fron
	main sour	ces, substituti	on of 0.049 to	nnes of stones	from washing	by stones from	n quarrying, ar	effective
							of £16.2/t, deriv	
							n effective aver	
							e market price	
	feed pelle	ts (15% moist	ure content) of	f £72.50/t (Ref	<ul> <li>2), substitutio</li> </ul>	on of 0.566 ton	nes of LimeX b	y agricultural
	lime, and	an assumed p	rice for bioeth	anol of £529.0	0/t (Ref. 3) and	d an effective r	price for 0.720	tonnes of
							thick juice (Re	
Contribution								
Contribution	Per			1		tput (kg eq C	-/	
	Unit	Dir	ect	Ind	irect	To	otal	Notes
		Value	Range	Value	Range	Value	Range	
	-	value	Range	value	Range	value	Range	
Cultivation and								
Harvesting:	ha.a	119	±40	690	±86	809	±95	(a)
- N Fertiliser	ha.a	-	-	62		62	00 _±9	(a)
			-					. ,
- P Fertiliser	ha.a	-	-	57	±9	57	±9	(a)
<ul> <li>K Fertiliser</li> </ul>	ha.a	-	-	15	<u>+2</u>	15	<u>+2</u>	(a)
- Pesticides	ha.a	-	-	2	-	2		(a)
- Herbicide	ha.a	_		1	-	1	-	(a)
		-	-		-		-	
<ul> <li>Insecticide</li> </ul>	ha.a	-	-	8	±1	8	±1	(a)
- Seed	ha.a	610	±96	76		686		(a)
- Diesel Fuel			_00	-	±33		±102	()
	ha -	60		-		70		(-)
Reference System:	ha.a	- 63	±10	- 7	±3	- 70	±10	(a)
- Diesel Fuel								
	ha.a	666	±104	904		1,570		
Sub-Totals	t be	108		147	±93	255	±140	(b)
Sub-Totals	l De	100	±17	147	±15	233	±23	(D)
Transport:					1.0			
		_				_		( )
- Diesel Fuel	t ssb	5	-	2	-	7	-	(a)
	t be	44	-	18	-	62	-	(c)
Washing, Shredding								
and Diffusion:								
<ul> <li>Natural Gas</li> </ul>	t csb	16	<u>+2</u>	2	±1	18	±2	(a)
- Electricity	t csb	-	-	13	+2	13	+2	(a)
- Sulphuric Acid	t csb	-						. ,
		-	-	-	-	-	-	(a)
- Gypsum	t csb	-	-	-	-	-	-	(a)
<ul> <li>Hydrochloric Acid</li> </ul>	t csb	-	-	-	-	-	-	(a)
- Formaldehyde	t csb	-	_	-		-		(a)
- Biocide			-		-		-	
	t csb	-	-	-	-	-	-	(a)
- Foam Oil	t csb	-	-	-	-	-	-	(a)
Credits:								
- Soil	t csb	_		_		_		(2)
		-	-	-	-	-	-	(a)
- Stones	t csb	-	-	-	-	-	-	(a)
Sub-Totals	t csb	16	<u>+2</u>	15	10	22	13	
					<u>±2</u>		<u>±3</u>	(み)
	t be	134	±19	126	±19	260	±26	(d)
Purification,		-						-
Concentration,								
Fermentation,								
Distillation and								
Dehydration:								
- Natural Gas	tooh	45	. –	3	14	48	. –	$(\mathbf{a})$
	t csb	40	±7		±1		±7	(a)
- Electricity	t csb	-	-	10	±1	10	<u>±1</u>	(a)
- Sulphur	t csb	-	-	-	-	-	-	(a)
- Soda	t csb	_		_		-		(a)
		-	-	-	-	-	-	• • •
- Anti-Scalant	t csb	-	-	-	-	-	-	(a)
- EDTA	t csb	-	-	-	-	-	-	(a)
- Limestone	t csb	-	-	-	-	-	_	(a)
- Coke		5	-	1	-	6		
	t csb	5	±1	1	-	-	±1	(a)
- Anti-Foam	t csb	-	-	-	-	-	-	(a)
- Sulphuric Acid	t csb	-	-	-	-	-	-	(a)
Credit:				1	-		-	(~)
				-		_		
- LimeX	t csb	-	-	- 8	±1	- 8	±1	(a)
Sub-Totals	t csb	50	±7	6	±0	56	±7	
					±2		±7	(-)
	t be	539	±75	64	±21	603	±78	(e)
Plant Construction	t be	-	-	24	±4	24	±4	(a)
Plant Maintenance	tbe	-	-	7	±1	7	±1	(a)
Distribution	t be	25	±1	7	±1	32	±1	(a)
				393		1,243		

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
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t csb = tonne of clean sugar bee	t csb :	= tonne	of clean	sugar	bee
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- t ssb = tonne of soiled sugar beet
- t be = tonne of bioethanol

- (a) Summation of results from previous spreadsheets with conversion using a global warming potential for methane of 24.5 kg eq CO<sub>2</sub>/kg CH<sub>4</sub> and a global warming potential for nitrous oxide of 320 kg eq CO<sub>2</sub>/kg N<sub>2</sub>O.
- (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:			point of distring turbine dur			gar beet usi	ng natural g	as-fired con	nbined heat	and power
Final Unit of Measuren		onne of bioe			'9					
Relevant Location:		ted Kingdor								
Relevant Period:	200									
Allocation Procedures:	Ba pric (we fror effe	sed on a ma e for 1.507 t basis) with n main sour ective avera	arket price for tonnes of su h a 80% moi rces, substitu ge price for	ugar beet to sture conte ution of 0.04 14.560 tonr	pps (dry mati nt (Ref. 2), s 49 tonnes of nes of thin ju	ter) of £10.0 substitution f stones fror uice (15% so	0/t, based or of 0.669 tor n washing b olids and 88	n an average ines of soil f by stones fro % sugar pu	e market pric rom washin m quarrying rity) of £16.2	ce of £2.00/i g by soil l, an //t, derived
Contribution	pric anii agr	e for 25.99 mal feed pe icultural lim	r thick juice ( 6 tonnes of p Ilets (15% m e, and an as sses (55% so	oulp (97% r oisture cor sumed pric	noisture con itent) of £72 e for bioeth 6.5% sugar p	ntent) of £2.8 50/t (Ref. 2 anol of £529	56/t, derived ), substitutio 0.00/t (Ref. 3 22.15/t, bas	from an ave on of 0.566 f 3) and an eff	erage marke tonnes of Lin fective price	et price for neX by for 0.720
Contribution	Unit		ect		rect	Feed	stock		tal	Notes
<u></u>		Value	Range	Value	Range	Value	Range	Value	Range	
Cult. and Harvest:										
<ul> <li>N Fertiliser</li> </ul>	ha.a	-	-	1,443	±577	2,739	±109	4,182	±587	(a)
<ul> <li>P Fertiliser</li> </ul>	ha.a	-	-	1,375	±206	-	-	1,375	±206	(b, c)
<ul> <li>K Fertiliser</li> </ul>	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, r) (c, g)
- Seed	ha.a	-	-	135	±10 ±20	-	-	135	±10 ±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 <b>t be</b>	7,948 <b>1,289</b>	±1,410 <b>±229</b>	5,964 <b>967</b>	±800 <b>±130</b>	2,739 <b>444</b>	±109 <b>±18</b>	16,651 <b>2,700</b>	±1,624 <b>±263</b>	(k)
Transport:										
- Diesel Fuel	t ssb t be	77 684	±3 <b>±27</b>	27 <b>240</b>	±3 <b>±27</b>	-	-	104 <b>924</b>	±4 ±36	(l) (m)
Washing, Shredding								•=.		()
and Diffusion:								10.0		<i>(</i> )
<ul> <li>Natural Gas</li> </ul>	t csb	386	±61	42	±20	-	-	428	±64	(c, n-p)
<ul> <li>Sulphuric Acid</li> </ul>	t csb	-	-	-	-	-	-	-	-	(q)
- Gypsum	t csb	-	-	1	-	-	-	1	-	(c, r)
<ul> <li>Hydrochlor. Acid</li> </ul>	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 t be	386 <b>3,243</b>	<i>±</i> 61 <b>±513</b>	40 <b>336</b>	<u>+</u> 20	-	-	426 3,579	<u>±64</u>	(y)
Purification,	1.00	0,240	1913	000	±168			3,573	±538	(9)
Concentration, Fermentation, Distillation and										
Dehydration:						1				,
<ul> <li>Natural Gas</li> </ul>	t csb	878	±139	97	<i>±</i> 46	-	-	975	±146	(c, n, p,z
- Sulphur	t csb	-	-	1	-	-	-	1	-	(aa)
- Soda	t csb	-	-	1	-	-	-	1	-	(bb)
<ul> <li>Anti-Scalant</li> </ul>	t csb	-	-	1	-	-	-	1	-	(cc)
- EDTA	t csb	-	-	-	-	-	-	-	-	(dd)
- Limestone	t csb	-	-	13	<u>+2</u>	-	-	13	<u>+</u> 2	(ee)
- Coke	t csb	51	±9	16	±5	-	-	67	±10	(c, ff)
- Anti-Foam	t csb	-		6		-	-	6		(c, gg)
- Sulphuric Acid	t csb	-	-	1	±1	_	_	1	±1	
Credit:			-		±1				±1	(hh)
- Electricity	t csb	- 32	±7	- 29	±6	-	-	- 61	±9	(c, ii)
- LimeX	t csb	-	-	- 94	±14	-	-	- 94	±14	(c, jj)
Sub-Totals	t csb t be	897 <b>9,669</b>	±139 <b>±1,503</b>	13 <b>140</b>	±49	-	-	910 <b>9,809</b>	±147 +1 592	(kk)
Diant Quant :		-			±526				±1,592	
Plant Construction	t be	-	-	475	±71	-	-	475	±71	(II) (mm)
	t be	-	-	142	±21	-	-	142	±21	(mm)
Plant Maintenance					146					. ,
Distribution Totals	t be t be	369 15,254	±14 ±1,605	129 2,429	±16 ±573	- 444	- ±18	498 18,127	±21 ±1,704	(nn)

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
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t ssb	= tonne of soiled sugar beet
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- t csb = tonne of clean sugar beet
- t be = tonne of bioethanol

- (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<sub>2</sub>O/ha.a assuming 1.205 kg K<sub>2</sub>O/kg K, and a total energy requirement for potash fertiliser of 9.3 MJ/ kg K<sub>2</sub>O (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.
- (I) 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  $1.190 \times 27,000 \times 3.5/7.5 = 14,994 \text{ MJ/hr}$  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 ± 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  $11 \pm 1$  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<sub>2</sub>) 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  $2.4 \pm 2.7$  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.

- (II) 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).

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# 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:				erived from su		ng natural gas	s-fired combi	ned heat
Final Unit of Measurement		of bioethanol		31	v			
Relevant Location:	United K							
		ingaoin						
Relevant Period:	2002		( 40 000 ·			1 000 00 "		-#- *
Allocation Procedures:	price for 1.5 (wet basis) from main s effective av from a price price for 25 animal feed agricultural	507 tonnes of s with a 80% mo sources, substi erage price for for thick juice .996 tonnes of I pellets (15% I lime, and an a	sugar beet tops pisture content itution of 0.049 r 14.560 tonne e (67% solids a pulp (97% mc moisture conte issumed price	nes of sugar be s (dry matter) of t (Ref. 2), subs t tonnes of stor s of thin juice ( and 92% sugar bisture content) ent) of £72.50/t for bioethanol 5% sugar purity	of £10.0/t, basi titution of 0.66 hes from wash (15% solids an purity) of £72. ) of £2.56/t, de : (Ref. 2), subs of £529.00/t (f	ed on an avera 9 tonnes of so ing by stones d 88% sugar p 48/t (Ref. 3), a rived from an titution of 0.56 Ref. 3) and an	age market pri il from washir from quarryin burity) of £16 und an effectiv average mark 6 tonnes of Li effective price	ce of £2.00/t ng by soil g, an 2/t, derived re average et price for imeX by e for 0.720
Contribution	. /			Carbon D	iovido Outout	(ka CO )		
Contribution	Per	i			ioxide Output	( )		
	Unit	Dir	ect	Indi	rect	То	tal	Notes
		Value	Range	Value	Range	Value	Range	
Cult. and Harvest .:			Ŭ		Ŭ		Ŭ	
- N Fertiliser	ha.a			196	(00	196	(00	(0)
		-	-		±28		<u>+</u> 28	(a)
- P Fertiliser	ha.a	-	-	61	<u>+</u> 9	61	<b>±9</b>	(b, c)
- K Fertiliser	ha.a	-	-	57	<u>±9</u>	57	±9	(c, d)
- Pesticides	ha.a	-	-	14	<u>+</u> 2	14	<u>+2</u>	(c, e)
- Herbicide	ha.a	-	-	2	-	2	-	(c, f)
- Insecticide	ha.a	-	-	1	-	1	-	(c, g)
- Seed	ha.a	_	_	7		7		(c, h)
- Diesel Fuel	ha.a	608		72	±1	680	±1	
	nd.a	000	±96	12	±33	000	±102	(c, i)
Reference System:	1.			_				
- Diesel Fuel	ha.a	- 63	±10	- 7	±3	- 70	±10	(c, j)
					±0		270	
Sub-Totals	ha.a	545	±97	403	45	948	407	
	t be	88	±16	65	± <b>45</b>	153	±107	(k)
			TIO		±7		±17	()
Transport:								
- Diesel Fuel	t ssb	5	-	2	-	7	-	(1)
	t be	44	-	18	-	62	-	(m)
Washing, Shredding and								(,
Diffusion:								
<ul> <li>Natural Gas</li> </ul>	t csb	20	<u>±</u> 3	1	±1	21	±3	(c, n - p)
<ul> <li>Sulphuric Acid</li> </ul>	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)
Durification			120		TO		120	())
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	-	-	_	-	_	-	(00)
- 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)
	t csb	Ē	-		-		- ±1	
		-	-	- 8	±1	- 8	±1	(c, jj)
- LimeX	1 000							1
- LimeX Sub-Totals	t csb	51	±7	- 9	±1	42	±7	(11)
	t csb t be	550	±75	- 97	±11	453	±78	(kk)
Sub-Totals Plant Construction	t csb t be t be			- 97 24	±11 ±4	453 24	±78 ±4	(kk) (II)
Sub-Totals	t csb t be	550	±75	- 97	±11	453	±78	. ,
Sub-Totals Plant Construction	t csb t be t be	550 -	±75 -	- 97 24	±11 ±4	453 24	±78 ±4	(II)

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

## Abbreviations

ha.a	= hectare year
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t csb	= te	onne	of	clean	sugar	bee
-------	------	------	----	-------	-------	-----

- t ssb = tonne of soiled sugar beet
- t be = tonne of bioethanol

#### <u>Notes</u>

- (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<sub>2</sub>/kg N (Ref. 6).
- (b) Phosphate fertiliser application rates of 38.0 kg P/ha.a (Ref. 5), or 87.0 kg P<sub>2</sub>O<sub>5</sub>/ ha.a assuming 2.290 kg P<sub>2</sub>O<sub>5</sub>/kg P, and a total carbon requirement for phosphate fertiliser of 0.700 kg CO<sub>2</sub>/kg P<sub>2</sub>O<sub>5</sub> (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<sub>2</sub>O/ha.a assuming 1.205 kg K<sub>2</sub>O/kg K, and a total carbon requirement for potash fertiliser of 0.453 kg CO<sub>2</sub>/ kg K<sub>2</sub>O (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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub> /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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0081 kg CO<sub>2</sub>/MJ and a total carbon requirement of 0.0767 kg CO<sub>2</sub>/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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0081 kg CO<sub>2</sub>/MJ and a total carbon requirement of 0.0767 kg CO<sub>2</sub>/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.
- (I) 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<sub>2</sub>/t-km, an indirect carbon requirement of 0.0161 ± 0.0017 kg CO<sub>2</sub>/tkm and a total carbon requirement of 0.0723 ± 0.0027 kg CO<sub>2</sub>/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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0017 kg CO<sub>2</sub>/MJ and a total carbon requirement of 0.0539 kg CO<sub>2</sub>/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 ± 0.16 kg CO<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sup>-5</sup> kg CO<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sup>-3</sup> kg CO<sub>2</sub>/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<sup>-3</sup> kg CO<sub>2</sub>/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<sub>2</sub>) consumption rate of 0.13 kg/t of clean sugar beet and a carbon requirement of  $0.89 \pm 0.24$  kg CO<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/kg and an indirect carbon requirement of 0.37 kg CO<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0539 kg CO<sub>2</sub>/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<sub>2</sub>/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.
- (II) Carbon dioxide output of 47,500 tonnes of CO<sub>2</sub> 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<sub>2</sub>/£ (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<sub>2</sub>/t-km, an indirect carbon requirement of 0.0161 ± 0.0017 kg CO<sub>2</sub>/t-km and a total carbon requirement of 0.0723 ± 0.0027 kg CO<sub>2</sub>/t-km (Ref. 11).

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## 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: Final Unit of Measuremer	and pov		distribution d am turbine du			ng natural ga	s-fired combi	ned heat
Relevant Location:	United K							
Relevant Period:	2002	gaom						
Allocation Procedures:	price for 1.5 (wet basis) from main s effective av from a price price for 25 animal feed agricultural	507 tonnes of with a 80% m sources, subst erage price fo e for thick juice .996 tonnes o I pellets (15% lime, and an a	for 13.296 toni sugar beet tops oisture content itution of 0.049 r 14.560 tonne e (67% solids a f pulp (97% mo moisture conte assumed price solids and 66.5	s (dry matter) ( (Ref. 2), subs tonnes of sto s of thin juice nd 92% sugar pisture content ent) of £72.50/ for bioethanol	of £10.0/t, bas stitution of 0.66 nes from wash (15% solids ar purity) of £72 ) of £2.56/t, de t (Ref. 2), subs of £529.00/t (I	ed on an avera 59 tonnes of sc ing by stones ad 88% sugar p .48/t (Ref. 3), a prived from an stitution of 0.56 Ref. 3) and an	age market pri ill from washir from quarrying burity) of £16.3 and an effectiv average mark 6 tonnes of Li effective price	ce of £2.00/ g by soil g, an 2/t, derived e average et price for meX by e for 0.720
Contribution	Per			Metha	ne Output (k	g CH₄)		
	Unit	Dii	ect		irect	<b>U</b> .7	otal	Notes
		Value	Range	Value	Range	Value	Range	
Cult. and Harvest .:			Ŭ		Ŭ		Ŭ	
- 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, r) (c, g)
- Seed	ha.a	-	_	0.008	+0.001	0.008	+0.001	(c, g) (c, h)
- Diesel Fuel	ha.a	- 0.005	- ±0.005	0.008	±0.001	0.008	±0.001	(C, I) (C, i)
Reference System:	na.a	0.000	10.005	0.101	±0.027	0.100	±0.028	(0, 1)
- Diesel Fuel	ha.a	- 0.001	±0.001	- 0.019	±0.003	- 0.020	40.000	(c, j)
	nara	0.001	10.007	01070	±0.003	0.020	±0.003	(0, ])
Sub-Totals	ha.a	0.004	±0.005	0.547	±0.068	0.551	±0.068	
	t be	0.001	±0.001	0.088	±0.000	0.089	±0.000	(k)
Transport:					201011		201011	
- Diesel Fuel	t ssb	-	-	0.002	-	0.002	-	(I)
	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	-	10.001	-	10.000	-	10.007	(c, 11 p)
- Gypsum	t csb	-		_		-		(c, r)
- Hydrochloric Acid	t csb	_	-	_	-	_	-	(0,1) (s)
- Formaldehyde	t csb	-	-	-	-	-	-	
5		-	-	-	-	-	-	(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	10.001	0.042	10.006	0.043	±0.007	
	t be	0.008	±0.001 <b>±0.008</b>	0.353	<i>±0.006</i> <b>±0.050</b>	0.361	±0.007	(y)
Purification,			70.000		10.000		20.001	
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	-	<u>~</u> 0.003	-	-0.013	-	<u>-</u> 0.015	(c,n,p, z (aa)
- Soda	t csb	-	-	-	-	-	-	(aa) (bb)
- Soda - Anti-Scalant	t csb	-	-	-	-	-	-	. ,
- Anti-Scalant - EDTA		-	-	-	-		-	(cc)
	t csb	-	-	-	-	-	-	(dd)
- Limestone	t csb	-	-	-	-	-	-	(ee)
- Coke	t csb	-	-	-	-	-	-	(c, ff)
- Anti-Foam	t csb	-	-	-	-	-	-	(c, gg)
- Sulphuric Acid	t csb	-	-	-	-	-	-	(hh)
Credit:				0.000		0.000		,
- 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	-	-	-	-	-	-	(II)
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	

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

## Abbreviations

ha.a	= hectare year
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t csb	= tonne o	fc	lean	sugar	bee
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- t ssb = tonne of soiled sugar beet
- t be = tonne of bioethanol

#### <u>Notes</u>

- (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<sub>4</sub>/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 x 10<sup>-5</sup> kg CH<sub>4</sub>/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<sub>2</sub>O/ha.a assuming 1.205 kg K<sub>2</sub>O/kg K, and a total methane requirement for potash fertiliser of 2.1 x 10<sup>-5</sup> kg CH<sub>4</sub>/ kg K<sub>2</sub>O (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  $1.8 \times 10^{-4}$  kg CH<sub>4</sub>/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  $1.8 \times 10^{-4}$  kg CH<sub>4</sub>/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 x 10<sup>-4</sup> kg CH<sub>4</sub>/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<sub>4</sub> /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  $6.0 \times 10^{-7}$  kg CH<sub>4</sub>/MJ, an indirect methane requirement of  $2.04 \times 10^{-5}$  kg CH<sub>4</sub>/MJ and a total methane requirement of  $2.1 \times 10^{-5}$  kg CH<sub>4</sub>/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 x 10<sup>-7</sup> kg CH<sub>4</sub>/MJ, an indirect methane requirement of 2.04 x 10<sup>-5</sup> kg CH<sub>4</sub>/MJ and a total methane requirement of 2.1 x 10<sup>-5</sup> kg CH<sub>4</sub>/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.
- Average round trip distance of 94 km (Ref. 2) by bulk road carrier transport with a direct methane requirement of 4.900 x 10<sup>-7</sup> ± 2.000 x 10<sup>-8</sup> kg CH<sub>4</sub>/t-km, an indirect methane requirement of 1.672 x 10<sup>-5</sup> ± 6.3 x 10<sup>-7</sup> kg CH<sub>4</sub>/t-km and a total methane requirement of 1.721 x 10<sup>-5</sup> ± 6.5 x 10<sup>-7</sup> kg CH<sub>4</sub>/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 x 10<sup>-6</sup> kg CH<sub>4</sub>/MJ, an indirect methane requirement of 1.1 x 10<sup>-4</sup> kg CH<sub>4</sub>/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<sub>4</sub>/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  $2.1 \times 10^{-5}$  kg CH<sub>4</sub>/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  $0.01 \pm 0.001$  kg CH<sub>4</sub>/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  $\times 10^{-7}$  kg CH<sub>4</sub>/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  $3.0 \times 10^{-7}$  kg CH<sub>4</sub>/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 x 10<sup>-4</sup> ± 7.0 x 10<sup>-5</sup> kg CH<sub>4</sub>/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 x 10<sup>-6</sup> kg CH<sub>4</sub>/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 x 10<sup>6</sup> kg CH<sub>4</sub>/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<sub>2</sub>) 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<sub>4</sub>/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<sub>4</sub>/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 x  $10^{-6}$  kg CH<sub>4</sub>/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 x 10<sup>-6</sup> kg CH₄/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  $2.1 \times 10^{-5}$  kg CH<sub>4</sub>/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<sub>4</sub>/kg and an indirect methane requirement of  $9.2 \times 10^{-3}$  kg CH<sub>4</sub>/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 x 10<sup>-6</sup> kg CH<sub>4</sub>/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<sub>4</sub>/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 x 10<sup>-4</sup> kg CH<sub>4</sub>/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 x 10<sup>-6</sup> kg CH<sub>4</sub>/MJ, an indirect

methane requirement of  $1.1 \times 10^{-4}$  kg CH<sub>4</sub>/MJ and a total methane requirement of  $1.1 \times 10^{-4}$  kg CH<sub>4</sub>/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  $3.9 \times 10^{-6}$  kg CH<sub>4</sub>/kg for lime (Ref. 7).
- (kk) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 85.7% to bioethanol.
- (II) 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  $1.192 \times 10^{-7}$  kg CH<sub>4</sub>/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<sub>4</sub>/t-km, an indirect methane requirement of  $1.672 \times 10^{-5} \pm 6.3 \times 10^{-7}$  kg CH<sub>4</sub>/t-km and a total methane requirement of  $1.721 \times 10^{-5} \pm 6.5 \times 10^{-7}$  kg CH<sub>4</sub>/t-km (Ref. 11).

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# 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)

$ \begin{tabular}{ c c c c c c c c c c c c c c c c c c c$	4).         Nitrous Oxide Output (kg N-0)         Total         Nature         Total         Nature         Total         Nature         Nature         Total         Nature	Hydrochloric Acid Formaldehyde Biocide Foam Oil credits: Soil Stones ub-Totals urification, Concentration, ermentation, Distillation nd Dehydration: Natural Gas Sulphur Soda Anti-Scalant EDTA Limestone Coke Anti-Foam Sulphuric Acid credit: Electricity LimeX ub-Totals
animal reed pellets (15% moisture content) of £22.500 (Ref. 2), substitution of 0.560 for 0.720 tornes of Unnex 5 y, solids and 66.5% sugar purity) of £122.15%, based on the price of thick juice (Ref. 4).           Contribution         Per         Direct         Total         Notes           0.001         20.101 (Ref. 2), substitution of 0.560 output (kg N,O).         Notes         Notes           0.101         Direct         Indirect         Total         Notes           0.101         Notes         0.004         ±0.283         (Ref. 4).           0.101         Direct         1.514         ±0.283         (Ref. 4).         (Ref. 4).           0.101         0.004         ±0.001         0.004         ±0.001         (Ref. 4).         (Ref. 4).           0.101         0.004         ±0.001         0.004         ±0.001         (Ref. 4).	4).         Nitrous Oxide Output (kg N <sub>2</sub> O)           Cultivation and Harvesting:         Na.a         0.371         ±0.125         1.514         ±0.253         1.885         ±0.283           Cultivation and Harvesting:         ha.a         0.371         ±0.125         1.514         ±0.253         1.885         ±0.283           - N Fertiliser         ha.a         -         -         0.001         -         0.001         ±0.001         0.004         ±0.001         0.004         ±0.001         -         0.004         ±0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         0.005         ±0.001         -         -         0.001         -         -         0.005         ±0.001         -         -         0.001         -         -         -         0.001         -         -         -         -         -         -         -         -         -         -         -         -         -         -         -         -         -         -	Hydrochloric Acid Formaldehyde Biocide Foam Oil credits: Soil Stones ub-Totals urification, Concentration, ermentation, Distillation nd Dehydration: Natural Gas Sulphur Soda Anti-Scalant EDTA Limestone Coke Anti-Foam Sulphuric Acid credit: Electricity LimeX ub-Totals
animal reed pellets (15% moisture content) of E72 500 (Ref. 2), substitution of 0.568 for 0.720 tonnes of LimeX by agricol transport.	4).         Nitrois Oxide Output (kg N <sub>2</sub> O).           Contribution         Unit         Direct         Indirect         Total         N           Cultivation and Harvesting:         ha.a         0.371         ±0.125         1.514         ±0.253         1.885         ±0.283         .           - N Fertiliser         ha.a         -         0.004         ±0.001         -         0.004         ±0.001         -         0.004         ±0.001         -         0.004         ±0.001         -         0.004         ±0.001         -         0.004         ±0.001         -         0.004         ±0.001         -         0.004         ±0.001         -         0.004         ±0.001         -         0.004         ±0.001         -         0.005         ±0.001         -         0.005         ±0.001         -         0.005         ±0.001         -         0.005         ±0.001         -         0.005         ±0.001         -         0.005         ±0.001         -         0.005         ±0.001         -         0.005         ±0.001         -         0.005         ±0.001         -         0.005         ±0.001         -         0.005         ±0.001         -         0.005         ±0.001         ±0.001	Hydrochloric Acid Formaldehyde Biocide Foam Oil credits: Soil Stones ub-Totals uu-Totals Uu-Tota
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	4).         Nitrous Oxide Output (kg N <sub>2</sub> O).           Contribution         Per Unit         Direct         Indirect         Total         Na           Cultivation and Harvesting:         ha.a         0.371         ±0.125         1.514         ±0.253         1.885         ±0.283         .           - N Fertiliser         ha.a         -         0.004         ±0.011         -         0.004         ±0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         -         -         -         -         -         -         -         -         -         -         -         -         -         0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         -         0.001         -         -         0.001         -         0.001         -         0.001         -         0.001         -         0.001 <t< td=""><td>Hydrochloric Acid Formaldehyde Biocide Foam Oil redits: Soil Stones ub-Totals urification, Concentration, ermentation, Distillation nd Dehydration: Natural Gas Sulphur Soda Anti-Scalant EDTA Limestone Coke Anti-Foam Sulphuric Acid redit: Electricity</td></t<>	Hydrochloric Acid Formaldehyde Biocide Foam Oil redits: Soil Stones ub-Totals urification, Concentration, ermentation, Distillation nd Dehydration: Natural Gas Sulphur Soda Anti-Scalant EDTA Limestone Coke Anti-Foam Sulphuric Acid redit: Electricity
animal feed pelles (15% moisture content) of 272.501 (Ref. 2), substitution of 0.582 cont(Ref. 3) and an effective price for 0.270 tonnes of vinasses (55% solids and 66.5% sugar purity) of £122.15/t, based on the price of thick fuice (Ref. 4),           Contribution         Per         Direct         Indirect         Total         Notes           Cultivation and Harvesting:         ha.a         0.371         ±0.125         1.514         ±0.253         1.885         ±0.283         (a)           P Feriliser         ha.a         0.371         ±0.125         1.514         ±0.263         1.885         ±0.283         (a)           P Feriliser         ha.a         -         0.004         ±0.001         -         (c, e)           P Sectiodes         ha.a         -         -         0.004         ±0.001         -         (c, e)           Seed         ha.a         -         -         0.004         ±0.001         (c, f)           Disesel Fuel         ha.a         -         -         -         -         -         (c, f)           Sub-Totals         ha.a         -         0.001         ±0.001         -         (c, f)           Sub-Totals         ha.a         -         10.125         1.528         ±0.263         1.903         ±0.28	4).         Nitrous Oxide Output (kg N <sub>2</sub> O).           Contribution         Per Unit         Direct         Indirect         Total         Name           Cullivation and Harvesting:         ha.a         0.371         ±0.125         1.514         ±0.253         1.885         ±0.283         .           - N Fertiliser         ha.a         -         -         0.004         ±0.001         -         0.004         ±0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         0.005         ±0.001         0.004         ±0.001         -         -         -         -         -         -         -         -         -         -         0.001         -         0.005         ±0.001         0.005         ±0.001         -         -         0.001         -         0.005         ±0.001         -         -         0.005         ±0.001         -         10.001         ±0.001         ±0.001         ±0.001	Hydrochloric Acid Formaldehyde Biocide Foam Oil redits: Soil Stones ub-Totals urification, Concentration, ermentation, Distillation nd Dehydration: Natural Gas Sulphur Soda Anti-Scalant EDTA Limestone Coke Anti-Foam Sulphuric Acid redit: Electricity
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	4).         Vitrous Oxide Output (kg N <sub>2</sub> O)           Contribution         Per Unit         Direct         Indirect         Total         N           Cultivation and Harvesting: - N Fertiliser         ha.a         0.371         ±0.125         1.514         ±0.253         1.885         ±0.283           - N Fertiliser         ha.a         -         -         0.004         ±0.001         0.004         ±0.001         -	Hydrochloric Acid Formaldehyde Biocide Foam Oil credits: Soil Stones ub-Totals urification, Concentration, ermentation, Distillation nd Dehydration: Natural Gas Sulphur Soda Anti-Scalant EDTA Limestone Coke Anti-Foam Sulphuric Acid
animal feed pellets (15% moisture content) of £72.50/t (Ref. 2), substitution 05.66 tonnes of Unex by tones 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 Direct Dir	4).         Nitrous Oxide Output (kg N,O)           Contribution         Per fullor         Nitrous Oxide Output (kg N,O)           Cultivation and Harvesting:         ha.a         0.371         ±0.125         1.514         ±0.253         1.885         ±0.283           - N Fertiliser         ha.a         -         -         0.001         -         -         0.001         -         0.001         -         0.001         -         -         0.001         -         1.528         ±0.021         ±0.026         ±0.021         ±0.026         ±0.026         ±0.011 <td>Hydrochloric Acid Formaldehyde Biocide Foam Oil redits: Soil Stones ub-Totals urification, Concentration, ermentation, Distillation nd Dehydration: Natural Gas Sulphur Soda Anti-Scalant EDTA Limestone Coke Anti-Foam</td>	Hydrochloric Acid Formaldehyde Biocide Foam Oil redits: Soil Stones ub-Totals urification, Concentration, ermentation, Distillation nd Dehydration: Natural Gas Sulphur Soda Anti-Scalant EDTA Limestone Coke Anti-Foam
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$\begin{array}{c c c c c c c c c c c c c c c c c c c $	4).         Nitrous Oxide Output (kg N <sub>2</sub> O)           Contribution         Per Unit         Direct         Indirect         Total         N           Cultivation and Harvesting:         na.a         0.371         ±0.125         1.514         ±0.253         1.885         ±0.283           - N Fertiliser         na.a         -         -         0.004         ±0.001         -         (Cultivation and Harvesting)           - N Fertiliser         na.a         -         -         0.004         ±0.001         -         (Cultivation and Harvesting)           - P Fertiliser         na.a         -         -         0.001         -         (Cultivation and Harvesting)         -         -         0.001         -         (Cultivation and Harvesting)         -         -         -         0.001         - <td>Hydrochloric Acid Formaldehyde Biocide Foam Oil rredits: Soil Stones ub-Totals urification, Concentration, ermentation, Distillation nd Dehydration: Natural Gas Sulphur Soda Anti-Scalant EDTA</td>	Hydrochloric Acid Formaldehyde Biocide Foam Oil rredits: Soil Stones ub-Totals urification, Concentration, ermentation, Distillation nd Dehydration: Natural Gas Sulphur Soda Anti-Scalant EDTA
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$\begin{array}{c c c c c c c c c c c c c c c c c c c $	4).         Nitrous Oxide Output (kg N <sub>2</sub> O)           Contribution         Per Unit         Direct         Indirect         Total         N           Cultivation and Harvesting:         ha.a         0.371 $\pm 0.125$ 1.514 $\pm 0.253$ 1.885 $\pm 0.283$ - N Fertiliser         ha.a         -         -         0.004 $\pm 0.001$ 0.004 $\pm 0.001$ -         0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         0.001         -         -         0.001         -         0.001         -         0.001         -         0.001         -         -         -         -         -         -         -         -         -         -         -         -         -         -         -	Hýdrochloric Acid Formaldehyde Biocide Foam Oil :redits: Soil Stones
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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).ContributionP r UnitDirectIndirectTotalNotesCultivation and Harvesting: - N Fertiliserha.a0.371 $\pm 0.125$ $1.514$ $\pm 0.253$ $1.885$ $\pm 0.283$ (a)- P Fertiliserha.a $  0.004$ $\pm 0.001$ $0.004$ $\pm 0.001$ (b, c)- P Fertiliserha.a $  0.004$ $\pm 0.001$ $-$ (c, d)- P Fertiliserha.a $  0.004$ $\pm 0.001$ (c, d)- P Secticidesha.a $  0.004$ $\pm 0.001$ (c, d)- P Secticideha.a $  0.004$ $\pm 0.001$ (c, f)- P Secticideha.a $   -$ (c, f)- Seedha.a $    -$ (c, f)- Seedha.a $    -$ (c, f)- Diesel Fuelha.a $    -$ (c, f)- Diesel Fuelha.a $    -$ (c, f)Sub-Totalsha.a $    -$ (f, f)- Diesel Fuelha.a $-$	4).         Nitrous Oxide Output (kg N <sub>2</sub> O)           Contribution         Per Unit         Direct         Indirect         Total         N           Cultivation and Harvesting:         ha.a         0.371 $\pm 0.125$ 1.514 $\pm 0.253$ 1.885 $\pm 0.283$ N Fertiliser         ha.a         -         -         0.004 $\pm 0.001$ 0.004 $\pm 0.001$ -         (           Pesticides         ha.a         -         -         0.004 $\pm 0.001$ 0.004 $\pm 0.001$ -         (         (           Herbicide         ha.a         -         -         0.001         -         0.001         -         (	Hydrochloric Acid Formaldehyde Biocide Foam Oil credits: Soil
$\begin{array}{ c c c c c c c c c c c c c c c c c c c$	4).         Nitrous Oxide Output (kg N <sub>2</sub> O)           Unit         Direct         Indirect         Total         N           Value         Range         Value         Nange         Value<	Hýdrochloric Acid Formaldehyde Biocide Foam Oil redits:
animal feed pellets (15% moisture content) of £72.50/t (Ref. 2), substitution of 0.568 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         Nitrous Oxide Output (kg N <sub>2</sub> O)         Notes           Contribution         Per         Direct         Indirect         Total         Notes           Cultivation and Harvesting:         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)           P Fertiliser         ha.a         -         -         0.004         ±0.001         -         (c, d)           Pesticides         ha.a         -         -         0.001         -         (c, d)         (c, f)           Insecticide         ha.a         -         -         0.001         -         (c, f)           Seed         ha.a         -         -         0.001         -         (c, f)           Sub-Totals         ha.a         -         -         -         -         -         (c, f)           Sub-	4).         Nitrous Oxide Output (kg N <sub>2</sub> O)           Contribution         Per Unit         Direct         Indirect         Total         N           Cultivation and Harvesting:         ha.a         0.371 $\pm 0.125$ 1.514 $\pm 0.253$ 1.885 $\pm 0.283$ - N Fertiliser         ha.a         -         -         0.004 $\pm 0.001$ 0.004 $\pm 0.001$ -         ()           - P Fertiliser         ha.a         -         -         0.004 $\pm 0.001$ 0.004 $\pm 0.001$ -         ()         ()           - Pestiliser         ha.a         -         -         0.001         -         0.001         -         () <td< td=""><td>Hydrochloric Acid Formaldehyde Biocide Foam Oil</td></td<>	Hydrochloric Acid Formaldehyde Biocide Foam Oil
animal feed pellets (15% moisture content) of £72.50/t (Ref. 2), substitution of 0.566 tonnes of LiméX by agricultural lime, and an assumed price for bioethanol of £529.00/t (Ref. 2), substitution of 0.566 tonnes of LiméX by agricultural lime, and an assumed price for bioethanol of £529.00/t (Ref. 2), substitution of 0.566 tonnes of LiméX by agricultural lime, and an assumed price for bioethanol of £529.00/t (Ref. 2), substitution of 0.566 tonnes of LiméX by agricultural lime, and an assumed price for bioethanol of £529.00/t (Ref. 2), substitution of 0.566 tonnes of LiméX by agricultural lime, and an assumed price for bioethanol of £529.00/t (Ref. 2), substitution of 0.566 tonnes of LiméX by agricultural lime, and an assumed price for bioethanol of £529.00/t (Ref. 2), substitution of 0.566 tonnes of LiméX by agricultural lime, and an assumed price for bioethanol of £529.00/t (Ref. 2), substitution of 0.566 tonnes of LiméX by agricultural lime, and an assumed price for bioethanol of £529.00/t (Ref. 2), substitution of 0.566 tonnes of LiméX by agricultural lime, and an assumed price for bioethanol of £529.00/t (Ref. 2), substitution of 0.566 tonnes of LiméX by agricultural lime, and an assumed price for bioethanol of £529.00/t (Ref. 2), substitution of 0.566 tonnes of LiméX by to 125 1.514 ±0.253 1.865 ±0.283 (a) to001 (b, c) Pesticides ha.a 0.0001 - 0.0001 ±0.001 (c, e) pesticides ha.a 0.0001 - 0.0001 ±0.001 (c, e) to 0.001 ±0.001 (c, f)Diesel Fuelha.a 0.001 0.0001 - 0.0001 ±0.001 (c, i) to 0.005 ±0.001 (c, i)Sub-Totalsha.a- 0.001 (c, g) to 0.005 ±0.001 (c, i)Sub-Totalsha.a- 0.001 (g)Narrayt be0.061 ±0.001 0.024 ±0.263 1.903 ±0.283 (k)Transport: Diesel Fuelt ssb	Nitrous Oxide Output (kg N20)ContributionPer UnitDirectIndirectTotalNCultivation and Harvesting: - N Fertiliserha.a $0.371$ $\pm 0.125$ $1.514$ $\pm 0.253$ $1.885$ $\pm 0.283$ Cultivation and Harvesting: - N Fertiliserha.a $0.371$ $\pm 0.125$ $1.514$ $\pm 0.253$ $1.885$ $\pm 0.283$ - N Fertiliserha.a $0.004$ $\pm 0.001$ $0.004$ $\pm 0.001$ (0.004)- Fertiliserha.a $0.001$ - $0.004$ $\pm 0.001$ (0.004)- Pestilidesha.a $0.004$ $\pm 0.001$ $0.004$ $\pm 0.001$ (0.004)- Herbicideha.a $0.004$ $\pm 0.001$ $0.004$ $\pm 0.001$ (0.004)- Insecticideha.a $0.004$ $\pm 0.001$ $0.004$ $\pm 0.001$ (0.001)- Seedha.a $0.004$ $\pm 0.001$ $0.004$ $\pm 0.001$ (0.001)- Diesel Fuelha.a $0.005$ $\pm 0.001$ $0.005$ $\pm 0.001$ (0.001)- Diesel Fuelha.a $0.005$ $\pm 0.125$ $1.528$ $\pm 0.253$ $1.903$ $\pm 0.283$ - Diesel Fuelha.a $0.020$ $0.248$ $\pm 0.041$ $0.309$ $\pm 0.283$ - Disesel Fuelt tssb Disesel Fuelt tsb Disesel Fuel<	Hydrochloric Acid Formaldehyde Biocide
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Relevant Period: 2002	Relevant Location: United Kingdom	elevant Location:
	Final Unit of Measurement: 1 tonne of bioethanol	
Final Unit of Measurement: 1 tonne of bioethanol Relevant Location: United Kingdom	Functional Unit: Bioethanol at point of distribution derived from sugar beet using natural gas-fired combined h and power with a steam turbine during processing	unctional Unit:

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
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t csb = tonne of clean sugar	beet
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- t ssb = tonne of soiled sugar beet
- t be = tonne of bioethanol

- (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<sub>2</sub>O/kg N (Ref. 5), an indirect nitrous oxide requirement of 0.0147 kg N<sub>2</sub>O/kg N (Ref. 7) and a total nitrous oxide requirement for ammonium nitrate of 0.0183 kg N<sub>2</sub>O/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<sub>2</sub>O/ha.a and a total nitrous oxide requirement for potash fertiliser of 9.4 x 10<sup>-6</sup> kg N<sub>2</sub>O/ kg K<sub>2</sub>O (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  $1.51 \times 10^{-3}$  kg N<sub>2</sub>O/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<sup>-3</sup> kg N<sub>2</sub>O/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<sup>-3</sup> kg N₂O/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<sub>2</sub>O /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<sup>-7</sup> kg N<sub>2</sub>O/MJ, an indirect nitrous oxide requirement of 2.60 x 10<sup>-8</sup> kg N<sub>2</sub>/MJ and a total nitrous oxide requirement of 5.90 x 10<sup>-7</sup> kg N<sub>2</sub>O/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<sup>-7</sup> kg N<sub>2</sub>O/MJ, an indirect nitrous oxide requirement of 2.60 x 10<sup>-8</sup> kg N<sub>2</sub>/MJ and a total nitrous oxide requirement of 5.90 x 10<sup>-7</sup> kg N<sub>2</sub>O/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.
- (I) 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<sub>2</sub>O/t-km, an indirect nitrous oxide requirement of  $2.1 \times 10^{-8} \pm 8 \times 10^{-10}$  kg N<sub>2</sub>O/t-km and a total nitrous oxide requirement of  $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8}$  kg N<sub>2</sub>O/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<sup>-8</sup> kg N<sub>2</sub>O/MJ, an indirect nitrous oxide requirement of 1.1 x 10<sup>-8</sup> kg N<sub>2</sub>O/MJ and a total nitrous oxide requirement of 1.0 x 10<sup>-7</sup> kg N<sub>2</sub>O/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<sub>2</sub>O/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 x 10<sup>-7</sup> kg N<sub>2</sub>O/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  $3.0 \times 10^{-4}$  kg N<sub>2</sub>O/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  $6.0 \times 10^{-9}$  kg N<sub>2</sub>O/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 x  $10^{.9}$  kg N<sub>2</sub>O/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 x 10<sup>-3</sup> ± 2.20 x 10<sup>-4</sup> kg N<sub>2</sub>O/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 x 10<sup>-8</sup> kg N<sub>2</sub>O/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 x 10<sup>-8</sup> kg N<sub>2</sub>O/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<sub>2</sub>) consumption rate of 0.13 kg/t of clean sugar beet and a nitrous oxide requirement of 6.6 x  $10^{-6} \pm 1.8 \times 10^{-6}$  kg N<sub>2</sub>O/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<sub>2</sub>O/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  $6.0 \times 10^{-8}$  kg N<sub>2</sub>O/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 x  $10^{-8}$  kg N<sub>2</sub>O/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  $3.5 \times 10^{-7}$  kg N<sub>2</sub>O/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<sub>2</sub>O/kg and an indirect nitrous oxide requirement of  $1.3 \times 10^{-6}$  kg N<sub>2</sub>O/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 x 10<sup>-8</sup> kg N<sub>2</sub>O/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<sub>2</sub>O/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 x 10<sup>-6</sup> kg N<sub>2</sub>O/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 x 10<sup>-8</sup> kg N<sub>2</sub>O/MJ, an

indirect nitrous oxide requirement of  $1.1 \times 10^8$  kg N<sub>2</sub>O/MJ and a total nitrous oxide requirement of  $1.0 \times 10^{-7}$  kg N<sub>2</sub>O/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<sup>-5</sup> kg N<sub>2</sub>O/kg for lime (Ref. 7).
- (kk) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 85.7% to bioethanol.
- (II) 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  $1.866 \times 10^{-9}$  kg N<sub>2</sub>O/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  $4.6 \times 10^{-7} \pm 1.7 \times 10^{-8}$  kg N<sub>2</sub>O/t-km, an indirect nitrous oxide requirement of  $2.1 \times 10^{-8} \pm 8 \times 10^{-10}$  kg N<sub>2</sub>O/t-km and a total nitrous oxide requirement of  $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8}$  kg N<sub>2</sub>O/t-km (Ref. 11).

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# 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 (Model 4a)

			ribution deriv	0	r beet using r	atural gas-fire	ed combined	heat
	1 tonne of bi		urbine during	processing				
	Jnited Kingd							
	v	OM						
	2002		0.005			<u> </u>		
priv (we fro effr fro priv ani agu tor	ce for 1.507 t et basis) with m main source ective averag m a price for ce for 25.996 imal feed pell ricultural lime	onnes of suga a 80% moistu ces, substitutic ge price for 14. thick juice (67 tonnes of pul lets (15% mois a, and an assu	IT beet tops (dr ITE content (Re on of 0.049 ton 560 tonnes of % solids and 9 o (97% moistu sture content) of med price for b	y matter) of $\pounds$ of 2), substitut nes of stones thin juice (15%) 02% sugar pur re content) of of $\pounds$ 72.50/t (Re bioethanol of $\pounds$	10.0/t, based o ion of 0.669 to from washing 6 solids and 88 ity) of £72.48/t £2.56/t, derive ef. 2), substitut 529.00/t (Ref.	£22.00/t (Ref. n an average in nnes of soil from by stones from 3% sugar purit (Ref. 3), and a d from an aver ion of 0.566 to 3) and an effe sed on the price	market price of om washing b a quarrying, a y) of £16.2/t, an effective a age market p nnes of Lime ctive price for	of £2.00/f y soil n derived verage rice for X by • 0.720
4).	Der		Tata		- C Outre	** //-= == 00	\	
Contribution	Per	5.				it (kg eq CO2	/	
	Unit	Dir	ect	Ind	rect	То	tal	Notes
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
- N Fertiliser	ha.a	119	±40	690	±86	809	±95	(a)
- P Fertiliser	ha.a	-	<u>≁</u> +∪	62		62		(a) (a)
- K Fertiliser		-	-		±9		±9	
	ha.a	-	-	57	±9	57	±9	(a)
- Pesticides	ha.a	-	-	15	<u>+</u> 2	15	<u>+2</u>	(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		686		(a)
Reference System:			<u>-</u> 00		±33		±102	(~)
- Diesel Fuel	ha.a	- 63	±10	- 7	±3	- 70	±10	(a)
Sub-Totals	ha.a	666		904		1 570		
Sub-Totals			±104		±93	1,570	±140	(1-)
	t be	108	±17	147	±15	255	±23	(b)
Transport	-			-	1.0		120	-
Transport:	( h	-		0		7		(-)
- 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	12	2	14	22	13	
		168	±3	17	±1	185	±3	(4)
	t be	001	±25	17	±8	100	±26	(d)
Purification, Concentration,								
Fermentation, Distillation and								
Dehydration:								
- Natural Gas	t csb	46	±7	3	±1	49	±7	(a)
- Sulphur	t csb	-	±1	-	-	-	- <b>'</b>	(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:								1
- Electricity	t csb	-	_	- 3	_	- 3	_	(a)
- LimeX	t csb	-	-	- 3	- ±1	- 8	- ±1	(a) (a)
			-				±1	(a)
Sub-Totals	t csb t be	51 <b>550</b>	±7 <b>±75</b>	- 7 <b>- 75</b>	±1 <b>±11</b>	44 475	±7 <b>±78</b>	(e)
Plant Construction	tbe	-	-	24	±4	24	±4	(a)
			-		±4 ±1	7	±4 ±1	
Plant Maintenance	t be							(a)
Distribution								
Distribution Totals	t be t be	25 895	±1 ±81	7 145	±1 ±21	32 1,040	±1 ±85	(a)

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
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t csb	= tonne of clean sugar beet
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- t ssb = tonne of soiled sugar beet
- t be = tonne of bioethanol

## <u>Notes</u>

- (a) Summation of results from previous spreadsheets with conversion using a global warming potential for methane of 24.5 kg eq CO<sub>2</sub>/kg CH<sub>4</sub> and a global warming potential for nitrous oxide of 320 kg eq CO<sub>2</sub>/kg N<sub>2</sub>O.
- (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:				ribution deriv		gar beet usi	ng natural g	as-fired con	nbined heat	and power
Final Unit of Measurem	ent: 1 to	onne of bioe	thanol	9 010003311	3					
Relevant Location:		ted Kingdor	n							
Relevant Period:	200	-								
Allocation Procedures:	for bas sou pric juic	1.507 tonnessis) with a 8 arces, substice for 14.56 ce (67% soli	es of sugar b 0% moisture itution of 0.0 0 tonnes of ds and 92%	beet tops (de e content (R 049 tonnes o thin juice (1 5 sugar purit	ry matter) of ef. 2), subst of stones fro 5% solids au y) of £72.48	£10.0/t, bat itution of 0.6 m washing nd 88% sug /t (Ref. 3), a	sed on an a 669 tonnes of by stones fr ar purity) of and an effect	verage marl of soil from om quarryin £16.2/t, der tive average	ket price of £ washing by s g, an effection ived from a	soil from main ve average price for thick 5.996 tonnes of
	mo	isture conte sumed price	nt) of £72.5 for bioetha	0/t (Ref. 2), nol of £529.	substitution	of 0.566 tor and an effe	nnes of Lime	eX by agricutor 0.720 tor	iltural lime, a ines of vinas	and an
Contribution	Per	ius anu oo.c	576 Suyai pu	inty) 01 £ 122		ary Energy				
Contribution	Unit	Dir	a at	ام ما	rect		Istock	Та	otal	Notes
	Offic		ect		1		1	Value		Notes
		Value	Range	Value	Range	Value	Range	value	Range	
Cult. and Harvest:	ha a			1 1 1 2	1577	0 700	1100	4 4 0 0	1507	(2)
- 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 <b>t be</b>	7,948 1,289	±1,410 <b>±229</b>	5,964 <b>967</b>	±800 <b>±130</b>	2,739 <b>444</b>	±109 <b>±18</b>	16,651 <b>2,700</b>	±1,624 <b>±263</b>	(k)
Transport:		1,200					_10	2,700		(14)
- Diesel Fuel	t ssb <b>t be</b>	77 684	±3 <b>±27</b>	27 <b>240</b>	±3 <b>±27</b>	-	-	104 <b>924</b>	±4 ±36	(l) (m)
Washing, Shredding										()
and Diffusion:										
- Natural Gas	t csb	386	±61	42	±20	-	-	428	±64	(c, n-p)
- Sulphuric Acid	t csb	-	-	72	±20			420	<i>±</i> 04	(c, n-p) (q)
- Gypsum	t csb	_	-	1	-	_	_	1	-	(q) (c, r)
- Hydrochlor. Acid	t csb	-	-	1	-			1	-	(c, r) (s)
- Formaldehyde	t csb	_	-	- '	-	_	_	- '	-	(c, t)
- Biocide	t csb	-	-	-	-	_	-	-	-	(c, u)
- Foam Oil	t csb	_			-	_	_	_	-	(v)
Credits:	1030	_	-	_	-		_	_	-	(v)
- Soil	t csb	_		- 4	4.1	_	_	- 4	+ 1	(c, w)
- Stones	t csb	-	-		± 1 -	-	-	- 4	± 1 -	(c, w) (c, x)
Sub-Totals	t csb t be	386 <b>3,243</b>	<i>±61</i> <b>±513</b>	40 <b>336</b>	<i>±20</i> <b>±168</b>	-	-	426 3,579	<i>±64</i> <b>±538</b>	(y)
Purification,										
Concentration,										
Fermentation,										
Distillation and										
Dehydration:										
<ul> <li>Natural Gas</li> </ul>	t csb	882	±141	97	<i>±</i> 46	-	-	979	±148	(c, n, p,z)
- Sulphur	t csb	-	-	1	-	-	-	1	-	(aa)
- Soda	t csb	-	-	1	-	-	-	1	-	(bb)
<ul> <li>Anti-Scalant</li> </ul>	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)
<ul> <li>Sulphuric Acid</li> </ul>	t csb	-	-	1	 ±1	-	-	1	±1	(hh)
Credit:					÷ '					
- Electricity	t csb	562	<u>±</u> 84	-1,412	±212	-	-	- 850	<i>±</i> 228	(c, ii)
- LimeX	t csb	-	-	- 94	±14	-	-	- 94	<u>±14</u>	(c, jj)
Sub-Totals	t csb <b>t be</b>	1,495 <b>16,115</b>	±164 <b>±1,768</b>	-1,370 <b>-14,768</b>	±217 <b>±2,339</b>	-	-	125 <b>1,347</b>	±272 <b>±2,932</b>	(kk)
			-							
Plant Construction	the	<b>F</b>	F	175	+71	5	<i>c</i>	175	+71	///\
Plant Construction	t be	-	-	475	±71 +21	-	-	475	±71 +21	(II) (mm)
Plant Construction Plant Maintenance Distribution	t be t be t be	- - 369	- - ±14	475 142 129	±71 ±21 ±16	-	-	475 142 498	±71 ±21 ±21	(ll) (mm) (nn)

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

- (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<sub>2</sub>O/ha.a assuming 1.205 kg K<sub>2</sub>O/kg K, and a total energy requirement for potash fertiliser of 9.3 MJ/ kg K<sub>2</sub>O (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 £259.00/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.
- (I) 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  $11 \pm 1$  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 1.176 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<sub>2</sub>) 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 ± 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 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.
- (II) 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).

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## 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:				erived from s	ugar beet usi	ng natural ga	s-fired combir	ned heat and
Final Unit of Measurement:		of bioethanol	oine during pro	ocessing				
Relevant Location:	United Ki							
Relevant Period:	2002	nguom						
Allocation Procedures:	Based on a for 1.507 to basis) with	nnes of sugar a 80% moistur	beet tops (dry e content (Ref	nes of sugar be matter) of £10 f. 2), substitutio	.0/t, based on on of 0.669 ton	an average mines of soil from	arket price of an washing by	22.00/t (wet soil from main
				stones from w % solids and 8				
	pulp (97% r	noisture conte	nt) of £2.56/t,	derived from a	n average mai	ket price for a	nimal feed pell	
				ubstitution of 0 0/t (Ref. 3) and				
		6.5% sugar p	urity) of £122.7	15/t, based on			4).	
Contribution	Per				Dioxide Outpu			
	Unit		ect	Indi			tal	Notes
0 10 11		Value	Range	Value	Range	Value	Range	
Cult. and Harvest .:				100		100		
- N Fertiliser	ha.a	-	-	196	<u>±</u> 28	196	<u>+</u> 28	(a)
- P Fertiliser	ha.a	-	-	61	<u>+</u> 9	61	<u>+</u> 9	(b, c)
- K Fertiliser	ha.a	-	-	57	<u>+</u> 9	57	<u>+</u> 9	(c, d)
- Pesticides	ha.a	-	-	14	<u>+2</u>	14	<u>+2</u>	(c, e)
- Herbicide	ha.a	-	-	2	-	2	<u></u>	(c, f)
- Insecticide	ha.a	-	-	1		1	-	(c, g)
- Seed	ha.a	_	_	7	-	7	-	(c, g) (c, h)
- Diesel Fuel		-	-	7 72	±1		±1	
- Diesel Fuel Reference System:	ha.a	608	±96	12	±33	680	±102	(c, i)
- Diesel Fuel	ha.a	- 63	±10	- 7	<u>+</u> 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:		-				-		(1)
- Diesel Fuel	t ssb	5	-	2	-	7	-	(I)
	t be	44	-	18	-	62	-	(m)
Washing, Shredding and								
Diffusion:								
- Natural Gas	t csb	20	<u>±</u> 3	1	±1	21	<u>±</u> 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 t be	20 <b>168</b>	±3	1 8	<u>±1</u>	21 <b>176</b>	±3	6.5
Purification,	t be	100	±25	0	±8	170	±26	(y)
Concentration,								
Fermentation, Distillation								
and Dehydration:			_	-			_	
- Natural Gas	t csb	46	±7	2	<u>±1</u>	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)
		5		1	-	0	±1	
- Anti-Foam	t csb	-	-	-	-	-	-	(c, gg)
- Sulphuric Acid Credit:	t csb	-	-	-	-	-	-	(hh)
- Electricity	t csb	29	±4	- 71	±11	-42	±12	(c, ii)
- LimeX	t csb	-	-	- 8	±1	- 8	±1	(c, jj)
	t csb	80 <b>862</b>	±8 <b>±86</b>	- 76 <b>- 819</b>	±11 <b>±118</b>	4 43	±14 <b>±146</b>	(kk)
Sub-Totals	the							
	t be							
Plant Construction	t be	-	-	24	±4	24	±4	(II)

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
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t csb	= te	onne	of	clean	sugar	bee
-------	------	------	----	-------	-------	-----

- t ssb = tonne of soiled sugar beet
- t be = tonne of bioethanol

#### <u>Notes</u>

- (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<sub>2</sub>/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<sub>2</sub>O/ha.a assuming 1.205 kg K<sub>2</sub>O/kg K, and a total carbon requirement for potash fertiliser of 0.453 kg CO<sub>2</sub>/ kg K<sub>2</sub>O (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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub> /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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0081 kg CO<sub>2</sub>/MJ and a total carbon requirement of 0.0767 kg CO<sub>2</sub>/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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0081 kg CO<sub>2</sub>/MJ and a total carbon requirement of 0.0767 kg CO<sub>2</sub>/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.
- (I) 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<sub>2</sub>/t-km, an indirect carbon requirement of 0.0161 ± 0.0017 kg CO<sub>2</sub>/tkm and a total carbon requirement of 0.0723 ± 0.0027 kg CO<sub>2</sub>/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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0017 kg CO<sub>2</sub>/MJ and a total carbon requirement of 0.0539 kg CO<sub>2</sub>/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

 $1.176 \times 96,480 \times 3.5/26.8 = 14,818$  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  $0.13 \pm 0.16$  kg CO<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sup>-3</sup> kg CO<sub>2</sub>/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<sup>-3</sup> kg CO<sub>2</sub>/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<sub>2</sub>) consumption rate of 0.13 kg/t of clean sugar beet and a carbon requirement of 0.89 ± 0.24 kg CO<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/kg and an indirect carbon requirement of 0.37 kg CO<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0017 kg CO<sub>2</sub>/MJ and a total carbon requirement of 0.0539 kg CO<sub>2</sub>/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<sub>2</sub>/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.
- (II) Carbon dioxide output of 47,500 tonnes of CO<sub>2</sub> 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<sub>2</sub>/£ (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<sub>2</sub>/t-km, an indirect carbon requirement of 0.0161 ± 0.0017 kg CO<sub>2</sub>/t-km and a total carbon requirement of 0.0723 ± 0.0027 kg CO<sub>2</sub>/t-km (Ref. 11).

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## Spreadsheet for Methane Outputs from Bioethanol Production from Sugar Beet using <u>a Natural Gas-fired Combined Heat and Power Plant with a Gas Turbine</u> (Model 4b)

Unit         Direct         Indirect         Total         Notes           Cult. and Havest.:              ha.a $             A = 0         $	$\begin{array}{c c c c c c c c c c c c c c c c c c c $
Value         Range         Value         Range         Value         Range         Value         Range           Cult and Harvest.:         h = a         -         -         0.002         0.002         -         (b, c)           P Fertiliser         ha.a         -         -         0.002         -         (b, c)           Pesticides         ha.a         -         -         0.001         -         (c, e)           Pesticide         ha.a         -         -         -         -         -         (c, e)           - Insectide         ha.a         -         -         -         -         -         (c, f)           - Seed         ha.a         -         -         -         0.008 $\pm 0.001$ 0.008 $\pm 0.001$ (c, h)           Sub-Totals         ha.a         0.004 $\pm 0.005$ 0.547 $\pm 0.068$ 0.551 $\pm 0.068$ (c, h)           Sub-Totals         ha.a         0.004 $\pm 0.005$ 0.547 $\pm 0.068$ 0.551 $\pm 0.068$ (c, h)           Sub-Totals         ha.a         -         0.002         -         (h)         (c, h)	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$
Value         Range         Value         Range         Value         Range         Value         Range           Cult and Harvest.:         ha.a         -         -         0.071 $\pm 0.062$ 0.371 $\pm 0.062$ 0.371 $\pm 0.062$ (a)           P Fertiliser         ha.a         -         -         0.002         -         (b, c)           Pesticides         ha.a         -         -         0.001         -         (c, e)           Herbicide         ha.a         -         -         -         -         (c, f)           Insecticide         ha.a         -         -         0.008 $\pm 0.001$ 0.008 $\pm 0.001$ (c, h)           Diesel Fuel         ha.a         -         -         0.005 $\pm 0.001$ -         0.022 $\pm 0.003$ -         0.028 $\pm 0.001$ (c, h)           Sub-Totals         ha.a         -         0.001 $\pm 0.001$ 0.088 $\pm 0.011$ (k)           Transport:         tbe         -         -         0.002         -         (m)           Obisel Fuel         tcsb         -         - <t< td=""><td><math display="block">\begin{array}{c ccccccccccccccccccccccccccccccccccc</math></td></t<>	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$
Value         Range         Value         Range         Value         Range         Value         Range           Cult and Harvest:         ha.a         -         -         0.002         -         (b, c)           P Fertiliser         ha.a         -         -         0.002         -         (b, c)           P Fertiliser         ha.a         -         -         0.001         -         (c, e)           Presticides         ha.a         -         -         0.001         -         (c, e)           Insecticide         ha.a         -         -         -         -         (c, f)           Seed         ha.a         -         -         -         -         (c, f)           Diesel Fuel         ha.a         -0.001 $\pm 0.001$ -0.019 $\pm 0.003$ -0.020 $\pm 0.003$ (c, i)           Sub-Totals         ha.a         0.001 $\pm 0.001$ -0.002         -         (l)         (l)           Transport:         tb         .         .         0.002         -         0.002         -         (l)           Vashing, Shredding and Diffusion         tb         .         .         .	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$
Value         Range         Value         Range         Value         Range         Value         Range           Cult and Harvest:         ha.a         -         -         0.371 $\pm 0.062$ 0.371 $\pm 0.062$ (a)           P Fertiliser         ha.a         -         -         0.002         -         (b, c)           Pesticides         ha.a         -         -         0.001         -         (c, e)           Pesticide         ha.a         -         -         -         0.001         -         (c, e)           Insecticide         ha.a         -         -         -         -         -         (c, f)           Seed         ha.a         -         -         0.008 $\pm 0.001$ 0.008 $\pm 0.003$ -         0.028 $\pm 0.003$ (c, i)           Sub-Totals         ha.a         0.004 $\pm 0.001$ $\pm 0.008$ $\pm 0.011$ (k) $\pm 0.003$ -         0.002         -         ((i)           Sub-Totals         ha.a         0.004 $\pm 0.001$ $0.002$ -         ((i)         .         .           Vashing, Shredding and Diffusion: </td <td>Insecticide       ha.a       -       -       -       -       -       -       -       -       (c, c)         Seed       ha.a       -       -       0.008       <math>\pm 0.001</math>       0.008       <math>\pm 0.001</math>       0.008       <math>\pm 0.002</math> <math>\pm 0.028</math>       (c, i)         Reference System:       ha.a       0.001       <math>\pm 0.001</math> <math>-0.019</math> <math>\pm 0.003</math> <math>-0.020</math> <math>\pm 0.003</math>       (c, i)         Sub-Totals       ha.a       0.004       <math>\pm 0.005</math> <math>0.547</math> <math>\pm 0.068</math> <math>0.551</math> <math>\pm 0.068</math> <math>\pm 0.011</math>       (k)         Transport:       tbe       0.001       <math>\pm 0.001</math> <math>0.088</math> <math>\pm 0.011</math>       (k)       (k)         Transport:       tbe       -       -       0.002       -       0.002       -       (l)         Vashing, Shredding and       tbe       -       -       0.0018       -       -       (c, n)         Vastural Gas       t csb       -       -       -       -       -       -       (c, n)         Sulphuric Acid       t csb       -       -       -       -       -       (c, n)         Pormaldehyde       t csb       -       -</td>	Insecticide       ha.a       -       -       -       -       -       -       -       -       (c, c)         Seed       ha.a       -       -       0.008 $\pm 0.001$ 0.008 $\pm 0.001$ 0.008 $\pm 0.002$ $\pm 0.028$ (c, i)         Reference System:       ha.a       0.001 $\pm 0.001$ $-0.019$ $\pm 0.003$ $-0.020$ $\pm 0.003$ (c, i)         Sub-Totals       ha.a       0.004 $\pm 0.005$ $0.547$ $\pm 0.068$ $0.551$ $\pm 0.068$ $\pm 0.011$ (k)         Transport:       tbe       0.001 $\pm 0.001$ $0.088$ $\pm 0.011$ (k)       (k)         Transport:       tbe       -       -       0.002       -       0.002       -       (l)         Vashing, Shredding and       tbe       -       -       0.0018       -       -       (c, n)         Vastural Gas       t csb       -       -       -       -       -       -       (c, n)         Sulphuric Acid       t csb       -       -       -       -       -       (c, n)         Pormaldehyde       t csb       -       -
Value         Range         Value         Range         Value         Range           Cult and Harvest.:         ha.a         -         -         0.371 $\pm 0.062$ 0.371 $\pm 0.062$ (a)           P Fertiliser         ha.a         -         -         0.003         -         (b, c)         (b, c)           Pesticides         ha.a         -         -         0.001         -         0.001         -         (c, c)           Insecticide         ha.a         -         -         0.001         -         (c, c)         (c, c)           Insecticide         ha.a         -         -         0.008 $\pm 0.001$ 0.008 $\pm 0.001$ (c, i)           Seed         ha.a         -         -         0.001 $\pm 0.003$ $\pm 0.027$ $0.168$ $\pm 0.001$ (c, i)           Sub-Totals         ha.a         0.001 $\pm 0.001$ $\pm 0.003$ $\pm 0.022$ $\pm 0.003$ (c, i)           Sub-Totals         ha.a         0.001 $\pm 0.001$ $\pm 0.002$ $\pm 0.011$ (k)           Transport:         b         -         -         0.002         - <td>Insecticide       ha.a       -</td>	Insecticide       ha.a       -
Value         Range         Value         Range         Value         Range           Cult and Harvest::         ha.a         -         -         0.371 $\pm 0.062$ 0.371 $\pm 0.062$ (a)           P Fertiliser         ha.a         -         -         0.003         -         0.003         -         (c, d)           Pesticides         ha.a         -         -         0.001         -         0.001         -         (c, c)           Insecticide         ha.a         -         -         -         -         -         (c, f)           Seed         ha.a         -         -         0.008 $\pm 0.001$ 0.008 $\pm 0.027$ 0.186 $\pm 0.021$ (c, i)           Diesel Fuel         ha.a         -         -         0.01 $\pm 0.027$ 0.186 $\pm 0.021$ (c, i)           Sub-Totals         ha.a         0.001 $\pm 0.001$ 0.088 $\pm 0.011$ 0.089 $\pm 0.011$ (k)           Transport:         Diesel Fuel         tsb         -         -         0.002         -         (0)         (f, n)           Natural Gas         t csb	Insecticide       ha.a       -
Value         Range         Value         Range         Value         Range         Value         Range           Cult. and Harvest.:         ha.a         -         -         0.371 $\pm 0.062$ 0.371 $\pm 0.062$ 0.371 $\pm 0.062$ 0.002         -         (b. c)         (c. c)	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$
Value         Range         Value         Range         Value         Range         Value         Range           Cult. and Harvest.:         ha.a         -         -         0.371 $\pm 0.062$ 0.371 $\pm 0.062$ (a)           P Fertiliser         ha.a         -         -         0.003         -         (b, c)           K Fertiliser         ha.a         -         -         0.003         -         (c, c)           Pesticides         ha.a         -         -         0.001         -         (c, c)           Insecticide         ha.a         -         -         -         -         -         -         (c, f)           Seed         ha.a         -         -         -         -         -         -         -         (c, f)           Reference System:         -         0.001 $\pm 0.001$ $\pm 0.027$ 0.186 $\pm 0.021$ $\pm 0.028$ (c, i)           Sub-Totals         ha.a         0.004 $\pm 0.005$ $0.547$ $\pm 0.068$ $0.551$ $\pm 0.068$ $\pm 0.011$ (k)           Transport:         -         0.001 $\pm 0.001$ $0.0022$ <td>Insecticide       ha.a       -       -       -       -       -       -       -       (c, c)         Seed       ha.a       -       -       0.008       <math>\pm 0.001</math>       0.008       <math>\pm 0.001</math>       (c, i)         Diesel Fuel       ha.a       0.005       <math>\pm 0.005</math>       0.181       <math>\pm 0.027</math>       0.186       <math>\pm 0.028</math>       (c, i)         Reference System:       -       -       0.001       <math>\pm 0.001</math>       -0.019       <math>\pm 0.027</math>       0.186       <math>\pm 0.028</math>       (c, i)         Sub-Totals       ha.a       0.004       <math>\pm 0.005</math>       0.547       <math>\pm 0.068</math>       0.551       <math>\pm 0.068</math> <math>\pm 0.011</math>       (k)         Transport:       -       -       0.002       -       0.002       -       (l)         Vashing, Shredding and Diffusion:       t be       -       -       0.001       <math>0.042</math> <math>\pm 0.006</math> <math>0.043</math> <math>\pm 0.007</math>       (c, n)         Natural Gas       t csb       -       -       -       -       -       (c, t)         Hydrochloric Acid       t csb       -       -       -       -       -       (c, t)         Sulphuric Acid       t csb       -       -       -</td>	Insecticide       ha.a       -       -       -       -       -       -       -       (c, c)         Seed       ha.a       -       -       0.008 $\pm 0.001$ 0.008 $\pm 0.001$ (c, i)         Diesel Fuel       ha.a       0.005 $\pm 0.005$ 0.181 $\pm 0.027$ 0.186 $\pm 0.028$ (c, i)         Reference System:       -       -       0.001 $\pm 0.001$ -0.019 $\pm 0.027$ 0.186 $\pm 0.028$ (c, i)         Sub-Totals       ha.a       0.004 $\pm 0.005$ 0.547 $\pm 0.068$ 0.551 $\pm 0.068$ $\pm 0.011$ (k)         Transport:       -       -       0.002       -       0.002       -       (l)         Vashing, Shredding and Diffusion:       t be       -       -       0.001 $0.042$ $\pm 0.006$ $0.043$ $\pm 0.007$ (c, n)         Natural Gas       t csb       -       -       -       -       -       (c, t)         Hydrochloric Acid       t csb       -       -       -       -       -       (c, t)         Sulphuric Acid       t csb       -       -       -
Value         Range         Value         Range         Value         Range           Cult. and Harvest:: - N Fertiliser         ha.a         -         - $0.371$ $\pm 0.062$ $0.371$ $\pm 0.062$ (a)           - P Fertiliser         ha.a         -         - $0.003$ -         (b, c)           - K Fertiliser         ha.a         -         - $0.003$ -         (c, d)           Pesticides         ha.a         -         - $0.003$ -         (c, f)           Insecticide         ha.a         -         -         -         -         -         (c, f)           Seed         ha.a         -         -         -         -         -         (c, i)           Reference System:         -         -         0.005 $\pm 0.011$ $\pm 0.003$ $-0.020$ $\pm 0.003$ (c, j)           Sub-Totals         ha.a         -0.001 $\pm 0.005$ $0.547$ $\pm 0.068$ $0.551$ $\pm 0.003$ (c, j)           Sub-Totals         ha.a         -         - $0.002$ -         (l)         (m)         model         model	Insecticide       ha.a       -       -       -       -       -       -       -       (c, c)         Seed       ha.a       -       -       0.008 $\pm 0.001$ 0.008 $\pm 0.001$ (c, c)         Diesel Fuel       ha.a       0.005 $\pm 0.001$ $-0.019$ $\pm 0.027$ $0.186$ $\pm 0.028$ (c, i)         Poisel Fuel       ha.a $-0.001$ $\pm 0.001$ $-0.019$ $\pm 0.003$ $-0.020$ $\pm 0.003$ (c, j)         Sub-Totals       ha.a $0.004$ $\pm 0.005$ $0.547$ $\pm 0.068$ $0.551$ $\pm 0.068$ $\pm 0.011$ (k)         Transport:       -       - $0.002$ - $0.002$ -       (l)         Disel Fuel       t ssb       -       - $0.002$ -       (l)       (l)         Vashing, Shredding and       -       t be       -       -       -       -       -       -       (c, n)         Sulphuric Acid       t csb       -       -       -       -       -       -       -       (c, t)         Hydrochloric Acid       t csb       -       -       -
Value         Range         Value         Range         Value         Range         Value         Range           Cult. and Harvest: - N Fertiliser         ha.a         -         -         0.371 $\pm 0.062$ 0.371 $\pm 0.062$ (a)           - P Fertiliser         ha.a         -         -         0.002         -         0.002         -         (b, c)           - K Fertiliser         ha.a         -         -         0.003         -         (c, d)           Pesticides         ha.a         -         -         0.001         -         0.003         -         (c, f)           - Herbicide         ha.a         -         -         -         -         -         -         (c, f)           - Seed         ha.a         -         -         -         -         -         -         (c, i)           Reference System:         -         -         0.001 $\pm 0.003$ -0.020 $\pm 0.003$ -0.020 $\pm 0.003$ +0.020 $\pm 0.003$ +0.031         (k)           Sub-Totals         ha.a         -0.001 $\pm 0.002$ -         0.002         -         (l)         - <t< td=""><td><math display="block">\begin{array}{c ccccccccccccccccccccccccccccccccccc</math></td></t<>	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$
Value         Range         Value         Range         Value         Range         Value         Range           Cult. and Harvest.:         ha.a         -         -         0.371 $\pm 0.062$ 0.371 $\pm 0.062$ (a)           - P Fertiliser         ha.a         -         -         0.003         -         0.003         -         (b, c)           - K Fertiliser         ha.a         -         -         0.003         -         0.003         -         (c, d)           - Pesticides         ha.a         -         -         0.001         -         (c, e)           - Herbicide         ha.a         -         -         -         -         -         (c, f)           - Insecticide         ha.a         -         -         0.005         0.181 $\pm 0.027$ 0.186 $\pm 0.021$ (c, i)           Seed         ha.a         0.001 $\pm 0.001$ $\pm 0.003$ -0.020 $\pm 0.003$ (c, j)           Sub-Totals         ha.a         0.004 $\pm 0.001$ $\pm 0.068$ $\pm 0.51$ $\pm 0.068$ $\pm 0.011$ (k)           Transport:         -         -	$\begin{array}{c c c c c c c c c c c c c c c c c c c $
Value         Range         Value         Range         Value         Range           Cult. and Harvest.:         -         -         0.371 $\pm 0.062$ 0.371 $\pm 0.062$ (a)           - N Fertiliser         ha.a         -         -         0.002         -         (b, c)           - K Fertiliser         ha.a         -         -         0.003         -         (c, d)           - Pesticides         ha.a         -         -         0.001         -         0.003         -         (c, f)           - Herbicide         ha.a         -         -         -         -         -         (c, f)           - Insecticide         ha.a         -         -         -         -         -         (c, f)           - Seed         ha.a         -         -         0.005         0.181 $\pm 0.027$ 0.186 $\pm 0.028$ (c, i)           Reference System:         -         0.001 $\pm 0.001$ -         0.019 $\pm 0.003$ -         0.020 $\pm 0.003$ (c, i)           Sub-Totals         ha.a         0.004 $\pm 0.005$ 0.547 $\pm 0.068$ $\pm 0.011$	$\begin{array}{c c c c c c c c c c c c c c c c c c c $
Value         Range         Value         Range         Value         Range           Cult. and Harvest.:         ha.a         -         - $0.371$ $\pm 0.062$ $0.371$ $\pm 0.062$ (a)           P Fertiliser         ha.a         -         - $0.002$ - $0.002$ -         (b, c)           K Fertiliser         ha.a         -         - $0.003$ -         (c, d)           Pesticides         ha.a         -         - $0.001$ - $0.001$ -         (c, f)           Insecticide         ha.a         -         -         -         -         -         -         (c, f)           Seed         ha.a         -         -         -         -         -         (c, i)           Reference System:         -         0.001 $\pm 0.001$ $\pm 0.003$ $-0.020$ $\pm 0.003$ $-0.020$ $\pm 0.003$ (c, j)           Sub-Totals         ha.a $-0.001$ $\pm 0.001$ $0.088$ $\pm 0.011$ $0.089$ $\pm 0.001$ (k)           Transport:         -         -         0.002         -	$\begin{array}{c c c c c c c c c c c c c c c c c c c $
Value         Range         Value         Range         Value         Range         Value         Range           - N Fertiliser         ha.a         -         -         0.371 $\pm 0.062$ 0.371 $\pm 0.062$ (a)           - P Fertiliser         ha.a         -         -         0.002         -         0.002         -         (b, c)         (c, d)           - P Fertiliser         ha.a         -         -         0.003         -         (c, d)           - Pesticides         ha.a         -         -         -         -         -         (c, f)           - Herbicide         ha.a         -         -         -         -         -         (c, f)           - Besel Fuel         ha.a         -         -         -         0.008 $\pm 0.001$ 0.008 $\pm 0.027$ 0.186 $\pm 0.028$ (c, i)           Reference System:         -         -         -         0.001 $\pm 0.001$ $\pm 0.003$ -0.020 $\pm 0.003$ (c, i)           Sub-Totals         ha.a         0.004 $\pm 0.005$ 0.547 $\pm 0.068$ 0.551 $\pm 0.068$ $\pm 0.011$	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$
Value         Range         Value         Range         Value         Range         Value         Range           - N Fertiliser         ha.a         -         -         0.371 $\pm 0.062$ 0.371 $\pm 0.062$ (a)           - F Fertiliser         ha.a         -         -         0.002         -         0.002         -         (b, c)           - K Fertiliser         ha.a         -         -         0.003         -         (c, d)           - Herbicide         ha.a         -         -         -         0.001         -         (c, c)           - Herbicide         ha.a         -         -         -         -         -         -         (c, f)           - Insecticide         ha.a         -         -         -         -         -         (c, f)           - Diesel Fuel         ha.a         0.005 $\pm 0.005$ $0.181$ $\pm 0.027$ $0.186$ $\pm 0.028$ (c, j)           Sub-Totals         ha.a         -0.001 $\pm 0.001$ $-0.019$ $\pm 0.003$ $-0.020$ $\pm 0.003$ (c, i)           Transport:         -         0.001 $\pm 0.001$	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$
Value         Range         Value         Range         Value         Range           Cult. and Harvest.:         ha.a         -         -         0.371 $\pm 0.062$ 0.371 $\pm 0.062$ (a)           - N Fertiliser         ha.a         -         -         0.002         -         (b, c)           - K Fertiliser         ha.a         -         -         0.003         -         (c, d)           - Pestiliser         ha.a         -         -         0.003         -         (c, d)           - Pestiliser         ha.a         -         -         -         0.001         -         (c, g)           - Herbicide         ha.a         -         -         -         -         -         (c, f)           - Insecticide         ha.a         -         -         -         -         (c, f)           - Seed         ha.a         -         0.005 $\pm 0.005$ $\pm 181$ $\pm 0.027$ $\pm 186$ $\pm 0.028$ (c, i)           Reference System:         -         0.001 $\pm 0.005$ $0.547$ $\pm 0.068$ $0.551$ $\pm 0.068$ $\pm 0.001$ (k)           Transpo	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$
Value         Range         Value         Range         Value         Range           Cult. and Harvest.:         -N Fertiliser         ha.a         -         - $0.371$ $\pm 0.062$ $0.371$ $\pm 0.062$ (a)           - P Fertiliser         ha.a         -         - $0.002$ - $0.002$ -         (b, c)           - K Fertiliser         ha.a         -         - $0.003$ -         (c, d)           - Pesticides         ha.a         -         - $0.001$ - $0.001$ -         (c, d)           - Insecticide         ha.a         -         -         -         -         -         (c, f)           - Seed         ha.a         -         -         0.005 $0.181$ $\pm 0.027$ $0.186$ $\pm 0.028$ (c, i)           Reference System:         -         -         0.001 $\pm 0.001$ $0.003$ $-0.020$ $\pm 0.003$ (c, j)           Sub-Totals         ha.a         -0.001 $\pm 0.005$ $0.547$ $\pm 0.068$ $0.551$ $\pm 0.068$ $\pm 0.011$ (k)           Transport	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$
Value         Range         Value         Range         Value         Range         Value         Range           Cult. and Harvest.:         -         -         0.371 $\pm 0.062$ 0.371 $\pm 0.062$ (a)           - N Fertiliser         ha.a         -         -         0.002         -         0.002         -         (b, c)           - Fertiliser         ha.a         -         -         0.003         -         (c, d)           - Pestiliser         ha.a         -         -         0.001         -         0.001         -         (c, d)           - Pestiliser         ha.a         -         -         -         -         -         (c, d)           - Insecticide         ha.a         -         -         -         -         -         (c, f)           - Insecticide         ha.a         -         -         0.008 $\pm 0.001$ 0.008 $\pm 0.001$ (c, h)           - Diesel Fuel         ha.a         -0.001 $\pm 0.005$ 0.547 $\pm 0.003$ -0.020 $\pm 0.003$ (c, i)           Sub-Totals         ha.a         -0.004 $\pm 0.005$ 0.547 $\pm 0.0$	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$
Value         Range         Value         Range         Value         Range         Value         Range           Cult. and Harvest.:         -         -         0.371 $\pm 0.062$ 0.371 $\pm 0.062$ (a)           - P Fertiliser         ha.a         -         -         0.002         -         (b, c)           - K Fertiliser         ha.a         -         -         0.003         -         (c, d)           - Pesticides         ha.a         -         -         0.001         -         (c, d)           - Herbicide         ha.a         -         -         -         -         -         (c, f)           - Insecticide         ha.a         -         -         -         -         -         (c, h)           - Seed         ha.a         -         -         -         -         (c, h)           - Diesel Fuel         ha.a         -0.005 $\pm 0.011$ $\pm 0.003$ -0.020 $\pm 0.003$ (c, j)           Sub-Totals         ha.a         -0.004 $\pm 0.005$ $0.547$ $\pm 0.068$ $0.551$ $\pm 0.003$ (c, j)           Sub-Totals         ha.a         0.004 </td <td><math display="block">\begin{array}{c ccccccccccccccccccccccccccccccccccc</math></td>	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$
Value         Range         Value         Range         Value         Range         Value         Range           Cult. and Harvest.:         -         -         0.371 $\pm 0.062$ 0.371 $\pm 0.062$ (a)           - P Fertiliser         ha.a         -         -         0.002         -         0.002         -         (b, c)           - Fertiliser         ha.a         -         -         0.003         -         0.003         -         (c, d)           - K Fertiliser         ha.a         -         -         0.001         -         0.001         -         (c, d)           - Herbicide         ha.a         -         -         -         -         -         (c, f)           - Insecticide         ha.a         -         -         -         -         -         (c, f)           - Diesel Fuel         ha.a         0.005 $\pm 0.005$ 0.181 $\pm 0.027$ 0.186 $\pm 0.028$ (c, i)           Reference System:         -         -         0.001 $\pm 0.005$ 0.547 $\pm 0.068$ $\pm 0.011$ (k)           Sub-Totals         ha.a         0.004 $\pm 0.005$ <	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$
Value         Range         Value         Range         Value         Range         Value         Range           Cult. and Harvest.:         -         -         0.371 $\pm 0.062$ 0.371 $\pm 0.062$ (a)           - P Fertiliser         ha.a         -         -         0.002         -         0.002         -         (b, c)           - Pesticides         ha.a         -         -         0.003         -         0.003         -         (c, d)           - Pesticides         ha.a         -         -         0.001         -         0.001         -         (c, f)           - Herbicide         ha.a         -         -         -         -         -         (c, f)           - Insecticide         ha.a         -         -         -         -         -         (c, f)           - Dissel Fuel         ha.a         -         -         -         -         -         (c, f)           Reference System:         -         -         0.001 $\pm 0.003$ $-0.020$ $\pm 0.003$ $\pm 0.023$ $\pm 0.003$ (c, j)           Sub-Totals         ha.a         0.004 $\pm 0.005$ $0.547$	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$
Value         Range         Value         Range         Value         Range         Value         Range           Cult. and Harvest.:         -         N Fertiliser         ha.a         -         - $0.371$ $\pm 0.062$ $0.371$ $\pm 0.062$ (a)           - P Fertiliser         ha.a         -         - $0.002$ - $0.002$ -         (b, c)           - K Fertiliser         ha.a         -         - $0.003$ - $0.003$ -         (c, d)           - Pesticides         ha.a         -         - $0.001$ -         (c, c)         (c, f)           - Herbicide         ha.a         -         -         -         -         -         (c, f)           - Insecticide         ha.a         -         -         -         -         -         (c, f)           - Seed         ha.a         -         -         0.005 $0.181$ $\pm 0.027$ $0.186$ $\pm 0.028$ (c, i)           Reference System:         -         -         0.001 $\pm 0.001$ $\pm 0.003$ $-0.020$ $\pm 0.003$ $\pm 0.003$ (c, j) </td <td>- Insecticide       ha.a       -       -       -       -       -       -       -       (c, c, c</td>	- Insecticide       ha.a       -       -       -       -       -       -       -       (c, c, c
Value         Range         Value         Range         Value         Range         Value         Range           Cult. and Harvest.:         -         -         0.371 $\pm 0.062$ 0.371 $\pm 0.062$ (a)           - N 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, d)           - Herbicide         ha.a         -         -         -         -         -         (c, g)           - Insecticide         ha.a         -         -         -         -         -         -         (c, f)           - Seed         ha.a         -         -         0.005         0.181 $\pm 0.027$ 0.186 $\pm 0.028$ (c, i)           Reference System:         -         -         0.001 $\pm 0.001$ $-0.020$ $\pm 0.003$ $-0.020$ $\pm 0.003$ (c, j)           Sub-Totals	- Insecticide       ha.a       -       -       -       -       -       -       (c, c, c
Value         Range         Value         Range         Value         Range         Value         Range           Cult. and Harvest.:         -         -         0.371 $\pm 0.062$ 0.371 $\pm 0.062$ (a)           - P Fertiliser         ha.a         -         -         0.002         -         0.002         -         (b, c)           - K Fertiliser         ha.a         -         -         0.003         -         0.003         -         (c, d)           - Resticides         ha.a         -         -         0.001         -         0.001         -         (c, g)           - Herbicide         ha.a         -         -         -         -         -         (c, g)           - Insecticide         ha.a         -         -         -         -         -         -         (c, g)           - Seed         ha.a         -         -         0.005         0.181 $\pm 0.027$ 0.186 $\pm 0.028$ (c, i)           Reference System:         -         -         0.001 $\pm 0.001$ $\pm 0.068$ $\pm 0.551$ $\pm 0.068$ $\pm 0.011$ (k)           Sub-Totals         h	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$
Value         Range         Value         Range         Value         Range         Value         Range           Cult. and Harvest.:         -         -         0.371 $\pm 0.062$ 0.371 $\pm 0.062$ (a)           - P Fertiliser         ha.a         -         -         0.002         -         0.002         -         (b, c)           - Fertiliser         ha.a         -         -         0.002         -         0.002         -         (b, c)           - Fertiliser         ha.a         -         -         0.003         -         (c, d)           - Pesticides         ha.a         -         -         0.001         -         0.001         -         (c, g)           - Herbicide         ha.a         -         -         -         -         -         -         (c, g)           - Insecticide         ha.a         -         -         -         -         -         -         (c, f)           - Diesel Fuel         ha.a         -         -         0.005         0.181 $\pm 0.027$ 0.186 $\pm 0.028$ (c, i)           Reference System:         -         -         0.001 $\pm 0.$	$\begin{array}{c c c c c c c c c c c c c c c c c c c $
ValueRangeValueRangeValueRangeCult. and Harvest.: - N Fertiliserha.a $0.371$ $\pm 0.062$ $0.371$ $\pm 0.062$ (a)- P Fertiliserha.a $0.002$ - $0.002$ -(b, c)- F Fertiliserha.a $0.003$ - $0.002$ -(c, d)- Pesticidesha.a $0.001$ - $0.001$ -(c, d)- Herbicideha.a(c, f)- Insecticideha.a(c, f)- Seedha.a0.005 $0.181$ $\pm 0.027$ $0.186$ $\pm 0.001$ (c, h)- Diesel Fuelha.a0.001- $0.003$ - $0.028$ (c, i)Reference System:0.001 $\pm 0.003$ $-0.020$ $\pm 0.003$ (c, j)Sub-Totalsha.a0.004 $\pm 0.005$ $0.547$ $\pm 0.068$ $0.551$ $\pm 0.068$ $\pm 0.011$ (k)Transport: $\pm 0.011$ (k) $\pm 0.011$ -	- Insecticide       ha.a       -       -       -       -       -       -       -       (c, c)         - Seed       ha.a       -       -       0.008 $\pm 0.001$ 0.008 $\pm 0.001$ (c, c)         - Diesel Fuel       ha.a       0.005 $\pm 0.005$ 0.181 $\pm 0.027$ 0.186 $\pm 0.028$ (c, i)         Reference System:       -       -       0.001 $\pm 0.001$ $-0.019$ $\pm 0.003$ $-0.020$ $\pm 0.003$ (c, j)         Sub-Totals       ha.a       0.004 $\pm 0.005$ $0.547$ $\pm 0.068$ $0.551$ $\pm 0.068$ $\pm 0.011$ (k)         Transport:       -       -       -       -       -       -       -       -       -       (c)
Value         Range         Value         Range         Value         Range           Cult. and Harvest.:         -         -         0.371 $\pm 0.062$ 0.371 $\pm 0.062$ (a)           - N 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, d)           - Pesticide         ha.a         -         -         0.001         -         (c, f)         (c, f)           - Insecticide         ha.a         -         -         -         -         -         (c, f)           - Diesel Fuel         ha.a         -         -         0.008 $\pm 0.001$ 0.008 $\pm 0.027$ 0.186 $\pm 0.028$ (c, j)           - Diesel Fuel         ha.a         -         0.001         -         0.020 $\pm 0.003$ (c, j)           Sub-Totals         ha.a         0.004 $\pm 0.005$ 0.547	- Insecticide       ha.a       -       -       -       -       -       -       (c, c)         - Seed       ha.a       -       -       0.008 $\pm 0.001$ 0.008 $\pm 0.001$ (c, c)         - Diesel Fuel       ha.a       0.005 $\pm 0.005$ 0.181 $\pm 0.027$ 0.186 $\pm 0.028$ (c, i)         Reference System:       -       -       0.001 $\pm 0.001$ $-0.019$ $\pm 0.003$ $-0.020$ $\pm 0.003$ (c, j)         Sub-Totals       ha.a       0.004 $\pm 0.005$ 0.547 $\pm 0.068$ 0.551 $\pm 0.068$ (b)
Value         Range         Value         Range         Value         Range           Cult. and Harvest.:         -         - $0.371$ $\pm 0.062$ $0.371$ $\pm 0.062$ (a)           - P Fertiliser         ha.a         -         - $0.002$ - $0.002$ -         (b, c)           - F Fertiliser         ha.a         -         - $0.002$ - $0.002$ -         (b, c)           - Festiliser         ha.a         -         - $0.003$ - $0.003$ -         (c, d)           - Pesticides         ha.a         -         - $0.001$ - $0.001$ -         (c, f)           - Herbicide         ha.a         -         -         -         -         -         (c, f)           - Insecticide         ha.a         -         -         -         -         -         (c, f)           - Diseel Fuel         ha.a         -         -         0.005 $0.181$ $\pm 0.027$ $0.186$ $\pm 0.028$ (c, i)           Reference System:         -         -         -         0.001	- Insecticide       ha.a       -       -       -       -       -       -       (c, c)         - Seed       ha.a       -       -       0.008 $\pm 0.001$ 0.008 $\pm 0.001$ (c, c)         - Diesel Fuel       ha.a       0.005 $\pm 0.005$ 0.181 $\pm 0.027$ 0.186 $\pm 0.028$ (c, c)         Reference System:       -       Diesel Fuel       ha.a       -0.001 $\pm 0.001$ -0.019 $\pm 0.003$ -0.020 $\pm 0.003$ (c, c)         Sub-Totals       ha.a       0.004 $\pm 0.005$ 0.547 $\pm 0.068$ 0.551 $\pm 0.068$
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Value         Range         Value         Range         Value         Range           Cult. and Harvest.:         -         -         0.371         ±0.062         0.371         ±0.062         (a)           - N Fertiliser         ha.a         -         -         0.002         -         0.002         -         (b, c)           - Fertiliser         ha.a         -         -         0.003         -         (c, d)           - K Fertiliser         ha.a         -         -         0.003         -         (c, d)           - Pesticides         ha.a         -         -         0.001         -         (c, e)           - Herbicide         ha.a         -         -         -         -         -         (c, f)           - Insecticide         ha.a         -         -         -         -         -         (c, g)	- Insecticide ha.a (c, g
Value         Range         Value         Range         Value         Range           Cult. and Harvest.:         -         -         0.371         ±0.062         0.371         ±0.062         (a)           - N Fertiliser         ha.a         -         -         0.002         -         0.002         -         (b, c)           - F Fertiliser         ha.a         -         -         0.003         -         (c, d)           - Fertiliser         ha.a         -         -         0.003         -         (c, d)           - Pesticides         ha.a         -         -         0.001         -         (c, e)           - Herbicide         ha.a         -         -         -         -         -         (c, f)	
Value         Range         Value         Range         Value         Range           Cult. and Harvest.:         -         -         0.371         ±0.062         0.371         ±0.062         (a)           - N Fertiliser         ha.a         -         -         0.002         -         0.002         -         (b, c)           - K Fertiliser         ha.a         -         -         0.003         -         (c, d)           - Pesticides         ha.a         -         -         0.001         -         (c, e)	
Value         Range         Value         Range         Value         Range           Cult. and Harvest.:         -         -         0.371         ±0.062         0.371         ±0.062         (a)           - N Fertiliser         ha.a         -         -         0.002         -         0.002         -         (b, c)           - F Fertiliser         ha.a         -         -         0.003         -         0.003         -         (b, c)	
Value         Range         Value         Range         Value         Range           Cult. and Harvest.:         -         -         0.371         ±0.062         0.371         ±0.062         (a)           - N Fertiliser         ha.a         -         -         0.002         -         0.002         -         (b, c)	
Value         Range         Value         Range         Value         Range           Cult. and Harvest.:         -         -         0.371         ±0.062         0.371         ±0.062         (a)	
Value         Range         Value         Range         Value         Range           Cult. and Harvest.:	
Value Range Value Range Value Range	
	Unit Direct Indirect Total Note
Contribution Per Methane Output (kg CH <sub>4</sub> )	Contribution Per Methane Output (kg CH <sub>4</sub> )
	Contribution Per Methane Output (kg CH <sub>4</sub> )

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
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t csb	= tonne	of clean	sugar	bee
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- t ssb = tonne of soiled sugar beet
- t be = tonne of bioethanol

#### <u>Notes</u>

- (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<sub>4</sub>/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 x 10<sup>-5</sup> kg CH<sub>4</sub>/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<sub>2</sub>O/ha.a assuming 1.205 kg K<sub>2</sub>O/kg K, and a total methane requirement for potash fertiliser of 2.1 x 10<sup>-5</sup> kg CH<sub>4</sub>/ kg K<sub>2</sub>O (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  $1.8 \times 10^{-4}$  kg CH<sub>4</sub>/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  $1.8 \times 10^{-4}$  kg CH<sub>4</sub>/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 x 10<sup>-4</sup> kg CH<sub>4</sub>/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<sub>4</sub> /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  $6.0 \times 10^{-7}$  kg CH<sub>4</sub>/MJ, an indirect methane requirement of  $2.04 \times 10^{-5}$  kg CH<sub>4</sub>/MJ and a total methane requirement of  $2.1 \times 10^{-5}$  kg CH<sub>4</sub>/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 x 10<sup>-7</sup> kg CH<sub>4</sub>/MJ, an indirect methane requirement of 2.04 x 10<sup>-5</sup> kg CH<sub>4</sub>/MJ and a total methane requirement of 2.1 x 10<sup>-5</sup> kg CH<sub>4</sub>/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.
- (I) 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<sub>4</sub>/t-km, an indirect methane requirement of  $1.672 \times 10^{-5} \pm 6.3 \times 10^{-7}$  kg CH<sub>4</sub>/t-km and a total methane requirement of  $1.721 \times 10^{-5} \pm 6.5 \times 10^{-7}$  kg CH<sub>4</sub>/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  $3.7 \times 10^{-6}$  kg CH<sub>4</sub>/MJ, an indirect methane requirement of  $1.1 \times 10^{-4}$  kg CH<sub>4</sub>/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  $1.176 \times 96,480 \times 3.5/26.8 = 14,818 \text{ MJ/hr}$  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<sub>4</sub>/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  $2.1 \times 10^{-5}$  kg CH<sub>4</sub>/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  $0.01 \pm 0.001$  kg CH<sub>4</sub>/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  $\times 10^{-7}$  kg CH<sub>4</sub>/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  $3.0 \times 10^{-7}$  kg CH<sub>4</sub>/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 x 10<sup>-4</sup> ± 7.0 x 10<sup>-5</sup> kg CH<sub>4</sub>/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 x 10<sup>-6</sup> kg CH<sub>4</sub>/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 x 10<sup>6</sup> kg CH<sub>4</sub>/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<sub>2</sub>) 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<sub>4</sub>/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<sub>4</sub>/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 x  $10^{-6}$  kg CH<sub>4</sub>/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  $1.0 \times 10^{-6}$  kg CH<sub>4</sub>/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  $2.1 \times 10^{-5}$  kg CH<sub>4</sub>/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<sub>4</sub>/kg and an indirect methane requirement of  $9.2 \times 10^{-3}$  kg CH<sub>4</sub>/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 x 10<sup>-6</sup> kg CH₄/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<sub>4</sub>/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  $4.0 \times 10^{-4}$  kg CH<sub>4</sub>/MJ for displaced grid electricity supplies in the UK in 1996 (Ref. 11), less  $1.176 \times 478$  of natural gas used to produce the surplus amount with a direct methane requirement of  $3.7 \times 10^{-6}$  kg CH<sub>4</sub>/MJ, an indirect methane requirement of  $1.1 \times 10^{-4}$  kg CH<sub>4</sub>/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<sup>-6</sup> kg CH₄/kg for lime (Ref. 7).
- (kk) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 85.7% to bioethanol.
- (II) 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  $1.192 \times 10^{-7}$  kg CH<sub>4</sub>/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<sub>4</sub>/t-km, an indirect methane requirement of  $1.672 \times 10^{-5} \pm 6.3 \times 10^{-7}$  kg CH<sub>4</sub>/t-km and a total methane requirement of  $1.721 \times 10^{-5} \pm 6.5 \times 10^{-7}$  kg CH<sub>4</sub>/t-km (Ref. 11).

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## 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)

Value         Range         Value         Range         Value         Range           - N Fertiliser         ha.a         0.371         ±0.125         1.514         ±0.233         1.885         ±0.283         (a)           - N Fertiliser         ha.a         -         0.001         ±0.001         0.004         ±0.001         (b, c)         (c, d)           - Sectiliser         ha.a         -         0.004         ±0.001         0.004         ±0.001         (c, d)           - Insecticide         ha.a         -         -         0.004         ±0.001         (c, l)           - Insecticide         ha.a         -         -         -         0.004         ±0.001         (c, l)           - Insecticide         ha.a         0.005         ±0.001         -         -         -         0.004         ±0.001         (c, l)           Sub-Totals         ha.a         0.005         ±0.020         0.288         ±0.253         1.903         ±0.263         ±0.263         ±0.263         ±0.264         (k)           - Disel Fuel         f.ssb         -         -         -         -         (l)         (m)         (m)         (m)         (m)         (m)         (m)	Final Unit of Measurement:         1 tome of bioenhanol           Relevant Location         United Kingdom           Relevant Location         Direct Kingdom           Alacation Procedures:         Based on a market price for 13.296 tonnes of sugar beet on the farm of £22.001 (Ref. 1) and an effective price for 14.590 tonnes of thin juice (15% solids and 25% sugar purity) of 15.27, derived from aprice for 14.590 tonnes of thin juice (15% solids and 25% sugar purity) of 15.27, derived from aprice for 0.720 tonnes of thems by aprice for	Functional Unit:					sugar beet usi	ng natural ga	s-fired combir	ned heat and
Relevant Pricio         United Kingdom           Relevant Prico         200           Allocation Procedures:         Based on a market price for 13.206 tornes of sugar beat on the farm of £2.201 (Ref. 1) and an effective pric for 1.307 tornes of sugar beat on the farm of £2.00 it (Ref. 2), substitution of 0.688 tornes of singer market price of 22.001 (Ref. 2), substitution of 0.089 tornes of singer torn washing by sample and floative average price for 22.888 tornes price (7% solids and 92% sugar purity) of £2.240 (Ref. 2), and an effective average price for 22.888 tornes puble (7% solids and 92% sugar purity) of £2.501, detret form an average market price for and an assumed price for brokethand of £2.800, detret form an average price for 22.888 tornes puble (7% solids and 92% sugar purity) of £2.501, detret form an average price for 22.888 tornes moisture content) of £2.501, detret 3) and an effective average price for 22.801 (Ref. 2), substitution of 0.568 tornes of times by agricultral line, and an assumed price for brokethand of £2.800, detret 2) and an effective price for 72.001 (Ref. 2).           Contribution         United         Nitrous Dock octuput (kg NLO)         Notes           Cultivation and Harvesting:         In a.a.         0.371 ±0.125         1.514         20.2031         0.004         2.0001         0.004         2.001         0.004         2.001         0.004         2.001         0.004         2.001         0.004         2.001         0.004         2.001         0.004         2.001         0.004         2.001         0.004         2.001         0.004         2.001	Relevant Procedures:         United Kingdom           Allocation Procedures:         Based on a market price for 13.286 tonnes of sugar best on the farm of E22.001 (Ref. 1) and an effective (for 1.300 tonnes of sugar best ops. (dry matery of E10.01, based on an avarage price for 2.2001 (Ref. 2) substitution of 0.468 tonnes of sugar by stores from submit/s, an effective average price for 2.2001 (Ref. 3) and an effective average price for 2.2001 (Ref. 3) substitution of 0.568 tonnes of Limm X by agricultural imma assumed price for 12.2001 (Ref. 3) and an effective average price for 2.2001 (Ref. 3) and an effective average price for 2.2001 (Ref. 3) and an effective price for 0.2001 (Ref. 4).           Contribution         Part Minimizer Content (Ref. 2), substitution of 0.568 tonnes of Limm X by agricultural imma faed pelles (15%) minimizer content of 252.001 (Ref. 3) and an effective price for 0.2001 (Ref. 4).         Not           Contribution         Part Minimizer         Not         Not Minimizer (Ref. 2) audit familiary price in 0.2001 (Ref. 4).         Not           Cultivation and Harvesting:         Na.a         0.371 ±0.125         15.14 ±0.2031 (Ref. 4).         10.001 ±0.001 (Ref. 4).           Cultivation and Harvesting:         Na.a         0.001 ±0.001 (Ref. 4).         Not         10.001 ±0.001 (Ref. 4).           Cultivation and Harvesting:         Na.a         0.001 ±0.001 (Ref. 4).         10.001 ±0.001 (Ref. 4).         10.001 (Ref. 4).           Cultivation and Harvesting:         Na.a         -         0.001 ±0.001 (Ref. 4).         10.001 (Ref. 4).	Final Unit of Measurement			me ouring pr	ocessing				
Relevant Period:         2002           Allocation Procedures:         Based on a market prote for 13.296 tormes of sugar best on the farm of £22.001 (Ref. 1) and an effective prior for 15.206 (see an energy emarket prior of £2.001 (ref. 1) and an effective prior bases) with a 80% moisture content (Ref. 2), substitution of 0.686 tormes of solid from washing by solid from	Relevant Period:         2002           Allocation Procedures:         Based on a market price for 13.296 tonnes of sugar beet on the farm of E22.001 (Ref. 1) and an effective price for 1.507 tonnes of sugar beet on the farm of E22.001 (Ref. 1) and an effective price for susaring by solines from subring by solines form subring by solines fore form soline by by solines fore fore form soline by									
Albcation Procedures:         Based on a market price for 13.286 tonnes of sugar beet on the farm of 222.001 (left. 1) and an effective price of 14.560 tonnes of sugar puty sole form any sources, substitution of 0.668 tonnes of sugarying, an effective average price for 14.560 tonnes of sugarying and effective average price for 14.560 tonnes of sugarying and effective average price for 14.560 tonnes of sugarying and effective average price for 14.560 tonnes of thin juice (15% sublat uno 10.566 tonnes of turnex by agricultural field polisite (15% substitution of 0.566 tonnes of turnex by agricultural field polisite (15% substitution of 0.566 tonnes of turnex by agricultural field polisite (15% substitution of 0.566 tonnes of turnex by agricultural field polisite (15% substitution of 0.566 tonnes of turnex by agricultural field polisite (15% substitution of 0.566 tonnes of turnex by agricultural field polisite (15% substitution of 0.566 tonnes of turnex by agricultural field polisite (15% substitution of 0.566 tonnes of turnex by agricultural field polisite (15% substitution of 0.566 tonnes of turnex by agricultural field polisite (15% substitution of 0.566 tonnes of turnex by agricultural field polisite (15% substitution of 0.566 tonnes of turnex by agricultural field polisite (15% substitution of 0.566 tonnes of turnex by agricultural field polisite (15% substitution of 0.566 tonnes of turnex by agricultural field polisite (15% substitution of 0.566 tonnes of turnex by agricultural field polisite (15% substitution of 0.566 tonnes of turnex by agricultural field polisite (15% substitution of 0.566 tonnes of turnex by agricultural field polisite (15% substitution of 0.566 tonnes of turnex by agricultural field polisite (15% substitution of 0.566 tonnes of turnex by agricultural field polisite (15% substitution of 0.566 tonnes of turnex by agricultural field polisite (15% substitution of 0.566 tonnes of turnex by agricultural field polisite (15% substitution of 0.566 tonnex by agricu	Allocation Procedures:         Based on a marke price for 13.296 tonnes of sugar beet on the farm of E22.001 (Ref. 1) and a mether price of 22.001, reg. 1) substitution of 0.696 tonnes of subar market price of 22.001, reg. 1) substitution of 0.696 tonnes of subar market price of 22.001, reg. 1) substitution of 0.696 tonnes of subar market price of 22.001, reg. 1) substitution of 0.696 tonnes of subar market price for 13.296, reg. 1) substitution of 0.696 tonnes of Lime X by aprice for 14.500 tonnes of time X by aprice for 14.500 tonnes of time X by aprice for 14.500 tonnes of time X by aprice for 14.500 tonnes of Lime X by aprice for 0 to 14.500 tonnes of Lime X by aprice for 0 to 14.500 tonnes of Lime X by aprice for 0 to 14.500 tonnes of Lime X by aprice for 0 to 14.500 tonnes of Lime X by aprice for 0 to 14.500 tonnes of Lime X by aprice for 0 to 14.500 tonnes of Lime X by aprice for 0 to 14.500 tonnes of Lime X by aprice for 0 to 14.500 tonnes of Lime X by aprice for 0 to 14.500 tonnes of Lime X by aprice for 0 to 14.500 tonnes of Lime X by aprice for 0 to 14.500 tonnes of Lime X by aprice for 0 to 14.500 to 1.500 tonnes of Lime X by aprice for 0 to 14.500 to 1.500 to 1.5000 to 1.5000 to 1.500 to 1.500 to 1.500 to 1.500 to 1.500 to 1.500		9	uum						
Instrume	Instruction         for 1.507 tones of sugar best tops (dry matter) of 12.0.01, based on an average marker loc of 12.0.01, based on average marker loc 12.0.01/ based on the submit and the submit of 0.48 tones of stores from washing by stores from quarrying, a refetche average for 25.98 bit more for 25.98 bit more discrete the submit of 0.78 bits and 92% sugar purity) of 127.484 (Ref. 3), and an effective average for 25.98 bits and 92% submit of 0.72 bits more of 11.850 tones of 1.850 tones of 1			arket price f	or 13 206 ton	hes of sugar b	eet on the form	of £22 00/# /E	Pef 1) and an a	offective price
assumed price for bioethanol of £22 000/t (Ref. 3) and an effective price for 0.720 momes of vinasses (55% solid and 66.5% sough of 66.5% solid and 66.5% s	assumed price for biodethanol of \$220.001 (Ref. 3) and an effective price for 0.720 burger (Kg N-Q)           Contribution         Per Unit         Notation (Kg N-Q)         Notation (Kg N-Q)           Cultivation and Harvesting:         h.a.a         0.371         20.125         1.514         40.253         1.885         10.283         (ange)           N Fertiliser         h.a.a         0.371         20.125         1.514         40.253         1.885         10.283         (ange)           P Fortiliser         h.a.a         -         0.004         20.001         0.004         20.001         (c)         (c)           - Pesticides         h.a.a         -         0.004         20.001         -         (c)         (c)           - Seedid         h.a.a         -         -         0.004         20.001         (c)         (c)           - Disel Fuel         h.a.a         0.005         20.001         -         -         0.001         (c)         (c)           - Disel Fuel         h.a.a         0.007         2.0253         1.903         40.2031         (c)         (c)           - Disel Fuel         h.a.a         0.007         2.0253         1.903         40.2046         (k)           -	fo ba sc pr ju	or 1.507 tonne asis) with a 8 ources, subst rice for 14.56 rice (67% soli	es of sugar 0% moistur titution of 0.0 0 tonnes of ids and 92%	beet tops (dry e content (Re 049 tonnes of thin juice (15 5 sugar purity)	r matter) of £10 f. 2), substituti stones from w % solids and 8 of £72.48/t (F	0.0/t, based on on of 0.669 tor vashing by stor 88% sugar purit Ref. 3), and an	an average m nes of soil from nes from quarr ty) of £16.2/t, of effective avera	arket price of a m washing by s ying, an effecti derived from a age price for 25	22.00/t (wet soil from main ve average price for thick 5.996 tonnes of
socide and 66.5% support of 0.720 menses (55% socide Output (kg N <sub>2</sub> O)           Contribution         Per         Nitrous Oxide Output (kg N <sub>2</sub> O)           Contribution         Per         Tritous Oxide Output (kg N <sub>2</sub> O)           Contribution and Harvesting:         ha.a         0.371         ±0.125         1.514         ±0.2283         (a)           N Fertiliser         ha.a         0.3001         0.0004         ±0.0004         ±0.0004         ±0.001         (c)         (c)           P Fertiliser         ha.a         -         0.004         ±0.004         ±0.004         ±0.004         ±0.001         (c)         (c)           Pesticides          -         -         -         -         (c)         (c)           Seed          0.005         ±0.001         -         -         -         -         -         -         -         -         -         -	assumed price for biodethanol of \$252.00() (Fer. 3) and an effective price for 0.720 (burger (4.).           Contribution         Per Unit         Direct         Nutrous Oxide Output (kg N_O)           Culturation and Harvesting:         ha.a         0.371         20.125         1.514         40.253         1.885         10.283         (a           N Fertiliser         ha.a         0.371         20.125         1.514         40.253         1.885         10.283         (a           P Fortiliser         ha.a         0.004         30.001         0.004         30.001         (b, 0.004         20.001         (c, 0.004         40.001         (c, 0.005         40.001         (c, 0.005         40.001         (c, 0.005         40.001         (c, c, 0.001         (c, c, 0.005         40.001         (c, c, 0.005         40.001         (c, c, 0.001									
Contribution         Per Unit         Direct         Nutrous Oxide Output (kg N_O)         Notes           Cultivation and Harvesting: • N Fertiliser         ha.a         0.371         ±0.125         1.574         ±0.283         1.885         ±0.283         (a)           - N Fertiliser         ha.a         0.371         ±0.125         1.574         ±0.263         1.885         ±0.004         ±0.007         (c, 0)           - N Fertiliser         ha.a         -         -         0.001         ±0.001         ±0.001         ±0.001         (c, 0)           - Pesticides         ha.a         -         -         0.001         ±0.001         ±0.001         (c, 0)           - Insecticide         ha.a         -         -         0.004         ±0.001         (c, 0)           - Desel Fuel         ha.a         -         -         0.004         ±0.001         (c, 1)           - Disel Fuel         ha.a         -0.001         -         -         -0.001         -         (c, 1)           Sub-Totals         ha.a         0.375         ±0.125         1.528         ±0.941         0.309         ±0.946         (k)           - Disel Fuel         ha.a         -         -         -	Contribution         Per Unit         Direct         Introus Oxide Output (kg N <sub>2</sub> O)         Not           Cultivation and Harvesting:         h.a.a         0.371         ±0.125         1.514         ±0.253         1.885         ±0.283         (kg N <sub>2</sub> O)           - N Fertiliser         h.a.a         -         0.004         ±0.001         0.004         ±0.001         -         (kg N <sub>2</sub> O)         (kg N <sub>2</sub> O)           - N Fertiliser         h.a.a         -         0.004         ±0.001         0.004         ±0.001         -         (kg N <sub>2</sub> O)         -         (kg N <sub>2</sub> O)	as	ssumed price	for bioetha	nol of £529.0	0/t (Ref. 3) and	d an effective p	rice for 0.720	tonnes of vinas	
Value         Range         Value         Range         Value         Range           - N Fartiliser         ha.a         0.371         ±0.125         1.514         ±0.253         1.885         ±0.283         (a)           - P Fortiliser         ha.a         -         0.004         ±0.001         0.004         ±0.001         (b, c)           - Pesticides         ha.a         -         0.004         ±0.001         0.004         ±0.001         (c, c)           - Pesticides         ha.a         -         0.004         ±0.001         0.004         ±0.001         (c, c)           - Seed         ha.a         -         -         0.004         ±0.001         (c, c)         (c, c)           Sub-Totals         ha.a         0.005         ±0.001         -         -         -         0.004         ±0.001         (c, c)           Sub-Totals         ha.a         0.005         ±0.020         0.288         ±0.041         -         (c, c)           Vashing.Shredding and         .         0.025         ±0.263         1.903         ±0.046         (k)           Vashing.Shredding and         .         .         -         .         .         ((n)	Value         Range         Value         Range         Value         Range           - 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         (c)           - Pesticides         ha.a         -         -         0.004         ±0.001         (c)         (c)           - Pesticides         ha.a         -         -         0.004         ±0.001         (c)         (c)           - Seed         ha.a         -         -         0.004         ±0.001         .         (c)           - Diesel Fuel         ha.a         -         -         0.004         ±0.001         .         (c)           Sub-Totals         ha.a         -         0.001         -         -         0.005         ±0.026         ±0.026         ±0.026         ±0.026         ±0.026         ±0.026         ±0.026         ±0.026         ±0.046         (c)         (	Contribution	Per			Nitrou	s Oxide Outp	out (kg N <sub>2</sub> O)		
Cultivation and Harvesting:         ha.a         0.371         ±0.125         1.514         ±0.253         1.885         ±0.283         (a)           P Fertiliser         ha.a         -         -         0.004         ±0.001         0.001         ±0.001         (b, c)           P settiliser         ha.a         -         -         0.001         0.001         ±0.001         (c, c)           Pestilide         ha.a         -         -         0.001         -         0.001         ±0.001         (c, c)           Insecticide         ha.a         -         -         0.004         ±0.001         0.004         ±0.001         (c, n)           Steed         ha.a         0.005         ±0.001         -         -         -         0.005         ±0.001         (c, n)           Dissel Fuel         ha.a         0.375         ±0.125         1.528         ±0.263         1.903         ±0.283         (k)           Transport:         -         -         -         -         -         (m)         (m)           Politruic Acid         t csb         -         -         -         -         (m)         (m)           Disele Fuel         t bb         -<	Cultivation and Harvesting:         ha.a         0.371         ±0.125         1.514         ±0.283         1.885         ±0.203         (b.a)           P Fertiliser         ha.a         -         -         0.004         ±0.001         0.004         ±0.001         0.001         ±0.001         (c. c. f. f. c. f. c. f. f. f. f. c. f. f. c. f.		Unit	Di	rect	Ind	irect	To	otal	Notes
N Fertiliser         ha.a         0.371         ±0.725         1.574         ±0.233         1.885         ±0.283         (a)           K Fertiliser         ha.a         -         0.001         ±0.001         ±0.001         0.004         ±0.001         (c, d)           Pesticides         ha.a         -         0.004         ±0.001         0.004         ±0.001         (c, d)           Insecticide         ha.a         -         -         0.004         ±0.001         0.004         ±0.001         (c, i)           Seed         ha.a         -         -         0.004         ±0.001         (c, i)           Piesal Fuel         ha.a         -         0.001         .         -         -         0.001         (c, i)           Sub-Totals         ha.a         -0.001         -         -         -         -         0.001         (c, i)           Washing, Shredding and         tbe         -         -         -         -         (c, n)           Ufusion:         -         -         -         -         -         (c, n)           Vashing, Shredding and         Ufusion:         -         -         -         (c, i)           Oppount <td>N Fertiliser         ha.a         0.371         <math>20.125</math>         1.514         <math>20.233</math>         1.882         <math>20.283</math>         (a.           K Fertiliser         ha.a         -         0.001         <math>20.001</math>         0.004         <math>20.001</math>         (b.         (c.         &lt;</td> <td></td> <td></td> <td>Value</td> <td>Range</td> <td>Value</td> <td>Range</td> <td>Value</td> <td>Range</td> <td></td>	N Fertiliser         ha.a         0.371 $20.125$ 1.514 $20.233$ 1.882 $20.283$ (a.           K Fertiliser         ha.a         -         0.001 $20.001$ 0.004 $20.001$ (b.         (c.         <			Value	Range	Value	Range	Value	Range	
N Fertiliser       ha.a       0.371       ±0.125       1.514       ±0.233       1.885       ±0.283       (a)         P Fertiliser       ha.a       -       0.001       ±0.001       ±0.001       (c, d)         N Fertiliser       ha.a       -       0.004       ±0.001       ±0.001       ±0.001       (c, d)         Nescticide       ha.a       -       -       0.004       ±0.001       0.004       ±0.001       (c, l)         - Insecticide       ha.a       -       -       0.004       ±0.001       0.004       ±0.001       (c, l)         - Diesel Fuel       ha.a       -       -       0.004       ±0.001       .       (c, l)         Sub-Totals       ha.a       -0.001       -       -       -       -0.001       .       (c, l)         Sub-Totals       ha.a       -0.001       -       -       -       -       (l)       (m)         Vashing, Shredding and       1       blseel Fuel       tssb       -       -       -       (c, n)         Vashing, Shredding and       1       tssb       -       -       -       -       (m)       (m)         Vastari Gas       tcssb	N Fertiliser         ha.a         0.371         20.125         1.514         20.233         1.885         20.283         (a.           N Fertiliser         ha.a         -         0.001         -         0.001         20.001         (b.004         20.001         (c.         c.           Pesticides         ha.a         -         0.001         -         0.001         -         0.001         (c.         c.           - Insecticide         ha.a         -         -         0.001         -         -         0.001         (c.         (c.         c.	Cultivation and Harvesting:			Ŭ		Ŭ		Ŭ	
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	P Fertiliser       ha.a       -       -       0.004       ±0.001       0.001       ±0.001 <t< td=""><td></td><td>ha.a</td><td>0.371</td><td>+0.125</td><td>1.514</td><td>+0.253</td><td>1.885</td><td>+0.283</td><td>(a)</td></t<>		ha.a	0.371	+0.125	1.514	+0.253	1.885	+0.283	(a)
K Fertiliser         ha.a         -         0.001         0.001         0.004 $\pm 0.001$ $\pm 0.026$ $\pm 0.283$ $\pm 0.026$	K Fertiliser         ha.a         -         0.001 $10000$ $20001$ $200001$ $200001$ $200001$ $200001$ $200001$ $200001$ $20001$ <			-						
- Pesticides       ha.a       -       -       0.001 $\pounds 0.001$ </td <td>- Pesticides         ha.a         -         -         0.004         ±0.001         ±0.004         ±0.004         ±0.004         ±0.004         ±0.004         ±0.001         (C, C, C</td> <td></td> <td></td> <td>-</td> <td>-</td> <td></td> <td></td> <td></td> <td></td> <td></td>	- Pesticides         ha.a         -         -         0.004         ±0.001         ±0.004         ±0.004         ±0.004         ±0.004         ±0.004         ±0.001         (C, C, C			-	-					
Herbicide         ha.a         -         -         0.001         -         0.001         -         0.001         0.0001         0.001         0.0001         0.001         0.0001	Herbicide         ha.a         -         -         0.001         -         -         0.001         - </td <td></td> <td></td> <td>-</td> <td>-</td> <td></td> <td></td> <td></td> <td></td> <td></td>			-	-					
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	Insecticide $ha.a$ $\cdot$ <			-	_		±0.001		±0.001	,
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	- Seed ha.a ba.a 0.004 ±0.001 0.004 ±0.001 (c. c. c			_	_		-		-	
Diesel Fuel         ha.a         0.005         ±0.001           0.005         ±0.001         (c, i)           Reference System:         ha.a         -0.001         .         .          0.005         ±0.001          (c, i)           Sub-Totals         ha.a         0.375         ±0.125         1.528         ±0.253         1.903         ±0.283         ±0.046         (k)           Transport:         -         -         -         -         -         -         (n)         (c, i)           Vashing, Shredding and Difusion:         tbe         -         -         -         -         -         (c, n)           Vashing, Shredding and Difusion:         tcsb         -         -         -         -         (c, n)           Vashing, Shredding and Difusion:         tcsb         -         -         -         -         (c, n)           Vashing, Shredding and Difusion:         tcsb         -         -         -         -         (c, n)           Vashing, Shredding and Costs         tcsb         -         -         -         -         (c, n)           Subition:         tcsb         -         -         -         -	Dissel Fuel         ha.a         0.005         ±0.001          0.005         ±0.001            Reference System:         ha.a         -0.001         -         -          -0.001          (c,           Sub-Totals         ha.a         0.375         ±0.125         1.528         ±0.253         1.903         ±0.283         ±0.046         (k           Transport:         -         -         -         -         -         -         -         (f, k)         (			_	-		-		-	
Reference System:       1000       100000       100000       1	Reference System:         Dotsel Fuel         ha.a         -0.001         -         -         -         -         0.001         -         (c,           Sub-Totals         ha.a         0.375         ±0.125         1.528         ±0.253         1.903         ±0.283         ±0.046         (k           Transport:         -         -         -         -         -         -         -         (l)         (k)			-	-	0.004	±0.001			
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	- Diesel Fuel         ha.a         - 0.001         -         -         -         -         -         -         0.001         -         (c, normality)           Sub-Totals         ha.a         0.375 $\pm 0.125$ $\pm 0.283$ $\pm 0.263$ $\pm 0.283$ $\pm 0.283$ $\pm 0.283$ $\pm 0.046$ (k           Tansport:         -         -         -         -         -         -         -         (l)         (l)           Vashing, Shredding and Diffusion:         tbe         -         -         -         -         -         -         (l)         (m)           Vashing Gas         t csb         -         -         -         -         -         -         (c, not set set set set set set set set set se		na.a	0.005	±0.001	-	-	0.005	±0.001	(C, I)
Sub-Totals         ha.a         0.375 $\pm 0.125$ $\pm 0.253$ $1.903$ $\pm 0.283$ $\pm 0.046$ (k)           Transport:         -         -         -         -         -         (l)           Diesel Fuel         t bs         -         -         -         -         -         (l)           Washing, Shredding and Diffusion:         t bs         -         -         -         -         -         (m)           Washing, Shredding and Diffusion:         -         -         -         -         -         (c, n - p)           Oldgesine         t csb         -         -         -         -         -         (c, n', p)           Subprote Acid         t csb         -         -         -         -         (c, n', p)           - Suppartic         t csb         -         -         -         -         (c, n', p)           - Formaldelryde         t csb         -         -         -         -         (c, n')           - Formaldelryde         t csb         -         -         -         -         (c, w)           - Solide         t csb         -         -         -         -         (c, w)	Sub-Totals         ha.a $0.375$ $\pm 0.125$ $1.528$ $\pm 0.253$ $1.903$ $\pm 0.283$ $\pm 0.283$ $\pm 0.046$ (k           Transport:         -         -         -         -         -         -         (l)           Diesel Fuel         t ssb         -         -         -         -         -         (l)           Washing, Shredding and Diffusion:         -         -         -         -         -         -         (l)           Subphruic Acid         t csb         -         -         -         -         -         (c, n)           Gypsum         t csb         -         -         -         -         -         (c, n)           Formaldehyde         t csb         -         -         -         -         -         (c, n)           Formaldehyde         t csb         -         -         -         -         -         (c, n)           Solid         t csb         -         -         -         -         -         (c, n)           Subphruic Acid         t csb         -         -         -         -         -         (c, n)           Solid		ha -	0.004				0.001		(- ))
t be         0.061 $\pm 0.020$ 0.248 $\pm 0.041$ 0.309 $\pm 0.046$ (k)           Transport: - Diesel Fuel         t ss         -         -         -         -         (n)           Washing, Shredding and Diffusion: - Natural Gas         t csb         -         -         -         -         (c, n - p)           Subphuric Acid         t csb         -         -         -         -         (c, n)           Hydrochloric Acid         t csb         -         -         -         -         (c, n)           Formaldehyde         t csb         -         -         -         -         (c, n)           Formaldehyde         t csb         -         -         -         -         (c, n)           Formaldehyde         t csb         -         -         -         -         (c, n)           Formaldehyde         t csb         -         -         -         -         (c, n)           Stones         t csb         -         -         -         -         (c, w)           Subpuric Acid         t csb         -         -         -         -         (c, w)           Purification, Concentration, Fermentation	tbe         0.061         ±0.020         0.248         ±0.041         0.309         ±0.046         (k           Transport:         -         -         -         -         -         -         -         (l)         0.309         ±0.046         (k)           Diesel Fuel         t sb         -         -         -         -         -         -         (l)         (l)           Washing, Shredding and Diffusion:         -         -         -         -         -         -         (c, n)         (c, n)           - Sulphuric Acid         t csb         -         -         -         -         -         -         (c, n)           - Hydrochloric Acid         t csb         -         -         -         -         -         (c, n)         (c, r)           - Formaldehyde         t csb         -         -         -         -         -         (c, r)         (c, r)           - Stoles         t csb         -         -         -         -         -         (c, r)         (c, r)           - Sola         t csb         -         -         -         -         -         (c, r)         (c, r)           - Sola <t< td=""><td>- Diesei Fuei</td><td>na.a</td><td>- 0.001</td><td>-</td><td>-</td><td>-</td><td>- 0.001</td><td>-</td><td>(C, J)</td></t<>	- Diesei Fuei	na.a	- 0.001	-	-	-	- 0.001	-	(C, J)
t be         0.061 $\pm 0.020$ 0.248 $\pm 0.041$ 0.309 $\pm 0.046$ (k)           Transport: - Diesel Fuel         t ssb         -         -         -         -         (n)           Washing, Shredding and Diffusion: - Natural Gas         t csb         -         -         -         -         (c, n - p)           Subphuric Acid         t csb         -         -         -         -         (c, n)           Hydrochloric Acid         t csb         -         -         -         -         (c, n)           Hydrochloric Acid         t csb         -         -         -         -         (c, n)           Hydrochloric Acid         t csb         -         -         -         -         (c, n)           Formaldehyde         t csb         -         -         -         -         (c, n)           Formalofit         t csb         -         -         -         -         (c, n)           Formalofit         t csb         -         -         -         -         (c)           Formalofithyde         t csb         -         -         -         -         (c)           Stotas         t csb <td>t be         0.061         ±0.020         0.248         ±0.041         0.099         ±0.026         (k           Transport: - Diesel Fuel         t ssb         -         -         -         -         -         (n)           Washing, Shredding and Diffusion: - Natural Gas         t csb         -         -         -         -         -         (n)           Yughoric Acid         t csb         -         -         -         -         -         (c, n)           - Gypsum         t csb         -         -         -         -         -         (c, n)           - Gypsum         t csb         -         -         -         -         -         (c, n)           - Gypsum         t csb         -         -         -         -         -         (c, n)           Formaldehyde         t csb         -         -         -         -         -         (c, n)           - Solid         t csb         -         -         -         -         -         (c, n)           - Stones         t csb         -         -         -         -         -         (c, n, n)           - Subphuric Acid         t csb         -         -&lt;</td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td>	t be         0.061         ±0.020         0.248         ±0.041         0.099         ±0.026         (k           Transport: - Diesel Fuel         t ssb         -         -         -         -         -         (n)           Washing, Shredding and Diffusion: - Natural Gas         t csb         -         -         -         -         -         (n)           Yughoric Acid         t csb         -         -         -         -         -         (c, n)           - Gypsum         t csb         -         -         -         -         -         (c, n)           - Gypsum         t csb         -         -         -         -         -         (c, n)           - Gypsum         t csb         -         -         -         -         -         (c, n)           Formaldehyde         t csb         -         -         -         -         -         (c, n)           - Solid         t csb         -         -         -         -         -         (c, n)           - Stones         t csb         -         -         -         -         -         (c, n, n)           - Subphuric Acid         t csb         -         -<									
Transport: - Diesel Fuel         t ssb         -         -         -         -         -         -         -         -         -         ()           Washing, Shredding and Diffusion: - Sulphuric Acid         t t ssb         -         -         -         -         -         -         (n)           Mashing, Shredding and Diffusion: - Sulphuric Acid         t c sb         -         -         -         -         -         (c, n - p           - Sulphuric Acid         t c sb         -         -         -         -         -         (c, n)           Hydrochloric Acid         t c sb         -         -         -         -         -         (c, r)           Formaldehyde         t c sb         -         -         -         -         (c, w)           Foarm Oil         t c sb         -         -         -         -         -         (c, w)           Stole         t c sb         -         -         -         -         -         (c, w)           Stole         t c sb         -         -         -         -         -         (c, w)           Stole         t c sb         -         -         -         -         -         (	Transport:         10.000         10.001         10.001         10.006         10.006           - Diesel Fuel         t ssb         -         -         -         -         -         -         0         <	Sub-Totals			±0.125		±0.253		±0.283	
Transport:       Use       I <thi< th=""> <th< td=""><td>Transport:       Dissel Fuel       t ssb       -       -       -       -       -       -       (I)         Washing, Shredding and Diffusion:       -       -       -       -       -       -       (C, n)         Natural Gas       t csb       -       -       -       -       -       -       -       (C, n)         Sulphuric Acid       t csb       -       -       -       -       -       -       -       (C, n)         Gypsum       t csb       -       -       -       -       -       -       -       (C, n)         - Formaldehyde       t csb       -       -       -       -       -       -       -       (C, n)         Foam Oil       t csb       -       -       -       -       -       -       -       (C, n)       (C, n)         Foam Oil       t csb       -       -       -       -       -       -       -       (C, n)       (C, n)         Foam Oil       t csb       -       -       -       -       -       -       (C, n)       -       -       -       (C, n)       -       -       -       -       -</td><td></td><td>t be</td><td>0.061</td><td>±0.020</td><td>0.248</td><td>±0.041</td><td>0.309</td><td></td><td>(k)</td></th<></thi<>	Transport:       Dissel Fuel       t ssb       -       -       -       -       -       -       (I)         Washing, Shredding and Diffusion:       -       -       -       -       -       -       (C, n)         Natural Gas       t csb       -       -       -       -       -       -       -       (C, n)         Sulphuric Acid       t csb       -       -       -       -       -       -       -       (C, n)         Gypsum       t csb       -       -       -       -       -       -       -       (C, n)         - Formaldehyde       t csb       -       -       -       -       -       -       -       (C, n)         Foam Oil       t csb       -       -       -       -       -       -       -       (C, n)       (C, n)         Foam Oil       t csb       -       -       -       -       -       -       -       (C, n)       (C, n)         Foam Oil       t csb       -       -       -       -       -       -       (C, n)       -       -       -       (C, n)       -       -       -       -       -		t be	0.061	±0.020	0.248	±0.041	0.309		(k)
- Diesel Fuel         t ssb         -         -         -         -         -         -         -         -         (n)           Washing, Shredding and Diffusion:         -         -         -         -         -         -         -         (m)           Natural Gas         t csb         -         -         -         -         -         -         (c, n - p           - Sulphuric Acid         t csb         -         -         -         -         -         -         (c, n)           - Sulphuric Acid         t csb         -         -         -         -         -         -         (c, r)           - Formaldehyde         t csb         -         -         -         -         -         (c, r)           - Foam Oil         t csb         -         -         -         -         -         -         (c, r)           - Foam Oil         t csb         -         -         -         -         -         (c, r)           Stones         t csb         -         -         -         -         -         (c, r)           Purification, Concentration, Fermentation, Distillation and Dehydration::         -         -         -	- Diesel Fuel $t ssb$ -         -         -         -         -         -         -         -         -         -         -         -         -         0         0(0)           Washing, Shredding and Diffusion:         Natural Gas $t csb$ -         -         -         -         -         -         -         (C, n)           Sulphuric Acid $t csb$ -         -         -         -         -         -         (C, n)           Gypsum $t csb$ -         -         -         -         -         -         (C, n)           Hydrochloric Acid $t csb$ -         -         -         -         -         -         (C, n)           Hydrochloric Acid $t csb$ -         -         -         -         -         (C, n)         (C, n)           Formaldehyde $t csb$ -         -         -         -         -         -         -         (C, n)           Solid $t csb$ -         -         -         -         -         -         (C, n)           Purification, Concentration,         Fermentation, Distiliation	Transport:							101010	
t be         -         -         -         -         -         (m)           Washing, Shredding and Diffusion: - Natural Gas         t csb         -         -         -         -         (c, n - p)           - Suphuric Acid         t csb         -         -         -         -         -         (c, n - p)           - Sypsum         t csb         -         -         -         -         -         (c, n)           - Solid         t csb         -         -         -         -         -         (c, n)           - Formaldehyde         t csb         -         -         -         -         -         (c, n)           - Formaldehyde         t csb         -         -         -         -         -         (c, n)           - Foam Oil         t csb         -         -         -         -         -         (c, n)           - Foam Oil         t csb         -         -         -         -         -         (c, n)           - Stoll         t csb         -         -         -         -         -         -         (c, n,p, z           - Sold         t csb         -         -         -         -	t be         -         -         -         -         -         -         (m)           Washing, Shredding and Diffusion: - Natural Gas         t csb         -         -         -         -         (c, n)           - Natural Gas         t csb         -         -         -         -         -         (c, n)           - Suphunic Acid         t csb         -         -         -         -         -         (c, n)           - Hydrochloric Acid         t csb         -         -         -         -         -         (c, n)           - Formaldehyde         t csb         -         -         -         -         -         (c, -           - Foran Oil         t csb         -         -         -         -         -         (c, -           - Foran Oil         t csb         -         -         -         -         -         (c, -           - Foran Oil         t csb         -         -         -         -         -         (c, -           - Stoll         t csb         -         -         -         -         -         (c, -           Sub-Totals         t csb         -         -         -         - <td></td> <td>tech</td> <td>_</td> <td>_</td> <td>_</td> <td></td> <td>_</td> <td>_</td> <td>(1)</td>		tech	_	_	_		_	_	(1)
Washing, Shredding and Diffusion: - Natural Gas       t csb       -	Washing, Shredding and Diffusion: - Natural Gas       t csb       -	- Diesei Fuei		-	-	-	-	-	-	
Diffusion:       -       -       -       -       -       -       -       -       (c, n - p)         - Natural Gas       t csb       -       -       -       -       -       -       (c, n - p)       ((q, n)         - Gypsum       t csb       -       -       -       -       -       -       (c, n)       ((c, n)         - Gypsum       t csb       -       -       -       -       -       (c, n)       (c, n)       (c, n)         - Hydrochloric Acid       t csb       -       -       -       -       -       (c, n)       (c, n) <td>Diffusion:       -       -       -       -       -       -       -       -       (c, n)         - Sulphuric Acid       t csb       -       -       -       -       -       -       (c, n)         - Gypsum       t csb       -       -       -       -       -       -       (c, n)         - Hydrochloric Acid       t csb       -       -       -       -       -       -       (c, n)         - Biocide       t csb       -       -       -       -       -       -       (c, n)         - Form Aldehyde       t csb       -       -       -       -       -       -       (c, n)         - Form Oil       t csb       -       -       -       -       -       -       (c, n)         - Soli       t csb       -       -       -       -       -       -       (c, n)         Sub-Totals       t csb       -       -       -       -       -       -       (c, n)         Purification, Concentration, Fermentation, Distillation and Dehydration:       -       -       -       -       (c)       (d)         - Natural Gas       t csb       -       <td< td=""><td>Washing Chredding and</td><td>t be</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>(11)</td></td<></td>	Diffusion:       -       -       -       -       -       -       -       -       (c, n)         - Sulphuric Acid       t csb       -       -       -       -       -       -       (c, n)         - Gypsum       t csb       -       -       -       -       -       -       (c, n)         - Hydrochloric Acid       t csb       -       -       -       -       -       -       (c, n)         - Biocide       t csb       -       -       -       -       -       -       (c, n)         - Form Aldehyde       t csb       -       -       -       -       -       -       (c, n)         - Form Oil       t csb       -       -       -       -       -       -       (c, n)         - Soli       t csb       -       -       -       -       -       -       (c, n)         Sub-Totals       t csb       -       -       -       -       -       -       (c, n)         Purification, Concentration, Fermentation, Distillation and Dehydration:       -       -       -       -       (c)       (d)         - Natural Gas       t csb       - <td< td=""><td>Washing Chredding and</td><td>t be</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>(11)</td></td<>	Washing Chredding and	t be	-	-	-	-	-	-	(11)
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	Natural Gas         t csb         -         -         -         -         -         -         -         -         -         -         -         -         -         -         -         -         (c, n)									
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	Sulphuric Acid         t csb         -									
Gypsum         t csb         -         -         -         -         -         -         -         -         (C, T)           Hydrochloric Acid         t csb         -         -         -         -         -         -         -         (C, T)           Formaldehyde         t csb         -         -         -         -         -         -         (C, T)           Form Oil         t csb         -         -         -         -         -         -         (C, T)           Formaldehyde         t csb         -         -         -         -         -         -         (C, T)           Formaldehyde         t csb         -         -         -         -         -         -         (C, N)           Credits:         -         -         -         -         -         -         -         (C, N)           Sub-Totals         t csb         -         -         -         -         -         -         (C, N)           Purification, Concentration,         -         t csb         -         -         -         -         -         (C, N)           Purification, Distitabion and Dehydration:         -	- Gypsum       t csb       -       -       -       -       -       -       -       (c,         Hydrochloric Acid       t csb       -       -       -       -       -       -       (c,         Formaldehyde       t csb       -       -       -       -       -       -       (c,         Foam Oil       t csb       -       -       -       -       -       -       (c,         Foam Oil       t csb       -       -       -       -       -       -       (c,         Formaldehyde       t csb       -       -       -       -       -       -       (c,         Foam Oil       t csb       -       -       -       -       -       -       (c,         Credits:       -       -       -       -       -       -       -       (c,         Sub-Totals       t csb       -       -       -       -       -       -       (c,         Purification, Concentration,       -       t csb       -       -       -       -       (c,       -       (c,         Subphuru       t csb       -       -       - <t< td=""><td></td><td></td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>(c, n - p)</td></t<>			-	-	-	-	-	-	(c, n - p)
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	- Hýdrochloric Acid         t csb         -         (c,         -         -         (c,         -         -         -         (c,         -         -         -         -         (c,         -         -         -         -         -         (c,         -         -         -         -         (c,         -         -         -         -         -         (c,         -         -         -         -         -         -         -         -         -         -         (c,         -			-	-	-	-	-	-	(q)
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	- Gypsum	t csb	-	-	-	-	-	-	(c, r)
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	<ul> <li>Hydrochloric Acid</li> </ul>	t csb	-	-	-	-	-	-	(s)
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	- Formaldehyde	t csb	-	-	-	-	-	-	(c, t)
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	- Biocide	t csb	-	-	-	-	-	-	(c, u)
Credits: $t csb$ $t csb$ $       (c, w)$ Solones $t csb$ $     (c, w)$ Sub-Totals $t csb$ $     (c, w)$ Sub-Totals $t csb$ $     -$ Purification, Concentration, Fermentation, Distillation and Dehydration: $   -$ <td>Credits:       <math>t csb</math> <math>   -</math></td> <td>- Foam Oil</td> <td>t csb</td> <td>-</td> <td>-</td> <td>-</td> <td>-</td> <td>-</td> <td>-</td> <td></td>	Credits: $t csb$ $   -$	- Foam Oil	t csb	-	-	-	-	-	-	
Soil       t csb       -       -       -       -       -       -       -       (c, w)         Stones       t csb       -       -       -       -       -       -       -       (c, w)         Sub-Totals       t csb       -       -       -       -       -       -       (c, w)         Sub-Totals       t csb       -       -       -       -       -       -       (c, w)         Purification, Concentration, Bermentation, Distillation and Dehydration:       -       -       -       -       -       (c, n, p, z)         - Natural Gas       t csb       -       -       -       -       -       -       (c, n, p, z)         - Sulphur       t csb       -       -       -       -       -       (c, a)         - Soda       t csb       -       -       -       -       -       (c)         - EDTA       t csb       -       -       -       -       -       (c)       (c)         - Coke       t csb       -       -       -       -       -       -       (c, ff)         - Sulphuric Acid       t csb       -       -       - <t< td=""><td><math display="block">\begin{array}{c c c c c c c c c c c c c c c c c c c </math></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>( )</td></t<>	$\begin{array}{c c c c c c c c c c c c c c c c c c c $									( )
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- Limestone       t csb       -       -       -       -       -       -       -       -       (ee)         - Coke       t csb       -       -       -       -       -       -       -       (c, ff)         - Anti-Foam       t csb       -       -       -       -       -       -       (c, fg)         - Sulphuric Acid       t csb       -       -       -       -       -       (c, gg)         - Sulphuric Acid       t csb       -       -       -       -       -       (c, ig)         Credit:       -       -       -       -       -       -       -       (hh)         - LimeX       t csb       -       -       -       -       0.001       -0.003 $\pm 0.001$ (c, ij)         Sub-Totals       t csb       -       -       -       -       0.004 $\pm 0.001$ $\pm 0.001$ $\pm 0.011$ (kk)         Plant Construction       t be       -       -       -       -       -       (III)         Plant Maintenance       t be       -       -       -       -       -       (mm)         Distribution <t< td=""><td>- Limestone       t csb       -       -       -       -       -       -       -       (ee         - Coke       t csb       -       -       -       -       -       -       -       (c, c)         - Anti-Foam       t csb       -       -       -       -       -       -       (c, c)         - Anti-Foam       t csb       -       -       -       -       -       -       (c, c)         - Sulphuric Acid       t csb       -       -       -       -       -       -       (c, c)         Credit:       -       -       -       -       -       -       -       (c, c)         - LimeX       t csb       -       -       -       -       0.001       -0.003       <math>\pm 0.001</math>       -       (c, c)         Sub-Totals       t csb       -       -       -       -       -       0.001       -       0.004       <math>\pm 0.001</math>       -       .       (c, c)         Sub-Totals       t csb       -       -       -       -       -       0.004       <math>\pm 0.001</math>       .       .       .       .       .       .       .       .       .&lt;</td><td></td><td></td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>. ,</td></t<>	- Limestone       t csb       -       -       -       -       -       -       -       (ee         - Coke       t csb       -       -       -       -       -       -       -       (c, c)         - Anti-Foam       t csb       -       -       -       -       -       -       (c, c)         - Anti-Foam       t csb       -       -       -       -       -       -       (c, c)         - Sulphuric Acid       t csb       -       -       -       -       -       -       (c, c)         Credit:       -       -       -       -       -       -       -       (c, c)         - LimeX       t csb       -       -       -       -       0.001       -0.003 $\pm 0.001$ -       (c, c)         Sub-Totals       t csb       -       -       -       -       -       0.001       -       0.004 $\pm 0.001$ -       .       (c, c)         Sub-Totals       t csb       -       -       -       -       -       0.004 $\pm 0.001$ .       .       .       .       .       .       .       .       .<			-	-	-	-	-	-	. ,
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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<sub>2</sub>O/kg N (Ref. 5), an indirect nitrous oxide requirement of 0.0147 kg N<sub>2</sub>O/kg N (Ref. 7) and a total nitrous oxide requirement for ammonium nitrate of 0.0183 kg N<sub>2</sub>O/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<sub>2</sub>O/ha.a and a total nitrous oxide requirement for potash fertiliser of 9.4 x 10<sup>-6</sup> kg N<sub>2</sub>O/ kg K<sub>2</sub>O (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<sup>-3</sup> kg N<sub>2</sub>O/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<sup>-3</sup> kg N<sub>2</sub>O/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<sup>-3</sup> kg N<sub>2</sub>O/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 N₂O /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<sup>-7</sup> kg N<sub>2</sub>O/MJ, an indirect nitrous oxide requirement of 2.60 x 10<sup>-8</sup> kg N<sub>2</sub>/MJ and a total nitrous oxide requirement of 5.90 x 10<sup>-7</sup> kg N<sub>2</sub>O/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<sup>-7</sup> kg N<sub>2</sub>O/MJ, an indirect nitrous oxide requirement of 2.60 x 10<sup>-8</sup> kg N<sub>2</sub>/MJ and a total nitrous oxide requirement of 5.90 x 10<sup>-7</sup> kg N<sub>2</sub>O/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.
- (I) 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<sub>2</sub>O/t-km, an indirect nitrous oxide requirement of  $2.1 \times 10^{-8} \pm 8 \times 10^{-10}$  kg N<sub>2</sub>O/t-km and a total nitrous oxide requirement of  $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8}$  kg N<sub>2</sub>O/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<sup>-8</sup> kg N<sub>2</sub>O/MJ, an indirect nitrous oxide requirement of 1.1 x 10<sup>-8</sup> kg N<sub>2</sub>O/MJ and a total nitrous oxide requirement of 1.0 x 10<sup>-7</sup> kg N<sub>2</sub>O/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  $1.176 \times 96,480 \times 3.5/26.8 = 14,818 \text{ MJ/hr}$  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 x 10<sup>-7</sup> ± 3.0 x 10<sup>-7</sup> kg N<sub>2</sub>O/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 x 10<sup>-7</sup> kg N<sub>2</sub>O/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  $3.0 \times 10^{-4}$  kg N<sub>2</sub>O/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  $6.0 \times 10^{-9}$  kg N<sub>2</sub>O/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 x  $10^{.9}$  kg N<sub>2</sub>O/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 x 10<sup>-3</sup> ± 2.20 x 10<sup>-4</sup> kg N<sub>2</sub>O/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 x 10<sup>-8</sup> kg N<sub>2</sub>O/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 x 10<sup>-8</sup> kg N<sub>2</sub>O/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<sub>2</sub>) consumption rate of 0.13 kg/t of clean sugar beet and a nitrous oxide requirement of 6.6 x  $10^{-6} \pm 1.8 \times 10^{-6}$  kg N<sub>2</sub>O/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<sub>2</sub>O/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  $6.0 \times 10^{-8}$  kg N<sub>2</sub>O/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 x  $10^{-8}$  kg N<sub>2</sub>O/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  $3.5 \times 10^{-7}$  kg N<sub>2</sub>O/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<sub>2</sub>O/kg and an indirect nitrous oxide requirement of  $1.3 \times 10^{-6}$  kg N<sub>2</sub>O/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 x 10<sup>-8</sup> kg N<sub>2</sub>O/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<sub>2</sub>O/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 x 10<sup>-6</sup> kg N<sub>2</sub>O/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 x 10<sup>-8</sup> kg N<sub>2</sub>O/MJ, an indirect nitrous oxide requirement of 1.0 x 10<sup>-7</sup> kg N<sub>2</sub>O/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<sup>-5</sup> kg N<sub>2</sub>O/kg for lime (Ref. 7).
- (kk) Clean sugar beet requirement of 12.578 t/t of bioethanol and allocation of 85.7% to bioethanol.
- (II) 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  $1.866 \times 10^{-9}$  kg N<sub>2</sub>O/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  $4.6 \times 10^{-7} \pm 1.7 \times 10^{-8}$  kg N<sub>2</sub>O/t-km, an indirect nitrous oxide requirement of  $2.1 \times 10^{-8} \pm 8 \times 10^{-10}$  kg N<sub>2</sub>O/t-km and a total nitrous oxide requirement of  $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8}$  kg N<sub>2</sub>O/t-km (Ref. 11).

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# 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 (Model 4b)

Functional Unit:		with a gas tu			sugar beet us	sing natural g		ned heat and
Final Unit of Measuremer		of bioethanc		proceeding				
Relevant Location:	United	Kingdom						
Relevant Period:	2002	Ŭ						
Allocation Procedures:	1.507 ton with a 809 substitution tonnes of	nes of sugar b % moisture cor on of 0.049 ton thin juice (15%	eet tops (dry r ntent (Ref. 2), nes of stones 6 solids and 8	natter) of £10. substitution of from washing 8% sugar purit	D/t, based on a 0.669 tonnes ( by stones from y) of £16.2/t, d	n average ma of soil from wa n quarrying, ar erived from a	rket price of £2. ashing by soil from effective avera price for thick ju	effective price for .00/t (wet basis) om main sources, age price for 14.560 uice (67% solids
	content) c (Ref. 2), s £529.00/t	of £2.56/t, deriv	ved from an av 0.566 tonnes o n effective prio	verage market of LimeX by ag ce for 0.720 to	price for anima ricultural lime,	al feed pellets and an assum		
Contribution	Per				house Gas	Output (ka e	a CO <sub>2</sub> )	
	Unit	Dir	ect	Ind	rect	To	otal	Notes
		Value	Range	Value	Range	Value	Range	
Cultiv. and Harvesting:		Value	rtango	Value	riango	Value	rtango	
- N Fertiliser	ha.a	119	±40	690	±86	809	±95	(a)
- P Fertiliser		119						. ,
	ha.a	-	-	62	<u>±9</u>	62	±9	(a)
- K Fertiliser	ha.a	-	-	57	±9	57	±9	(a)
- Pesticides	ha.a	-	-	15	<u>±2</u>	15	±2	(a)
- Herbicide	ha.a	-	-	2	-	2	-	(a)
<ul> <li>Insecticide</li> </ul>	ha.a	-	-	1	-	1		(a)
- Seed	ha.a	-	-	8	- ±1	8	_ 1	(a)
- Diesel Fuel	ha.a	610	<i>±</i> 96	76		686		(a)
Reference System:		0.0	<u>~</u> 30		±33	000	±102	(~)
- Diesel Fuel	ha.a	- 63	±10	- 7	±3	- 70	±10	(a)
Sub-Totals	ha.a <b>t be</b>	666 <b>108</b>	<i>±104</i> <b>±17</b>	904 147	<u>+</u> 93	1,570 <b>255</b>	±140	(b)
Transport					±15		±23	
Transport:	1 1	-		0		7		(-)
- Diesel Fuel	t ssb	5	-	2	-	7	-	(a)
	t be	44	-	18	-	62	-	(c)
Washing, Shredding and Diffusion:								
<ul> <li>Natural Gas</li> </ul>	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		-		-		-	1 1
	i CSD	-	-	-	-	-	-	(a)
Credits:								
- Soil	t csb	-	-	-	-	-	-	(a)
- Stones	t csb	-	-	-	-	-	-	(a)
Sub-Totals	t csb	20	±3	2 17	<u>±1</u>	22	±3	(4)
D 10 11	t be	168	±25	17	±8	185	±26	(d)
Purification, Concentration, Fermentation, Distillation and								
Dehydration:	4	40				50		
- 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:	1 000	-	-	_	-	_	-	(a)
- Electricity	tooh	29		- 74		- 45	140	(0)
- LimeX	t csb t csb	- 29	±4 -	- 74 - 8	±11 ±1	- 45 - 8	±12 ±1	(a) (a)
Sub-Totals	t csb	80	±8	- 77	±11	3	±14	. ,
-	t be	862	±86	- 830	±118	32	±146	(e)
Plant Construction						24		
Plant Construction	t be	-	-	24	±4	24	±4	(a)
Plant Construction Plant Maintenance Distribution						24 7 32		

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
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t csb	= tonne of clean sugar beet
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- 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<sub>2</sub>/kg CH<sub>4</sub> and a global warming potential for nitrous oxide of 320 kg eq CO<sub>2</sub>/kg N<sub>2</sub>O.
- (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 dis	tribution deriv	red from sugar	r beet using s	traw-fired c	ombined heat	and power with	a steam turbi	ne durina
	processin	g		eu nom suga	i beet dailig a	aaw-mea e	ombined near	and power with	a steam torbi	ne duning
Final Unit of Measurement:										
Relevant Location:	United King	dom								
Relevant Period:	2002									
Allocation Procedures:	Based on a	market price	for 13.296 ton	nes of sugar	beet on the fa	rm of £22.0	0/t (Ref. 1) ar	nd an effective p	rice for 1.507	tonnes of
:	substitution o stones from c from a price f	f 0.669 tonnes luarrying, an e or thick juice (	s of soil from v effective avera 67% solids ar	washing by so age price for 1 nd 92% sugar	il from main s 4.560 tonnes purity) of £72	ources, sub of thin juice 2.48/t (Ref. 3	ostitution of 0. (15% solids 3), and an effe	sis) with a 80% n 049 tonnes of st and 88% sugar p ctive average p I pellets (15% m	ones from was purity) of £16. rice for 25.996	shing by 2/t, derived 6 tonnes of
								bioethanol of £5, based on the p		
Contribution	Per Unit	Dir		Indi	rect		dstock	Tota		Notes
Cultivation and Llanvaatu		Value	Range	Value	Range	Value	Range	Value	Range	
Cultivation and Harvest:						0 700		4 4 6 6	. 507	( )
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:	na.a	0,070	11,402	970	1400	-	-	9,040	1,477	(0, 1)
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	
Transport:	t be	1,289	±229	967	±130	444	±18	2,700	±263	(k)
Diesel Fuel	t ssb <b>t be</b>	77 684	±3 <b>±27</b>	27 <b>240</b>	±3 <b>±27</b>	-	-	104 <b>924</b>	±4 ±36	(I) (m)
Straw Baling:										()
	ha.a	_	_	830	±332	1 577	+62	2 107	±338	(n)
N Fertiliser		-	-			1,577	±63	2,407		(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	01	211	175	±26	
Maintenance	lid.d	-	-	175	120	-	-	175	120	(c, t)
Sub-Totals	ha.a	343	±51	2,971	±512	1,671	±63	4,985	±518	
Straw Transport:	t be	181	±27	1,567	±270	881	±33	2,629	±273	(u - w)
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	±13	168	±26	523	±42	(u, v, y)
	tbe	120	110	255	121	100	120	525	142	(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, gg) (c, hh)
		-	-	-	-	-	-	-	-	
Foam Oil Credits:	t csb	-	-	-	-	-	-	-	-	(c, ii)
Soil	t csb	-	-	- 4	± 1	-	-	- 4	± 1	(c, jj)
Stones	t csb	-	-	-	-	-	-	- '	-	(c, kk)
				2				0		(3, 14)
Sub-Totals	t csb t be	-	-	- 2 - 17	±1 <b>±8</b>	-	-	- 2 - 17	±1 <b>±8</b>	(II)
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	<u>+2</u>	-	-	13	±2	(c, qq)
Coke	t csb	51	±9	16			_	67		(c, qq) (c, rr)
		51	±9		±5				±10	
Anti-Foam	t csb	-	-	6	±1	-	-	6	±1	(c, ss)
Sulphuric Acid Credit:	t csb	-	-	1	±1	-	-	1	±1	(c, tt)
Electricity LimeX	t csb t csb	- 2,140 -	±321	- - 94	-	-	-	- 2,140 - 94	±321	(c, uu) (c, vv)
		2 000			±14				±14	(3, ••)
Sub-Totals	<i>t csb</i> t be	- 2,089 <b>- 22,518</b>	±32 <i>1</i> <b>±3,461</b>	- 55 <b>- 593</b>	±15 <b>±162</b>	-	-	- 2,144 <b>- 23,110</b>	<i>±</i> 32 <i>1</i> <b>±3,465</b>	(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 <b>t be</b>	66 <b>6</b>	±2	23 2	±3 -	-	-	89 <b>8</b>	±4 -	(ab) (ac)
				- <b>-</b>	-					(40)
Distribution	t be	369	±14	129	±16	-	-	498	±21	(ad)

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<sub>2</sub>O/ha.a assuming 1.205 kg K<sub>2</sub>O/kg K, and a total energy requirement for potash fertiliser of 9.3 MJ/ kg K<sub>2</sub>O (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 £259.00/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.
- (I) 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<sub>2</sub>O<sub>5</sub>/ 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<sub>2</sub>O<sub>5</sub> (Ref. 7).

- (p) Potash fertiliser application rate of 123.8 kg K<sub>2</sub>O/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<sub>2</sub>O (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 ± 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 ± 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  $11 \pm 1$  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).
- (II) 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<sub>2</sub>) 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  $2.4 \pm 2.7$  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).

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## Spreadsheet for Carbon Dioxide Outputs from Bioethanol Production from Sugar Beet using a Straw-fired Combined Heat and Power Plant with a Steam Turbine (Model 8)

	Bioethanol at poir during processin	g	derived from suga	ar beet using nat	ural steam-fired	combined heat a	nd power with a	steam turbine
	tonne of bioetha	nol						
	Inited Kingdom							
Relevant Period: 2	2002							
Allocation Procedures:	Based on a marke	et price for 13.29	6 tonnes of suga	r beet on the far	m of £22.00/t (Re	ef. 1) and an effe	ctive price for 1.5	507 tonnes of
	sugar beet tops ( substitution of 0.	dry matter) of £1 669 tonnes of so	10.0/t, based on a il from washing b	an average mark by soil from main	et price of £2.00, sources, substit	t (wet basis) with ution of 0.049 tor	n a 80% moisture nnes of stones fr	e content (Ref. 2) om washing by
	stones from quar from a price for t							
	pulp (97% moist							
	£72.50/t (Ref. 2),							
	and an effective							
	(Ref. 4).			•	• •	• ·		
Contribution	Per				n Dioxide Output			
	Unit		ect		rect		otal	Notes
		Value	Range	Value	Range	Value	Range	
Cultivation and Harvesting:								
N Fertiliser	ha.a	-	-	196	±28	196	±28	(a)
P Fertiliser K Fertiliser	ha.a	-	-	61 57	±9	61 57	±9	(b, c)
· Pesticides	ha.a ha.a	-	-	14	±9	14	±9	(c, d)
· Herbicide	ha.a	-	-	2	±2	2	±2	(c, e) (c, f)
Insecticide	ha.a	-	_	1	-	1	-	(c, r) (c, g)
Seed	ha.a	-	_	7	-	7	-	(c, g) (c, h)
Diesel Fuel	ha.a	608	±96	72	±1	680	±1	(c, i)
Reference System:					±33		±102	(-, .,
Diesel Fuel	ha.a	- 63	±10	- 7	10	- 70	-10	(c, j)
					±3	-	±10	
Sub-Totals	ha.a	545	±97	403	±45	948	±107	
	t be	88	±16	65	±45 ±7	153	±107 ±17	(k)
Transport:	taab	F		2		7		(1)
Diesel Fuel	t ssb t be	5 44	-	2 18	-	7 62	-	(l) (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)
	ha a	22	10	202	140	0.46	110	
Sub-Totals	ha.a	23 12	±3 <b>±2</b>	223 118	±18 <b>±10</b>	246 130	±19 <b>±10</b>	(··· ··· »
Straw Transport:	t be	12	12	110	±10	130	±ΊŲ	(u - w)
Straw Transport: Diesel Fuel	t bws	4	±1	1	-	5	14	(54)
Diesel Fuel	t be	4	±7 ±2	2	-	9	±1 ±2	(x)
Straw Storage:	l be	1	12	2	-	9	12	(u, v, y)
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)
Nash., 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:	toot							(a ::)
Soil Stones	t csb t csb	-	_	-	_	-	-	(c, jj) (c, kk)
0.01103	1 650	-	-	-	-	-	-	(0, KK)
Sub-Totals	t csb	-	-	-	-	-	-	
Purific Cono Eormant	t be		-	-	-	-	-	(II)
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:		oc :						
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 t be	- 4	-	-	-	- 4	-	(ab) (ac)
Distribution	t be	25	±1	7	±1	32	±1	(ad)
Totals	t be	- 3,221	±517	254	±119	- 2,967	±530	

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 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<sub>2</sub>/kg N (Ref. 6).
- (b) Phosphate fertiliser application rates of 38.0 kg P/ha.a (Ref. 5), or 87.0 kg P<sub>2</sub>O<sub>5</sub>/ ha.a assuming 2.290 kg P<sub>2</sub>O<sub>5</sub>/kg P, and a total carbon requirement for phosphate fertiliser of 0.700 kg CO<sub>2</sub>/kg P<sub>2</sub>O<sub>5</sub> (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<sub>2</sub>O/ha.a assuming 1.205 kg K<sub>2</sub>O/kg K, and a total carbon requirement for potash fertiliser of 0.453 kg CO<sub>2</sub>/ kg K<sub>2</sub>O (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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub> /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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0081 kg CO<sub>2</sub>/MJ and a total carbon requirement of 0.0767 kg CO<sub>2</sub>/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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0081 kg CO<sub>2</sub>/MJ and a total carbon requirement of 0.0767 kg CO<sub>2</sub>/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.
- 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<sub>2</sub>/t-km, an indirect carbon requirement of 0.0161 ± 0.0017 kg CO<sub>2</sub>/tkm and a total carbon requirement of 0.0723 ± 0.0027 kg CO<sub>2</sub>/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<sub>2</sub>/MJ N for ammonium nitrate (Ref. 6).
- (o) Phosphate fertiliser application rate of 24.54 kg P<sub>2</sub>O<sub>5</sub>/ 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<sub>2</sub>O<sub>5</sub> (Ref. 7).

- (p) Potash fertiliser application rate of 123.8 kg K<sub>2</sub>O/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<sub>2</sub>O (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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0081 kg CO<sub>2</sub>/MJ and a total carbon requirement of 0.0767 kg CO<sub>2</sub>/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<sub>2</sub>/ha.a, Hesston baler of 14.4 kg CO<sub>2</sub>/ha.a and telescopic handler for loading in field of 1.9 kg CO<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/ha.a, of Hesston baler of 6.8 kg CO<sub>2</sub>/ha.a and of telescopic handler for loading in the field of 0.65 kg CO<sub>2</sub>/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<sub>2</sub>/MJ, an indirect carbon requirement of 0.0081 kg CO<sub>2</sub>/MJ and a total carbon requirement of 0.0767 kg CO<sub>2</sub>/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<sub>2</sub>/kg for low density polyethylene (Ref. 21).
- (bb) Carbon dioxide output from manufacture of telescopic handler of 1.0 kg CO<sub>2</sub>/t of baled wheat straw (Ref. 21).
- (cc) Carbon dioxide output from maintenance and repair of telescopic handler of 0.3 kg CO<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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  $0.59 \pm 0.04$  kg CO<sub>2</sub>/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<sup>-3</sup> kg CO<sub>2</sub>/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<sup>-3</sup> kg CO<sub>2</sub>/kg for sand (Ref. 18).
- (II) 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<sub>2</sub>) consumption rate of 0.13 kg/t of clean sugar beet and a carbon requirement of  $0.89 \pm 0.24$  kg CO<sub>2</sub>/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  $2.13 \pm 0.64$  kg CO<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/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<sub>2</sub>/kg and an indirect carbon requirement of 0.37 kg CO<sub>2</sub>/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<sub>2</sub>/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  $0.13 \pm 016$  kg CO<sub>2</sub>/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<sub>2</sub>/ 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<sub>2</sub>/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<sub>2</sub> 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<sub>2</sub>/£ (Ref. 14).
- (yy) Carbon dioxide output of 138,485 tonnes of CO<sub>2</sub> 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 strawfired 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<sub>2</sub>/t-km, an indirect carbon requirement of 0.0161 ± 0.0017 kg CO<sub>2</sub>/t-km and a total carbon requirement of 0.0723 ± 0.0027 kg CO<sub>2</sub>/tkm (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<sub>2</sub>/t-km, an indirect carbon requirement of 0.0161 ± 0.0017 kg CO<sub>2</sub>/tkm and a total carbon requirement of 0.0723 ± 0.0027 kg CO<sub>2</sub>/t-km (Ref. 11).

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## Spreadsheet for Methane Outputs from Bioethanol Production from Sugar Beet using <u>a Straw-fired Combined Heat and Power Plant with a Steam Turbine</u> (Model 8)

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t csb t csb t be t csb	-	-	-			-	(c, kk) (II) (c, mm)
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t csb	-	-	-	-	-	-	(c, ii)
	-	-	-	-	-	-	(c, gg) (c, hh)
t csb	-	-	-	-	-	-	(c, ff)
t csb	-	-	-	-	-	-	(c, ee)
t csb	-	-	-	-	-	-	(c, dd)
t be	•	-	0.002	-	0.002	-	(u, v, y)
t bws	-	-	0.001	-	0.001	-	
t bws	-	-	-	-	-	-	(C, DD) (C, CC)
	-	-	-	-	-	-	(c, aa) (c, bb)
t bws	-	-	0.001	-	0.001	-	(c, z)
t be	-	-	0.002	-	0.002	-	(u, v, y)
t bws	-	-	0.001	-	0.001	-	(x)
ha.a <b>t be</b>	-	-	0.224 <b>0.118</b>	±0.036 ±0.019	0.224 <b>0.118</b>	±0.036 ±0.019	(u - w)
	-	-		-		-	(c, t)
	-	-	-	-	-	-	(c, s)
ha.a	-	-	-	-	-	-	(c, r)
ha.a	-	-	0.007	-	0.007	-	(c, q)
ha.a	-	-	0.001	-	0.001	-	(c, o) (c, p)
	-	-					(n)
t ssb t be	-	-	0.002 <b>0.018</b>	-	0.002 <b>0.018</b>	-	(l) (m)
100	0.001	±0.001	0.068	±0.011	0.089	±0.011	(k)
ha.a	0.004	±0.005	0.547	±0.068	0.551	±0.068	(1-)
ha.a	- 0.001	±0.001	- 0.019	±0.003	- 0.020	±0.003	(c, j)
ha.a	0.005	±0.005	0.181	±0.027	0.186	±0.028	(c, i)
ha.a	-	-	0.008	±0.001	0.008	±0.001	(c, h)
ha.a	-	-	-	-	-	-	(c, r) (c, g)
	-	-		-		-	(c, e) (c, f)
ha.a	-	-	0.003	-	0.003	-	(c, d)
ha.a	-	-	0.371	±0.062 -	0.371	±0.002 -	(a) (b, c)
he e							(c)
Unit							Notes
(Ref. 4). Per			Ме	thane Output (ko	CH <sub>4</sub> )		
stones from quar from a price for t pulp (97% moisti £72.50/t (Ref. 2) and an effective	rying, an effectiv hick juice (67% s ure content) of £ substitution of 0	ve average price solids and 92% su 2.56/t, derived fro 0.566 tonnes of L	for 14.560 tonne: ugar purity) of £7 om an average m imeX by agricultu	s of thin juice (15 2.48/t (Ref. 3), a arket price for ar ural lime, and an	% solids and 88 nd an effective a nimal feed pellets assumed price f	% sugar purity) of verage price for a solution of the second seco	of £16.2/t, derive 25.996 tonnes o content) of 2529.00/t (Ref. 3
2002					( <b>1</b> ) and an affect		507
United Kingdom							
	nol						
	processing t tonne of bioetha Jinted Kingdom 2002 Based on a marke sugar beet tops ( substitution of 0. stones from quar from a price for ti pulp (97% moisti £72.50/t (Ref. 2), and an effective (Ref. 4). Per Unit ha.a	processing           1 tonne of bioethanol           Jnited Kingdom           2002           Based on a market price for 13.29(           sugar beet tops (dry matter) of £'           substitution of 0.668 tonnes of sc           store for mick juice (67% sc           pulp (97% moisture content) of £           £72.50/t (Ref. 2), substitution of 0           and an effective price for 0.720 tr           (Ref. 4).           Value           ha.a           ft be           tha.a           ha.a           ha.a           ha.a           ha.a           ha.a           tbe     <	processing	Ionne of bioethanol           Jnited Kingdom           2002           Based on a market price for 13.296 tonnes of sugar beet on the farm sugar beet tops (dry matter) of £10.0t, based on an average marks substitution of 0.669 tonnes of solids and 92% sugar purity) of £7           pulp (97% moisture content) of £2.56/t, derived from an average from a price for thick juice (67% solids and 92% sugar purity) of £7           Per         Me           Unit         Direct           Per         Me           Unit         Direct           Na.a         -           ha.a         0.005           ha.a         0.005           ha.a         0.004           ±0.005         0.547           ha.a         -           ha.a         -           ha.a         -           ha.a         -	processing         0         0           1 tonne of bioethanol	processing	processing         0         0         0           Intere of bioethanol

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 x 10<sup>-3</sup> ± 0.6 x 10<sup>-3</sup> kg CH₄/kg N (Ref. 6).
- (b) Phosphate fertiliser application rates of 38.0 kg P/ha.a (Ref. 5), or 87.0 kg P<sub>2</sub>O<sub>5</sub>/ ha.a assuming 2.290 kg P<sub>2</sub>O<sub>5</sub>/kg P, and a total methane requirement for phosphate fertiliser of 2.3 x 10<sup>5</sup> kg CH<sub>4</sub>/kg P<sub>2</sub>O<sub>5</sub> (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<sub>2</sub>O/ha.a assuming 1.205 kg K<sub>2</sub>O/kg K, and a total methane requirement for potash fertiliser of 2.1 x 10<sup>5</sup> kg CH<sub>4</sub>/ kg K<sub>2</sub>O (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  $1.8 \times 10^{-4}$  kg CH<sub>4</sub>/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  $1.8 \times 10^{-4}$  kg CH<sub>4</sub>/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 x 10<sup>-4</sup> kg CH<sub>4</sub>/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<sub>4</sub> /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 x 10<sup>-7</sup> kg CH<sub>4</sub>/MJ, an indirect methane requirement of 2.04 x 10<sup>-5</sup> kg CH<sub>4</sub>/MJ and a total methane requirement of 2.1 x 10<sup>-5</sup> kg CH<sub>4</sub>/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 x 10<sup>-7</sup> kg CH<sub>4</sub>/MJ, an indirect methane requirement of 2.04 x 10<sup>-5</sup> kg CH<sub>4</sub>/MJ and a total methane requirement of 2.1 x 10<sup>-5</sup> kg CH<sub>4</sub>/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.
- (I) 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<sub>4</sub>/t-km, an indirect methane requirement of  $1.672 \times 10^{-5} \pm 6.3 \times 10^{-7}$  kg CH<sub>4</sub>/t-km and a total methane requirement of  $1.721 \times 10^{-5} \pm 6.5 \times 10^{-7}$  kg CH<sub>4</sub>/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 x 10<sup>-3</sup> ± 0.6 x 10<sup>-3</sup> kg CH<sub>4</sub>/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 x 10<sup>-5</sup> kg CH<sub>4</sub>/kg P<sub>2</sub>O<sub>5</sub> (Ref. 7).

- (p) Potash fertiliser application rate of 123.8 kg K<sub>2</sub>O/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<sup>-5</sup> kg CH<sub>4</sub>/ kg K<sub>2</sub>O (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<sup>-7</sup> kg CH<sub>4</sub>/ MJ, an indirect methane requirement of 2.04 x 10<sup>-5</sup> kg CH<sub>4</sub>/ MJ and a total methane requirement of 2.1 x 10<sup>-5</sup> kg CH<sub>4</sub>/ 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  $1.192 \times 10^{-7}$  kg CH<sub>4</sub>/ 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<sup>-7</sup> kg CH₄/ 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<sup>-7</sup> kg CH<sub>4</sub>/ MJ primary energy input to manufacturing (Ref. 16).
- Straw-fired combined heat and power plant based on a steam turbine with an overall efficiency of 85% and (u) 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  $4.900 \times 10^{-7} \pm 2.000 \times 10^{-8}$  kg CH<sub>4</sub>/t-km, an indirect methane requirement of  $1.672 \times 10^{-5} \pm 6.3 \times 10^{-7}$  kg CH<sub>4</sub>/t-km and a total methane requirement of  $1.721 \times 10^{-5} \pm 6.5 \times 10^{-7}$  kg CH<sub>4</sub>/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  $6.0 \times 10^{-7}$  kg CH<sub>4</sub>/ MJ, an indirect methane requirement of  $2.04 \times 10^{-5}$  kg CH<sub>4</sub>/ MJ and a total methane requirement of  $2.1 \times 10^{-5}$  kg CH<sub>4</sub>/ 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<sup>-7</sup> kg CH<sub>4</sub>/ 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<sup>-7</sup> kg CH₄/ 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<sup>-7</sup> kg CH<sub>4</sub>/ 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  $2.7 \times 10^{-4} \pm 3.0 \times 10^{-4}$  kg CH<sub>4</sub>/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  $2.1 \times 10^{-5}$  kg CH<sub>4</sub>/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  $0.01 \pm 0.001$  kg CH<sub>4</sub>/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  $\times 10^{-7}$  kg CH<sub>4</sub>/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  $3.0 \times 10^{-7}$  kg CH<sub>4</sub>/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  $7.7 \times 10^{-4} \pm 7.0 \times 10^{-5}$  kg CH<sub>4</sub>/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<sup>-6</sup> kg CH<sub>4</sub>/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<sup>6</sup> kg CH₄/kg for sand (Ref. 18).
- (II) 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<sub>2</sub>) 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<sub>4</sub>/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  $7.2 \times 10^{-4} \pm 2.0 \times 10^{-5}$  kg CH<sub>4</sub>/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<sub>4</sub>/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  $1.0 \times 10^{-6}$  kg CH<sub>4</sub>/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<sup>-5</sup> kg CH₄/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  $9.5 \times 10^{-6} \times 28.1 = 2.7 \times 10^{-4}$  kg CH<sub>4</sub>/kg and an indirect methane requirement of  $9.2 \times 10^{-3}$  kg CH<sub>4</sub>/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  $4.0 \times 10^{-6}$  kg CH<sub>4</sub>/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  $2.7 \times 10^{-4} \pm 3.0 \times 10^{-4}$  kg CH<sub>4</sub>/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<sup>-4</sup> kg CH<sub>4</sub>/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<sup>-6</sup> kg CH₄/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<sub>4</sub>/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  $(25\% \times 66.8\%)$ +  $(75\% \times 85.7\%) = 81\%$ .

- (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  $1.192 \times 10^{-7}$  kg CH<sub>4</sub>/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 x 10<sup>-7</sup> kg CH<sub>4</sub>/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<sub>4</sub>/t-km, an indirect methane requirement of  $1.672 \times 10^{-5} \pm 6.3 \times 10^{-7}$  kg CH<sub>4</sub>/t-km and a total methane requirement of  $1.721 \times 10^{-5} \pm 6.5 \times 10^{-7}$  kg CH<sub>4</sub>/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<sub>4</sub>/t-km, an indirect methane requirement of  $1.672 \times 10^{-5} \pm 6.3 \times 10^{-7}$  kg CH<sub>4</sub>/t-km and a total methane requirement of  $1.721 \times 10^{-5} \pm 6.5 \times 10^{-7}$  kg CH<sub>4</sub>/t-km (Ref. 12).

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## 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)

		f distribution d	lerived from sug	ar beet using nat	ural gas-fired co	mbined heat and	power with a ga	s turbine during
Final Unit of Measurement: 1 tonne	ssing of bioethanol							
	Kingdom							
Relevant Period: 2002	anguom							
	on a market pr	ice for 13.296	tonnes of suga	beet on the farm	n of £22.00/t (Re	f. 1) and an effect	ctive price for 1.5	07 tonnes of
sugar substi stone from a pulp ( £72.5 and a	beet tops (dry tution of 0.669 s from quarryin price for thick 97% moisture 0/t (Ref. 2), su n effective price	matter) of £1 tonnes of soing, an effective cjuice (67% si content) of £2 bstitution of 0	0.0/t, based on a il from washing b e average price olids and 92% s 2.56/t, derived fro .566 tonnes of L	an average mark by soil from main for 14.560 tonne ugar purity) of £7 om an average m imeX by agricult	et price of £2.00/ sources, substit s of thin juice (15 72.48/t (Ref. 3), a narket price for a ural lime, and an	It (wet basis) with ution of 0.049 to 5% solids and 88 and an effective a nimal feed pellet assumed price f	n a 80% moisture nnes of stones fro % sugar purity) o average price for s (15% moisture for bioethanol of f	e content (Ref. 2) om washing by of £16.2/t, derived 25.996 tonnes of
(Ref	4). Per			Nitr	ous Oxide Outpu	ut (ka N₂O)		
Contribution	Unit	D	irect		irect		otal	Notes
		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 Reference System:	ha.a	0.005	±0.001	-	-	0.005	±0.001	(c, i)
- Diesel Fuel	ha.a	- 0.001	-	-	-	- 0.001	-	(c, j)
Sub-Totals	ha.a	0.375	10.105	1.528		1.903		
	t be	0.375 0.061	±0.125 ±0.020	0.248	±0.253 ±0.041	0.309	±0.283 ±0.046	(k)
Transport:								
- Diesel Fuel	t ssb t be	-	-	-	-	-	-	(l) (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 <b>t be</b>	0.213 <b>0.112</b>	±0.033 ±0.017	0.872 <b>0.460</b>	±0.125 ±0.066	1.085 <b>0.572</b>	±0.135 ±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 - Machinery	t bws t bws	-	-	-	-	-	-	(c, aa)
- Maintenance	t bws	-	-	-	-	-	-	(c, bb) (c, cc)
- Maintenance	1.0003	-	-	-	-	-	-	(0, 00)
Sub-Totals	t bws	-	-	-	-	-	-	
	t be	-	-	-	-	-	-	(u, v, y)
Washing, Shredding and Diffusion:								(2, 1, ))
- 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	-	-	-	-	-	-	705
Purific., Conc., Fermentation,	t be	-	-	-	-	-	-	(II)
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 - Coke	t csb	-	-	-	-	-	-	(c, qq)
- Соке - Anti-Foam	t csb t csb			-				(c, rr) (c, ss)
- Anti-Foam - Sulphuric Acid	t csb		_	-	_	_	_	(c, ss)
Credit:	1 650	-	-	-	-	-	-	(c, tt)
- 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	
Direct Environi	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 Plant Maintenance	t be t be	-	-	-	-	-	-	(yy - zz) (yy - ab)
Ash Disposal	t ash	-	-		-	-	-	(yy - ab) (ac)
	t be	-	-	-	-	-	-	(ad)
			1		-	-	-	(22)
Distribution Totals	t be t be	- 0.171	- ±0.039	- 0.697	- ±0.078	0.868	±0.087	(ae)

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<sub>2</sub>O/kg N (Ref. 5), an indirect nitrous oxide requirement of 0.0147 kg N<sub>2</sub>O/kg N (Ref. 7) and a total nitrous oxide requirement for ammonium nitrate of 0.0183 kg N<sub>2</sub>O/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<sub>2</sub>O/ha.a and a total nitrous oxide requirement for potash fertiliser of 9.4 x 10<sup>6</sup> kg N<sub>2</sub>O/ kg K<sub>2</sub>O (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  $1.51 \times 10^{-3}$  kg N<sub>2</sub>O/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  $1.51 \times 10^{-3}$  kg N<sub>2</sub>O/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<sup>-3</sup> kg N<sub>2</sub>O/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<sub>2</sub>O /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<sup>-7</sup> kg N<sub>2</sub>O/MJ, an indirect nitrous oxide requirement of 2.60 x 10<sup>-8</sup> kg N<sub>2</sub>/MJ and a total nitrous oxide requirement of 5.90 x 10<sup>-7</sup> kg N<sub>2</sub>O/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<sup>-7</sup> kg N<sub>2</sub>O/MJ, an indirect nitrous oxide requirement of 2.60 x 10<sup>-8</sup> kg N<sub>2</sub>/MJ and a total nitrous oxide requirement of 5.90 x 10<sup>-7</sup> kg N<sub>2</sub>O/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.
- (I) Average round trip distance of 94 km (Ref. 2) by bulk road carrier transport with a direct nitrous oxide requirement of  $4.6 \times 10^{-7} \pm 1.7 \times 10^{-8} \text{ kg N}_2\text{O}/\text{t-km}$ , an indirect nitrous oxide requirement of  $2.1 \times 10^{-8} \pm 8 \times 10^{-10} \text{ kg N}_2\text{O}/\text{t-km}$  and a total nitrous oxide requirement of  $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8} \text{ kg N}_2\text{O}/\text{t-km}$  (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<sub>2</sub>O/kg N (Ref. 5), an indirect nitrous oxide requirement of 0.0147 kg N<sub>2</sub>O/kg N (Ref. 6) and a total nitrous oxide requirement for ammonium nitrate of 0.0183 kg N<sub>2</sub>O/kg N (Ref. 6).
- (o) Phosphate fertiliser application rate of 24.54 kg P<sub>2</sub>O<sub>5</sub>/ 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<sub>2</sub>O/kg P<sub>2</sub>O<sub>5</sub> (Ref. 7).

- (p) Potash fertiliser application rate of 123.8 kg K<sub>2</sub>O/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<sup>-6</sup> kg N<sub>2</sub>O/ kg K<sub>2</sub>O (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<sup>-7</sup> kg N<sub>2</sub>O/MJ, an indirect nitrous oxide requirement of 2.60 x 10<sup>-8</sup> kg N<sub>2</sub>O/MJ and a total nitrous oxide requirement of 5.90 x 10<sup>-7</sup> kg N<sub>2</sub>O/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<sup>-9</sup> kg N<sub>2</sub>O/ 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<sup>-9</sup> kg N₂O/ 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<sup>-9</sup> kg N<sub>2</sub>O/ MJ primary energy input to manufacturing (Ref. 18).
- Straw-fired combined heat and power plant based on a steam turbine with an overall efficiency of 85% and (u) 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  $4.6 \times 10^{-7} \pm 1.7 \times 10^{-8}$  kg N<sub>2</sub>O/t-km, an indirect nitrous oxide requirement of  $2.1 \times 10^{-8} \pm 8 \times 10^{-10}$  kg N<sub>2</sub>O/t-km and a total nitrous oxide requirement of  $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8}$  kg N<sub>2</sub>O/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  $5.64 \times 10^{-7}$  kg N<sub>2</sub>O/MJ, an indirect nitrous oxide requirement of  $2.60 \times 10^{-8}$  kg N<sub>2</sub>O/MJ and a total nitrous oxide requirement of  $5.90 \times 10^{-7}$  kg N<sub>2</sub>O/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<sup>-9</sup> kg N<sub>2</sub>O/ 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<sup>-9</sup> kg N<sub>2</sub>O/ 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<sup>-9</sup> kg N<sub>2</sub>O/ 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<sup>-7</sup> ± 3.0 x 10<sup>-7</sup> kg N₂O/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  $5.9 \times 10^{-7}$  kg N<sub>2</sub>O/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<sup>-4</sup> kg N<sub>2</sub>O/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  $6.0 \times 10^{-9}$  kg N<sub>2</sub>O/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<sub>2</sub>O/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  $1.79 \times 10^{-3} \pm 2.20 \times 10^{-4}$  kg N<sub>2</sub>O/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<sup>-8</sup> kg N<sub>2</sub>O/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<sup>-8</sup> kg N<sub>2</sub>O/kg for sand (Ref. 18).
- (II) 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<sub>2</sub>) consumption rate of 0.13 kg/t of clean sugar beet and a nitrous oxide requirement of 6.6 x  $10^{-6} \pm 1.8 \times 10^{-6}$  kg N<sub>2</sub>O/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  $1.8 \times 10^{-5} \pm 0.5 \times 10^{-6}$  kg N<sub>2</sub>O/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  $6.0 \times 10^{-8}$  kg N<sub>2</sub>O/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<sub>2</sub>O/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  $3.5 \times 10^{-7}$  kg N<sub>2</sub>O/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  $4.0 \times 10^{-9} \times 28.1 = 1.1 \times 10^{-7}$  kg N<sub>2</sub>O/kg and an indirect nitrous oxide requirement of  $1.3 \times 10^{-6}$  kg N<sub>2</sub>O/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<sup>-8</sup> kg N<sub>2</sub>O/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  $2.0 \times 10^{-7} \pm 3.0 \times 10^{-7}$  kg N<sub>2</sub>O/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<sup>-6</sup> kg N<sub>2</sub>O/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<sup>-5</sup> kg N<sub>2</sub>O/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<sub>2</sub>O/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 x 10<sup>-9</sup> kg N<sub>2</sub>O/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 x 10<sup>.9</sup> kg N<sub>2</sub>O/MJ primary energy input to construction (Ref. 16), assuming 85.7% contribution to bioethanol by price of coproducts.
- (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<sub>2</sub>O/t-km, an indirect nitrous oxide requirement of  $2.1 \times 10^{-8} \pm 8 \times 10^{-10}$  kg N<sub>2</sub>O/t-km and a total methane requirement of  $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8}$  kg N<sub>2</sub>O/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<sub>2</sub>O/t-km, an indirect nitrous oxide requirement of  $2.1 \times 10^{-8} \pm 8 \times 10^{-10}$  kg N<sub>2</sub>O/t-km and a total nitrous oxide requirement of  $4.8 \times 10^{-7} \pm 1.8 \times 10^{-8}$  kg N<sub>2</sub>O/t-km (Ref. 11).

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- 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"
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## 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:			n derived from su	ugar beet using s	traw-fired combin	ned heat and pov	wer with a steam	turbine during
First Halt of Managements	process							
Final Unit of Measurement: Relevant Location:	1 tonne of bioeth United Kingdom	idi iUl						
Relevant Period:	2002		00 1					507 1
Allocation Procedures:	sugar beet to 2), substitutio washing by si £16.2/t, derive for 25.996 tor moisture cont bioethanol of	ps (dry matter) o n of 0.669 tonne tones from quarr ed from a price fo nes of pulp (979 ent) of £72.50/t	f £10.0/t, based s of soil from wa ying, an effective or thick juice (67 % moisture conte (Ref. 2), substitu 3) and an effectiv	on an average m shing by soil fror average price f % solids and 92 <sup>6</sup> ent) of £2.56/t, de tion of 0.566 ton /e price for 0.720	n main sources,	.00/t (wet basis) substitution of 0. of thin juice (159 f £72.48/t (Ref. 3 erage market pri agricultural lime,	with a 80% mois 049 tonnes of sto % solids and 88% ), and an effectiv ce for animal fee and an assumed	ture content (Ref. ones from 6 sugar purity) of re average price d pellets (15% d price for
Contribution	Per		· · · J· · · ( ·		nhouse Gas Outp	out (ka ea CO <sub>2</sub> )		
Contribution	Unit	Dir	ect		irect		otal	Notes
	•••••	Value	Range	Value	Range	Value	Range	110100
Cultivation and Harvesting:		Value	runge	Value	rtange	Value	rtange	
- N Fertiliser	ha.a	119	±40	690	±86	809	±95	(a)
- P Fertiliser	ha.a	-	-	62	00 	62	±9	(a)
- K Fertiliser	ha.a	-	-	57	0 ±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:	L			-				1-1
- Diesel Fuel	ha.a	- 63	±10	- 7	±3	- 70	±10	(a)
Sub Totolo	ha -	660		004		4 570		
Sub-Totals	ha.a	666 <b>108</b>	±104	904 147	±93	1,570 <b>255</b>	±140	(b)
	t be	100	±17	147	±15	200	±23	(0)
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)
Cub Totala	40.0	00		507	146	500	1.47	
Sub-Totals	ha.a t be	89 <b>47</b>	±11 <b>±6</b>	507 <b>267</b>	±46 <b>±24</b>	596 <b>314</b>	±47 ±25	(4)
Straw Transport:	r be	4/	10	207	124	314	125	(d)
- Diesel Fuel	t bws	4	-	1	-	5		(0)
- Dieser Fuer	t be	4 7	-	2	-	9	-	(a) (d)
Straw Storage:	l De	1	-	2	-	3	-	(u)
- 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	:			ĺ				
- 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:	tooh							(0)
- Soil - Stones	t csb t csb	-	-					(a) (a)
- 0101163	1 650	-	-	-	-	-	-	(a)
Sub-Totals	t csb	-	-	-	-	-	-	
	t be	-	-	-	-	-	-	(e)
Purific., Conc., Fermentation				İ	1			(0)
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)
		-	-	-	-	-	-	(a)
- Sulphuric Acid	t csb			1		- 346	±48	(a)
- Sulphuric Acid Credit:		0.40	+40					
- Sulphuric Acid Credit: - Electricity	t csb	- 346	±48	-	-			
- Sulphuric Acid Credit:		- 346 -	±48 -	- - 8	- ±1	- 8	±1	(a)
- Sulphuric Acid Credit: - Electricity - LimeX	t csb t csb	-	-			- 8	±1	
- Sulphuric Acid Credit: - Electricity	t csb t csb t csb	- - 341	- ±48	- 7	±1	- 8 - 348	±1 ±48	(a)
- Sulphuric Acid Credit: - Electricity - LimeX Sub-Totals	t csb t csb	- - 341 <b>- 3,676</b>	- ±48 <b>±517</b>	- 7 - 75	±1 <b>±11</b>	- 8 - 348 <b>- 3,751</b>	±1 ±48 <b>±517</b>	(a) (f)
- Sulphuric Acid Credit: - Electricity - LimeX Sub-Totals Direct Emissions	t csb t csb t csb t be	- - 341 <b>- 3,676</b> 41	- ±48 ±517 ±6	- 7 - 75 -	±1 ±11 -	- 8 - 348 <b>- 3,751</b> 41	±1 ±48 ±517 ±6	(a) (f) (f)
- Sulphuric Acid Credit: - Electricity - LimeX Sub-Totals Direct Emissions Plant Construction	t csb t csb t csb t be t be	- - 341 - 3,676 41 -	- ±48 ±517 ±6 -	- 7 - 75 - 69	±1 ±11 - ±8	- 8 - 348 - 3,751 41 69	±1 ±48 ±517 ±6 ±8	(a) (f) (f) (a)
- Sulphuric Acid Credit: - Electricity - LimeX Sub-Totals Direct Emissions Plant Construction Plant Maintenance	t csb t csb t csb t be t be t be	- - 341 - 3,676 41 - -	- ±48 ±517 ±6 -	- 7 - 75 - 69 24	±1 ±11 - ±8 ±3	- 8 - 348 - 3,751 41 69 24	±1 ±48 ±517 ±6 ±8 ±3	(a) (f) (f) (a) (a)
- Sulphuric Acid Credit: - Electricity - LimeX Sub-Totals Direct Emissions Plant Construction	t csb t csb t csb t be t be t ash	- - 341 - 3,676 41 -	- ±48 ±517 ±6 -	- 7 - 75 - 69	±1 ±11 - ±8 ±3 -	- 8 - 348 - 3,751 41 69	±1 ±48 ±517 ±6 ±8 ±3 -	(a) (f) (a) (a) (a)
- Sulphuric Acid Credit: - Electricity - LimeX Sub-Totals Direct Emissions Plant Construction Plant Maintenance	t csb t csb t csb t be t be t be	- - 341 - 3,676 41 - -	- ±48 ±517 ±6 -	- 7 - 75 - 69 24	±1 ±11 - ±8 ±3	- 8 - 348 - 3,751 41 69 24	±1 ±48 ±517 ±6 ±8 ±3	(a) (f) (f) (a) (a)

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
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t csb	= te	onne	of	clean	sugar	bee
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- 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<sub>2</sub>/kg CH<sub>4</sub> and a global warming potential for nitrous oxide of 320 kg eq CO<sub>2</sub>/kg N<sub>2</sub>O.
- (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.