Well-to-Wheel Evaluation for Production of Ethanol from Wheat

A Report by the LowCVP Fuels Working Group, WTW Sub-Group

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EXECUTIVE SUMMARY

1. This Report records the findings of the 'Well to Wheel sub-group' for the 'Fuels Working Group' of the 'Low Carbon Vehicle Partnership'. The brief of the group was to reach consensus on the energy and greenhouse gas balances for conventional UK biofuels. 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. Because of differences between the existing studies, the Low Carbon Vehicle Partnership asked for a sound and transparent scientific basis for their recommendations to policy makers. This is the aim of this study.

2. Rather than reconcile differences between existing reports, the working group has pooled its extensive knowledge and experience to prepare a new well-to-wheel evaluation, based on the elements within the existing studies, but adding new insights where needed. This study describes the energy and greenhouse gas emissions associated with producing bioethanol from wheat, using technology currently feasible for the UK. Bioethanol from wheat was chosen to simplify the extensive workload and because previous work has shown large variations for this particular biofuel.

3. The basic pathway describes standard processes including wheat farming and ethanol production via hydrolysis and fermentation. There are three main factors that can have a profound impact on the outcome of the pathway:
   - The heat & power generation scheme used in the ethanol plant.
   - The fate of straw: ploughed back into the field or use as fuel for the ethanol plant.
   - The fate of DDGS[1]: used as an animal feed or energy source.

4. For the ethanol plant heat & power scheme, three basic Models are examined together with various sub-options. All of these Models are technically realistic but with no bioethanol production existing within the UK the question of commercial viability remains unanswered.
   - **Model a** utilises a natural gas-fired boiler and "imported" grid electricity (no Combined Heat & Power –CHP).
   - **Models b** explores adding CHP capability to this basic configuration. Model b1 adds a steam turbine, while **Model b21** replaces the boiler with a gas turbine and steam recovery from the exhaust gases. **Model b22** further extends the efficiency by adding supplementary natural gas firing to the steam generator.
   - Finally **Models c1 and c2** utilise a straw-fired CHP plant with a steam turbine with/without condensing turbine respectively.

   All these scenarios except **Model a**, generate surplus electricity for export to the grid. In each case it is assumed that the bioethanol is blended with gasoline at <5% volume, and that the wheat is grown on rotational set-aside land.

Straw	Heat & Power Generation
Ploughed in	a Conventional NG boiler
..	b1 Conventional NG boiler + CHP (steam turbine)
..	b21 NG gas turbine + steam generator + CHP (steam turbine)
..	b22 NG gas turbine + fired steam generator + CHP
Used as fuel	c1 Straw boiler + CHP (steam turbine)
..	c2 Straw boiler + CHP (steam turbine + condensing turbine)

5. The group reached consensus on the input data for all of the Models. To achieve transparency, the data have been fully explained in the tables of this report. Farming inputs are well established with the exception of field N_2O emissions, where new data from JRC

[1] Distillers' Dark Grains with Solubles: the residue of grain fermentation after separation of the alcohol

have been used. New data were also included on the ethanol production process, both to clarify the basic energy needs of the process, and determine realistic efficiencies for producing the energy. The group also agreed on a consensus approach to by-product credits.

6. Most of the scenarios considered here have two by-products: electricity exported to the United Kingdom (UK) grid and Distillers' Dark Grains and Solubles (DDGS). These by-products are a significant feature of modern integrated manufacturing (bio-refineries) and fundamentally affect the outcome of the assessment, so need to be given credits to complete the assessment. All of the Working Group agreed that 'substitution' is the preferred methodology where data on the product to be substituted exist, and this method has been used here. For electricity, it was assumed that the electricity export substitutes electricity from the UK mix, thereby achieving a credit for avoiding power generation elsewhere in the UK. DDGS can also be used as energy in heat & power generation (biomass co-firing in coal fired power stations), however its most usual application at present is as animal feed. Here, the calculation of credits is more complex. It is generally assumed that DDGS will substitute maize or soya products, perhaps from the USA. The complexity of the substitution chain and its sensitivity to economic factors mean that there is some uncertainty in the estimates. DDGS credits for use both as animal feed and as an energy source have been calculated.

7. To show the potential savings, the energy use and GHG emissions for each model have been compared with the Well-to-Tank (WTT) energy and GHG emissions for gasoline.

8. The results show that all the bioethanol Models give lower WTT greenhouse gas emissions when compared with gasoline, but that the process models and how the by-products are used strongly affect the results. We have divided the total greenhouse benefit only by the GJ ethanol produced, although it can be argued that the benefit should be apportioned between all 3 products: ethanol, DDGS and electricity. The main results and indicators are summarised in the table below.

Model		a NG boiler + grid	b1 NG boiler + steam turbine	b21 NG GT+ steam gen+ steam turbine	b22 NG GT+ co-fired steam gen+ steam turbine	c1 Straw boiler + steam turbine	c2 Straw boiler + steam turbine + condensing turbine	Gasoline
Fossil energy balance	GJf/GJ road fuel							
Gross		1.02	0.95	1.46	1.11	0.45	0.45	1.14
Net of credits								
DDGS as animal feed		0.90	0.67	0.30	0.41	0.10	0.03	
DDGS as energy		0.24	0.01	-0.36	-0.25	-0.56	-0.63	
GHG emissions	kg CO2eq/GJ road fuel							
Gross		94.7	91.9	121.2	100.6	75.7	75.7	85.8
Net of credits								
DDGS as animal feed		79.5	68.1	51.4	55.4	48.0	44.7	
DDGS as energy		54.3	43.0	26.3	30.3	22.9	19.6	
GHG avoided	kg CO2eq/GJ road fuel							
DDGS as animal feed		6.4	17.7	34.4	30.4	37.8	41.1	
DDGS as energy		31.5	42.9	59.5	55.5	63.0	66.3	
Cost parameters (DDGS as animal feed)								
Cost relative to b1		1.03	1.00	0.91	1.00	1.32	1.36	
Relative cost of GHG avoided		2.87	1.00	0.47	0.58	0.61	0.58	

Not surprisingly the worst performance is displayed by Model a which, without a CHP configuration can now be considered as outdated industrial practice, and is unlikely to be selected for new plants. The other models give better energy/GHG results principally because they export electricity efficiently produced by CHP, replacing grid electricity. The best performance is demonstrated by Model c2 which shows the combined benefits of CHP and fuelling the bioethanol production with straw. Displacing additional UK electricity with renewable electricity from DDGS offers a large additional benefit. The most likely commercial option in the short term is Model b21 or b22 which employs a natural gas fired gas turbine combined with CHP, and DDGS as animal feed. Which option may be the most financially attractive will depend on the values of marginal electricity and fuel.

9. All of the Models considered generate net fossil energy savings. The worst performing scenario (Model a) uses 0.9GJ of fossil fuel to produce 1 GJ of bioethanol. Some Models actually save more fossil energy than is contained in the produced ethanol as a result of the large energy saving attached to electricity production. The GHG savings follow a similar pattern, but are reduced because of the GHG emissions in farming, principally the N_2O emissions.

10. In reaching the above conclusions the study has highlighted the significance of several key factors: Firstly, by-product use and the associated credits are essential to the environmental performance of the bioethanol facility. This is not surprising for an integrated bio-refinery, which produces both electricity and liquid biofuel. The CHP scheme selected and the use to which the DDGS is put are very important. Finally, because the production of bioethanol is energy-intensive, the use of renewable fuel (straw) to power the ethanol facility would be a very positive step if economically feasible.

11. An analysis was conducted on cost to assess the relative ranking of the scenario's with regard to 'cost of reducing GHG emissions'. The data presented follow a simplified economic model, and are not meant to be used for financial decisions. The cost of CO_2 avoided appears to be lowest for Model b21. Use of DDGS as fuel generates higher energy and GHG savings, but delivers less economic return than use as animal feed. It may not be commercially viable to invest in the enhanced carbon savings unless more value can be gained from the additional environmental benefit. This aspect, including the cost of GHG reduction relative to other measures in the transport sector or other sectors, requires further study and is beyond the remit of this report.

12. This study highlights that the way in which fuels are produced has a significant impact on energy balance, GHG emissions and costs. Regulators should consider fuel production processes as well as final fuel properties when deciding policy for future fuels. In particular
    - Incorporation of CHP into the ethanol plant significantly improves energy and GHG balances
    - Use of straw as an energy source further improves energy and GHG savings
    - Use of DDGS as energy for power generation rather than as animal feed gives much greater energy and GHG savings (although it is unlikely to be the most economic option)

13. The calculations are very sensitive to certain input numbers that cannot be quantified with great certainty and need further study
    - N_2O emissions from agriculture have a large impact on the GHG balance (20-30% of emissions). The level of emission varies greatly according to the type of land, agricultural practices and weather factors.
    - The large credit for burning DDGS is perhaps surprising, but is consistent with the overall effectiveness of biomass use for electricity generation. To better quantify this, improved data on the heating value of DDGS are needed.

1. Background

WTW/Life Cycle Analysis is important as a means to understanding the energy and Greenhouse Gas (GHG) impact of new fuel/vehicle technologies. Conventional biofuels (ethanol and FAME) are generally used as blends with petrol or diesel in existing vehicles, so comparison of the fuel production cycles is the most important aspect of the analysis. Biofuels discussions in the UK have been guided by recent studies from

1. N Mortimer et al at Sheffield Hallam University (SHU) [1,2]
2. J Woods et al at Imperial College (ICCEPT) [3]
3. The EUCAR/JRC/CONCAWE WTW study (notably R. Edwards at JRC and J-F. Larivé at CONCAWE) [4]

However, there are differences in the approaches taken in the different studies which merit further evaluation.

At the LOWCVP Fuels Working Group meeting on 29 April 2004, a sub-group was formed, headed by David Rickeard of ExxonMobil and Gary Punter of British Sugar, with the task of facilitating discussion between the experts to reach a consensus on the energy/GHG balances for conventional biofuels. An initial meeting of the group identified the following factors as leading to different results from the existing studies:

- Scenario differences
- Calculation methodologies
- Input data, particularly for the ethanol production process
- Data presentation; overall output or per MJ of biofuel
- Reference systems: gasoline/diesel, agriculture

In order to produce results in a reasonable timeframe, efforts were concentrated on the production of ethanol from wheat, since this pathway showed the greatest variation between the existing studies. Appropriate scenarios for the UK were agreed, and actions assigned to fill data gaps and calculate the results using an agreed methodology. This report represents new research and explains in a transparent way the consensus input data and methodologies, and how different options for ethanol production from wheat affect the energy and GHG balances.

2. Basic wheat-to-ethanol pathway

In this study we assumed that ethanol is produced from wheat grain via the conventional hydrolysis and fermentation process. Although cellulosic fermentation processes offer promise for the future, they are not yet ready for large scale production and are beyond the scope of this report.

The basic process for production of ethanol from wheat grain is shown in ***Figure 1***. Just over one acre of good arable land (0.44 ha) can produce 3.5 tonnes of wheat grain at 16% moisture (8 t/ha) which, after drying, gives 3.03 tonnes of dried wheat grain (dwg, 3% moisture). About 1.4tonnes of straw is also produced which, depending on the circumstances can be left in the field and ploughed back or used either for various agricultural purposes or as a source of energy. The stored grain is transported by road to the ethanol plant where, after milling, hydrolysis, fermentation, distillation and dehydration, 1 tonne of ethanol is produced, giving a yoeld of $2.3t_{EtOH}$/ha. In addition, the residue, after drying, yields 1.14 tonnes of DDGS (Distillers' Dark Grain'S, the residue from the fermentation process). This protein-rich product is conventionally used as animal feed, where it commands a high value, but can also be used as a source of energy. Ethanol is distributed by road.

Various inputs are required for the farming and ethanol production processes. Presentation and discussion of the different ways of achieving this in practice in the UK context are the subject of this report.

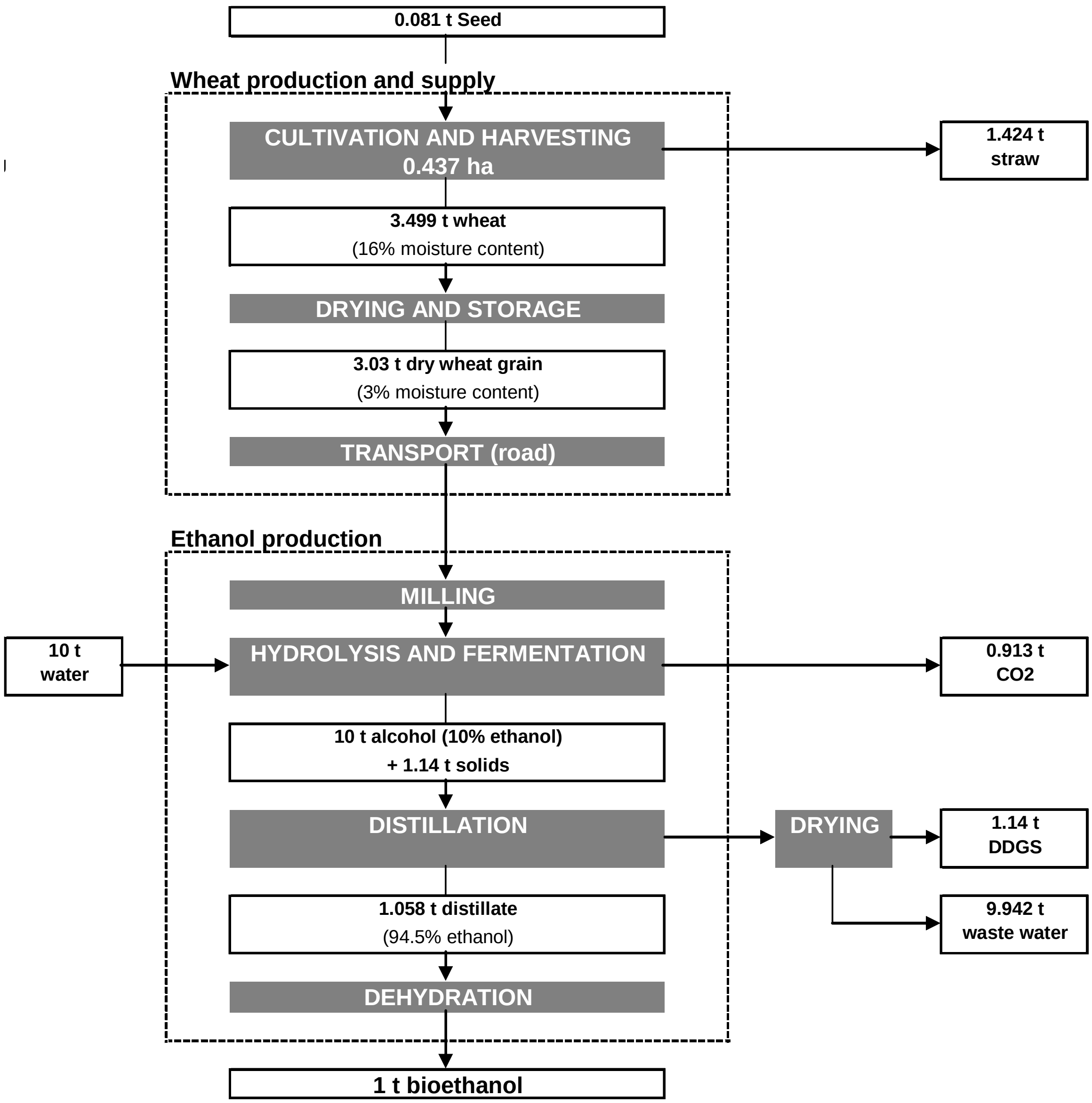


Figure 1. The Production Pathway for Ethanol from Wheat Grain

In this study, analysis has concentrated on a case where additional wheat is grown on set-aside land in the UK. As a result, the straw by-product has only two alternative uses i.e. ploughing back in the field (thereby saving some fertilizers and improving the soil quality) or use as a source of energy for the ethanol production process itself.

It is assumed that the ethanol produced is blended into gasoline to produce a fuel meeting EN228, and is used in standard gasoline vehicles. Under this scenario, it is justified to assume, as in the JEC WTW study, that the efficiency of the engine remains unchanged on switching to the ethanol blend. Although some studies have suggested a small efficiency improvement for ethanol-containing fuels, the data remain unconvincing. Further work is needed to resolve this question. Here it has therefore been assumed that ethanol substitutes for gasoline on the basis of its energy content. This report concentrates on the WTT energy and GHG balances which are primarily governed by the fuel production process. Subsequent calculations show the energy use and GHG emissions associated with producing 1GJ of ethanol (together with the associated DDGS and electricity) and compare this with the figures for 1GJ of conventional petrol. The configurations that give the best energy and GHG savings may not be the most economical, and so indicative figures for investment and operating cost have been included.

3. Scenarios

Within the framework of the generic pathway described in *section 2*, a number of scenarios have been considered, exploring various options in three areas

- Heat & power generation scheme used in the ethanol plant.
- Fate of straw: ploughed back into the field or used as fuel for the ethanol plant.
- Fate of DDGS: used as animal feed or energy source.

As will be seen, every one of these options has a significant impact on the final energy and GHG balance of the whole pathway.

3.1. Ethanol plant utility generation models

Three configurations were identified that cover the range of realistic options for a new ethanol plant, and can be used as a basis for evaluating the impact on energy use and GHG emissions.

a) Basic configuration: conventional natural gas-fired boiler and imported electricity

Model a is the simplest and also least capital-intensive configuration. Heat is provided to the process in the form of steam generated by an on-site boiler. Electricity is simply purchased from the grid.

b) Optimised fossil fuelled plant: combined heat and power

Model b encompasses three configurations that take advantage of the fact that both low-temperature heat and electricity are required. This is a favourable situation for application of combined heat and power generation.

In **Model b1**, the natural gas boiler of Model a is supplemented by a backpressure steam turbo-generator. This produces electricity, while the exhaust steam still contains enough energy to meet the ethanol plant needs.

With more investment, a more sophisticated plant is possible (**Model b21**) consisting of

- a natural gas-fired gas turbine producing electricity,
- a heat recovery steam generator (HRSG) using the exhaust from the gas turbine to produce high pressure steam,
- a back-pressure steam turbine producing more electricity and low pressure steam suitable to drive the ethanol production process.

In an HRSG, additional heat can be produced with a very high efficiency through additional natural gas firing. The additional investment required is relatively modest, and this option (**Model b22**) may be attractive for such schemes (depending on the electricity price).

Most of the energy required by the process is in the form of heat so that it is reasonable to assume that the heat requirement will determine the size of the equipment.

In all of these configurations, it is assumed that the surplus electricity can be exported to the grid.

Models:	Unfired HRSG	Fired HRSG
NG boiler + steam turbine	b1	-
NG gas turbine + steam turbine	b21	b22

c) CHP fuelled by straw:

In some cases the straw associated with the processed grain will be available to fuel the process plant. The configuration then includes a straw-fired boiler producing high pressure steam which feeds an extraction steam turbine producing electricity and low pressure steam for the process. Here again the surplus electricity will be exported to the grid.

In view of the additional complexity brought about by the handling and burning of straw, it is likely that the plant size would be maximised and all available straw would be processed. Besides the electricity surplus, this will produce excess steam. Given additional capital availability the excess steam can be used to generate additional electricity through a condensing turbine.

Models:	
Straw boiler + steam turbine	c1
Straw boiler + steam turbine + condensing turbine	c2

This configuration could be applied in cases where a contract is passed between a wheat producer and an ethanol producer to take the whole crop from the land. Because all the straw is removed from the land, additional fertiliser must be added to replenish the soil.

The Models need to be compared with care, taking into account the type and amount of input energy, the different amounts of electricity produced in addition to the ethanol and DDGS, and the capital and operating costs.

3.2. By-Products

The two by-products associated with ethanol from wheat are straw and DDGS. In Models b and c above, electricity is also a by-product.

a) Straw

The impact of use of straw in the ethanol processing plant is covered by Models c1 and c2 above. In Models a and b, the straw is considered to be left in the field and ploughed back in, which leads to a reduction in the amount of chemical fertiliser needed.

b) DDGS

DDGS is a protein-rich product that has a high value as animal feed. If its use for this purpose replaces other animal feed material, the energy used and GHG emitted for growing and processing these crops will be saved. Calculation of a realistic credit is challenging, and is discussed further in *section 4.1*. If the market for animal feed becomes saturated, DDGS still has a value as fuel. Some DDGS is already exported to electricity generators in which case substitution of conventional electricity provides a further GHG saving.

c) Electricity

Where electricity is produced by the plant, we have calculated credits for energy and GHG emissions based on substitution of UK-mix electricity.

4. Methodology for by-product credits

Calculation of the basic crop production and ethanol processing is fairly straightforward, and any variations between the studies are likely to come from assumptions on heat generation efficiency or input data differences. However, the way in which by-product credits are handled can significantly affect the conclusions and needs careful evaluation.

All the participants were agreed that the best way of calculating by-product credits is the 'substitution' method. For the cases studied, this means that the energy and GHG emissions avoided by use of straw and DDGS are calculated by studying the materials they replace. For example, if DDGS is used as animal feed it could replace feed produced from maize gluten feed and/or soya beans imported from the USA - the energy and GHG associated with producing soya meal/maize gluten is therefore 'avoided' and provides a credit. Similarly, the savings from use of straw as a fuel to replace electricity and natural gas can be calculated. The difficulties of this approach are twofold: firstly the calculation rapidly expands both technically and geographically beyond the area of immediate study, and the ripple effects can result in a very complex calculation: there is a danger that an incomplete evaluation may underestimate the credit. Secondly, which products will actually be substituted will depend on market conditions, which may vary with time and production volumes. These challenges have led some researchers to apply other 'allocation' techniques, where the input energy to the ethanol process is partitioned among the by-products in some other way. All participants agreed that allocation by mass was unsatisfactory because different dispositions of the by-products can produce very different GHG impacts, which would not be reflected in the calculation. Direct allocation by price is also intellectually unsatisfactory because, in the short term, price changes can change the calculation, whereas in reality the use and GHG impact of the products may not change.

There was agreement, however, that economic factors are important in determining how by-products are used and that these choices could change over time as prices vary to reflect saturation of markets or other external economic factors. Hence, if we assume that DDGS is used for animal feed and there is a GHG saving because less animal feed is produced from other sources as a consequence, it has been implicitly assumed that a perfectly functioning market is operating. If the DDGS has a low market value due to a subsequent surplus of animal feed, it can still be used as a fuel either by export to power generators or in the ethanol plant if this includes its own power and heat generation.

In this study, the substitution method has been adopted, with the two options below for use of DDGS (animal feed and energy) covering the range of economic scenarios that can be envisaged, and export of surplus electricity to the grid.

4.1. DDGS

(a) DDGS as animal feed

DDGS, the dried residue after the fermentation and distillation process, is valuable as a protein animal feed. If used for this purpose it will displace maize gluten feed from the US wet milling ethanol industry or the DDGS from the dry milling ethanol industry or soya protein feed from soya oil production.

The displacement of maize protein products for feeding to ruminant animals (cows & sheep) is likely to occur first because it has a close match to the protein levels and amino acid profile of the wheat DDGS [15]. Soya protein has a higher protein level and is used for mono-gastric animals (such as pigs). Some secondary substitution of soya protein could occur.

This study has used soya protein as the substitution product as data were available from the JEC study. If maize gluten was to be used the credits are likely to be larger, so soya protein represents the lower end of the range. The uncertainty is quantified through comparison with results from other studies in *section 7.*

The alternative use of DDGS as a fuel for power generation, described below, generates much higher energy and GHG credits.

(b) DDGS as energy

DDGS can potentially be used in power generation. The basis for this scenario is the increasing practice in UK power stations of co-firing biomass in thermal power plants, as well as in dedicated biomass power plants. This growth has been enabled by the current Renewables Obligation (UK legislation Utilities Act 2000), which sets in place an annual 1% increase (to 2015) in renewable electricity. Currently, Office of Gas and Electricity Market reports show that 28 power stations (including Drax, Ferrybridge, Ratcliffe, etc.) have registered for co-firing, with a combined renewable output of 454 MW, and that 1.2 million MWh of co-fired electricity have been produced since 2002 (about half the current level of wind power).

Where the ethanol plant includes a straw boiler plus sufficient steam turbine capacity, the DDGS may also be used for power generation within the ethanol plant, although this scenario has not been considered in this study. In either case, there are primary energy and GHG emissions credits from UK grid electricity displaced by the extra electricity generated from the DDGS. Similar credits accrue to surplus electricity generated in Natural Gas-fired ethanol plants.

4.2. Straw

In the scenarios considered here, straw is either ploughed back or used as fuel in the ethanol production plant. The main credit for using the straw accrues from saving fossil fuel (natural gas) and also producing additional electricity. A debit is also factored in to take into account the increase of fertiliser input required when the straw is removed. The effect of removing straw from the land on wheat yield is an area for further discussion beyond the scope of this report.

4.3. Natural gas and electricity

Any natural gas and electricity used or saved need to attract a debit/credit (energy and GHG emissions) corresponding to a realistic production scenario and compiled on a “well-to-tank” basis. For natural gas, the EU-mix factor computed in the Joint European study has been used (it is believed that UK-mix figures would be similar). For electricity a UK-mix figure has been adopted.

It must be noted that, in view of the large amounts of electricity produced by some of the models, and fairly large variations amongst electricity generation figures, the choice of the latter is not trivial and can significantly affect the final numbers.

4.4. Attribution of credits to the ethanol

Where the ethanol is the main product from the pathway, credits arising from the by-products can be simply factored into the overall energy/GHG balances for the ethanol. This is the approach taken in most studies, with the figures being expressed per MJ or tonne of ethanol produced. Unfortunately, real scenarios often have large by-product components, which in the case of electricity and DDGS can have their own environmental benefit. In these cases (Models b and c), the effect of by-product credits will have a significant impact on how the bioethanol production is perceived.

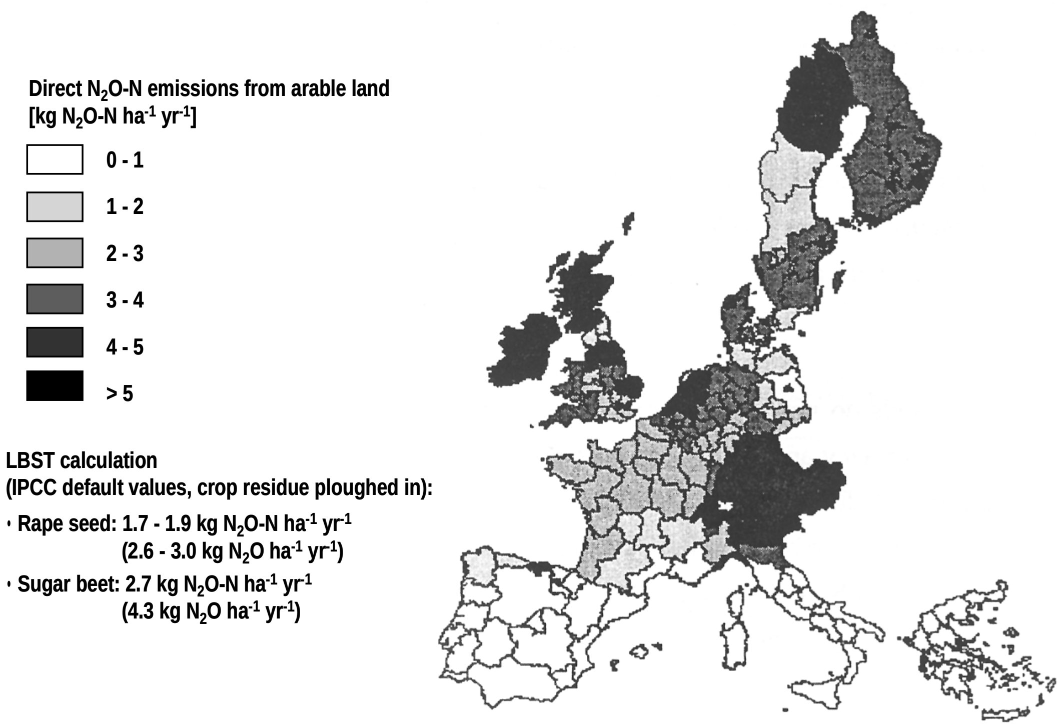
This study attempts to consider ‘real scenarios’, which are being driven by the need to produce bioethanol. By-product credits are significant so the study gives a transparent presentation of the effect of these credits. When considering the final results (including by-product credits) the reader needs to be aware that it is the ‘whole plant’ and all the products that are being measured – not just the bioethanol. Thus, we have quoted the fossil fuel and GHG savings on the basis of a unit production of ethanol, but the reader should bear in mind that the production of ethanol always implies the production also of DDGS and (usually) electricity.

5. Evaluation of the Production Chain

A study prepared for the US Department of Agriculture in 2002 [5] provides a historical analysis of ethanol production and notes that, since the 1980s, there have been improvements in grain yields, lower energy use in fertiliser production, as well as in the ethanol plant improvements discussed in more detail below.

5.1. Agriculture

The differences in agricultural data assumed by the different European studies were fairly small, and did not greatly affect the calculations. Crop yields, agricultural energy inputs and fertiliser use are well established, and do not seem to need further discussion. The amount of fertiliser needed will be less where straw is ploughed back into the land and this is reflected in the different models analysed. Estimation of emissions of N_2O from agriculture remains an issue, especially as its impact on the overall GHG emissions is significant. Work by JRC has reduced uncertainty in previous studies (see discussion in section 7.2), and concluded that large variations can occur, even over small distances, depending on soil types, agricultural practices, and weather. This is illustrated by the following map, taken from [7, citing 6], , which shows large variations across the UK. The figures used in this study are explained in *Section 7.2.*



Source: Freibauer, A., Kaltschmitt, Institut für rationelle Energieanwendungen (IER), Stuttgart: Biogenic Greenhouse Gas Emissions from Agriculture in Europe, European Summary Report of the EU Concerted Action FAIR3-CT96-1877, financed by EU DG VI, February 2001

Figure 2. Direct N_2O emissions from arable land in Europe

Drying of the grain is assumed to be part of the agricultural process, with dried wheat grain (dwg, around 3% moisture) being delivered to the ethanol plant. Since harvested wheat grain can contain 16% or more of moisture, care must be taken to specify exactly which product is being referred to. As part of the agricultural process a small amount of energy (diesel fuel and electricity) is therefore taken into account for drying and also for storage and transport of the grain.

5.2. Ethanol production

Basic energy needs

The amount of energy needed in the ethanol production plant proved to be the greatest source of variation between the different studies, and was reviewed in some detail. Comparisons are hampered by the fact that many published studies are influenced by different fossil fuel choices, and are not always clear whether the quoted figures relate to steam/electricity energy, to fossil fuel use at the plant, or to a full WTT evaluation of primary energy needs.

To resolve this, the team went back to basics and studied how much steam and electricity energy is needed to power the basic ethanol production process of milling, fermentation, distillation and dehydration of the ethanol and drying of the DDGS. Valuable data were found in the comprehensive study prepared for the US Department of Agriculture in 2002 [5] which surveyed the actual US ethanol industry and also the literature. Although ethanol in the USA is produced from corn (maize) rather than wheat, the dry-milling process used is analogous to that use for wheat, so numbers can be compared with some confidence.

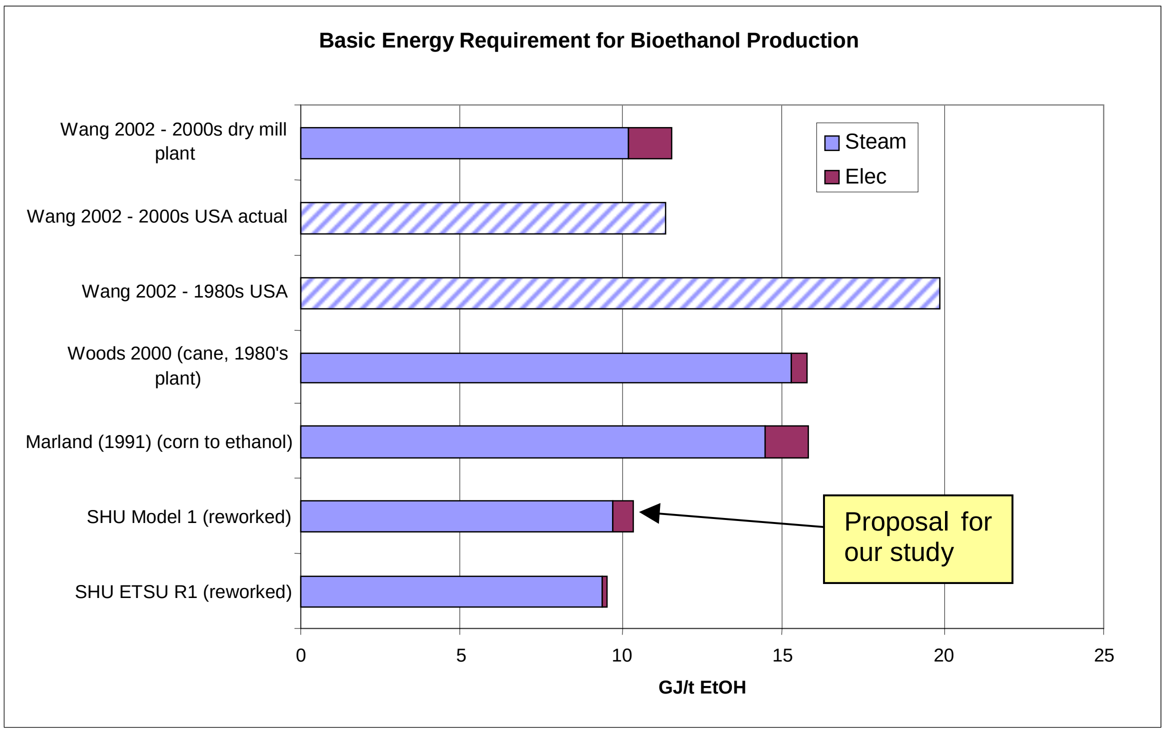


Figure 3. Energy Needs (Steam plus Electricity) for Bioethanol Plants

Selected values for the basic energy requirements of bioethanol production are shown in ***Figure 3***. All figures have been converted to represent the energy content of steam plus electricity at the plant. Starting at the top with the USDA figures, the improvements in process efficiency since the 1980's are clear. Better heat integration in modern ethanol plants probably accounts for a large amount of the improvement. In addition, the use of vapour-phase molecular sieves for final dehydration of the ethanol in place of azeotropic distillation since the early 1990s has led to a drop in energy consumption [8]. The actual values for dry mill plants represent the results of a US survey in September 2001, so can be considered typical of current production. The difference between this figure and that for the 1980s technology goes a long way towards explaining the wide variations reported in literature studies.

The two centre bars represent two studies of older plants (Marland for corn ethanol in 1990 [9], Woods for a plant in Zimbabwe using 1980s technology [10]). These confirm the higher energy consumption of older plants.

ETSU's 1996 study [11] has been widely quoted, but has also been criticised for the high primary energy value calculated for ethanol production. The authors of this report agree that the value of 0.78GJ of primary energy per GJ primary, or 20.8 GJ/t $_{EtOH}$, calculated in the ETSU study is too high. However, the basic requirements for steam and electricity used by ETSU (and as input to the JEC report) look reasonable and close to those for the current US dry-mill average.

The bottom bar shown on ***Figure 3*** is SHU's 'Model 1'. It represents a plant fuelled by natural gas and electricity, so is representative of Model a. The values in [2] have been used to back-calculate the basic steam and electricity needs for the plant using the information provided in the notes. The energy needed to dry the DDGS has also been added back into the figures (this was handled separately and not included in the tables of the original SHU study due to allocation by price rather than substitution). These values are slightly lower than the US dry-mill average for the 2000s, and are considered typical of a new plant using existing best practices.

There is, therefore, a consensus among these different studies that for a new plant, energy of around 0.4 GJ/GJ $_{EtOH}$, or 10.7 GJ/t $_{EtOH}$, expressed as steam plus electricity, is needed to power the ethanol plant, including dehydration/drying of the alcohol and the DDGS. SHU's Model 1 [2] has been chosen as the baseline for this study.

Efficient use of primary energy in ethanol production

Clearly, the efficiency with which the above basic energy needs can be produced from primary energy will impact the overall energy and GHG figures. The process flow schemes of the different models have been carefully considered to arrive at realistic numbers also representative of best practice and latest technology.

6. Reference Systems

6.1. Agriculture

In considering energy/GHG impacts of the agricultural crop, it is necessary to consider how the land would have been used if wheat for ethanol were not grown - the impact of producing ethanol is then calculated by difference. Attention has been restricted to land already in agriculture, since ploughing up grassland or removing forest cover releases significant amounts of soil carbon and should be discouraged. In terms of land use, it has been assumed that the wheat is grown on set-aside land, or land otherwise not used for cultivation. While the amount of set-aside land is limited in the long term, it remains a realistic short term option.

A credit has been applied for the avoided maintenance of set-aside land. It has been assumed that straw can be removed from the field without detriment to the soil. In practice, there is a potential for subsequent crops to suffer water stress, except in well-watered areas. This is due to a reduction in the organic carbon content of the soil, which is released as carbon dioxide. A report from the Netherlands [19] calculates that taking straw every year leads to a cumulative loss of about 1/3 of the soil carbon, equivalent to a total CO_2 release of 92 $kgCO_2$/ha. That would be enough to negate the benefit of taking straw for more than 60 years. However, other experts think the effect is much smaller, or could be drastically reduced by changes in crop rotations.

The wheat yield from set-aside land may in practice be less than the assumption of 8t/ha - this figure is relevant to the best arable land (Eurostat figures for 1997 to 2003 show a UK average of 7.68t/ha). Where a wheat crop replaces a break crop or fallow on land intensively used for cereal production, there is likely to be some reduction in wheat yields in this and future years. The magnitude of the reduction will depend on the specific rotation pattern, and no correction has been applied here. However, although the agricultural inputs would remain the same at lower yields, the overall energy and GHG balances per tonne of ethanol produced are only slightly affected by changing this parameter.

6.2. Reference Petrol and Diesel

The energy/GHG associated with production of petrol is needed to calculate the impact of its substitution by ethanol. The WTT (crude production/transport, refining, product distribution) process for petrol and diesel is efficient, using only about 15% of delivered fuel energy.

However, partitioning the refining energy/GHG emissions between petrol and diesel (and other refinery products) presents some problems. Historically, efforts have been made to estimate the amount of processing needed for the two fuels, awarding less energy/GHG to diesel than to gasoline, which undergoes more extensive processing in the refinery. A recent example of this approach for Europe is the 2002 study by GM [7].

More recently, the JEC joint WTW study [4] used CONCAWE's refinery model to calculate the marginal impact of reducing petrol or diesel production, for example in response to substitution by biofuels. This calculation indicated that in Europe more energy/GHG emission is associated with producing marginal barrels of diesel than for petrol. This arises because diesel demand in Europe is high, with refineries producing maximum quantities. By comparison, changing petrol output is less energy intensive.

WTT balance	**Petrol**		**Diesel**	
	Energy GJ_{ex}/GJ_f	GHG $kgCO_2eq/GJ_f$	energy GJ_{ex}/GJ_f	GHG $kgCO_2eq/GJ_f$
GM Euro Study 2002	0.16	13.1	0.12	10.2
JEC 2003	0.14	12.5	0.16	14.2

Table 1. WTT balance for conventional fuels

Note (i) Suffix ex indicates the energy expended in producing the fuel; suffix f denotes fuel delivered to the vehicle; CO_2eq includes GHG effects of CO_2, CH_4 and N_2O:
Note (ii): CO_2 emitted on fuel combustion is 73.3gCO_2eq/MJ for 2000 gasoline, 73.2gCO_2eq/MJ for diesel.

The marginal calculation using the CONCAWE model is believed to provide the best estimate for Europe today. However, as shown in ***Table 1*** the differences are relatively small and will not impact on the calculations as much as the assumptions for ethanol production.

7. Consensus Input Data

Based on the above considerations, input data have been agreed that are representative of future options for the UK.

7.1. Basic Data

Farming data

	Yield t/ha	LHV GJ/t
Harvested wheat grain (16% water)	8.0	17.0
Dried wheat grain (3% water)	6.9	19.6
Straw	3.3	14.6
Ethanol	2.3	26.7
	t/t EtOH	
DDGS (10% moisture)	1.14	18.2

Greenhouse gas factors

	kg CO2eq/kg
N2O	296
CH4	21

Fuel and energy data

Diesel		
Primary energy factor	GJp/GJ	1.16
Direct CO2 emissions from diesel burning	kg CO2/GJ	73.2
CO2 emissions factor	kg CO2/GJ	87.4
Gasoline		
Primary energy factor	GJp/GJ	1.14
Direct CO2 emissions from diesel burning	kg CO2/GJ	73.3
CO2 emissions factor	kg CO2/GJ	85.8
NG (EU-mix)		
Primary energy factor	GJp/GJ	1.06
Emission factor	kg CO2/GJ	61
Electricity (UK-mix)		
Energy factor	GJp/GJe	3.08
Emission factor	kg CO2/GJe	160

Table 2. Basic input data

After drying the yield is 6.9 t/ha of dwg supplied to the processing plant. Overall, 2.3 t/ha of ethanol can be produced, corresponding to a figure of 3.03 tonnes dwg per tonne ethanol. This latter figure is taken from the SHU and ETSU studies [2,11]. In addition, 3.3 tonnes of straw are produced per hectare.

The energy used in the production of diesel (used as fuel in agriculture and transport), natural gas (used as fuel in the production plant) and gasoline (the reference fuel) is reflected in the Primary Energy Factors of 1.16, 1.06 and 1.14 respectively [4], and are based on the EU average. The CO_2 emissions associated with the WTT energy are added to the CO_2 released upon combustion to give a WTT CO_2 emission figure.

Similar figures are shown for electricity. As mentioned in *section 4.3* these figures represent a UK-average. Finding sufficiently detailed and reliable data which would include all impacts of the production process (well-to-tank), proved surprisingly difficult - the figures used [12], which were agreed as satisfactory by the team, are representative for the UK, and somewhat higher than the European average.

7.2. Grain production and delivery to the processing plant

Table 3 shows the figures used for wheat production. There seems to be good agreement on the energy needs for agriculture and the differences seen between studies were not large. The figures for fertiliser are all expressed per kg of elemental N, P or K. Production energy and GHG figures follow the study of Kaltschmitt and Reinhardt [13].

Field N_2O emissions remain a difficult area. As shown in ***Figure 2***, Freibauer and Kaltschmitt [6] give figures from 1-5 kg of nitrogen emitted as N_2O per hectare of land for different regions of the UK (1.6-7.8 kg N_2O/ha). Extensive work has been carried out in this area by the Soils and Waste Unit, Institute of Environment and Sustainability, JRC, Ispra. We used their database-model, GReenhouse Emissions from Agricultural Soils in Europe (GREASE) [14], to calculate average UK emissions. The calculation is based on detailed data for the UK, including soil types, weather and which croplands are used for wheat. The result of this calculation, a UK average of 4.36kg N_2O per hectare has been used.

Strictly, we should correct for the N_2O emissions associated with fallow land. However in the absence of reliable figures and in view of the very high variability of the estimates, no correction has been applied. Similarly, as explained above, no correction to wheat yield has been made for the loss of the break crop. Information on the calculation method and data sources is given in appendix 2, but this remains an area where further research is needed.

The inputs of N P and K fertilisers are significantly more when the straw is removed, eventually resulting in a 30% increase in GHG emissions from agriculture. The agricultural inputs were adjusted according to figures provided by SHU.

Case		Basic Energy Inputs	Straw ploughed back	All straw removed
B1. Wheat farming				
Diesel for cultivation				
Consumption	GJ/ha	5.02		
Credit for use of set-aside	GJ/ha	-0.92		
Total primary energy	GJp/ha	4.8		
Total GHG emissions	kg CO2/ha	358		
Agrochemicals and fertilizers				
Usage	kg/ha			
K fertilizer (as K)			46	164
P fertilizer (as P)			41	53
N fertilizer (as N)			185	253
Pesticides			2	2
Seed material			185	185
Production primary energy	MJ/kg			
K fertilizer		9.3		
P fertilizer		15.8		
N fertilizer		40.6		
Pesticides		274.1		
Seed material		13.5		
Production GHG emissions	kg CO2/kg			
K fertilizer		0.46		
P fertilizer		0.71		
N fertilizer		6.69		
Pesticides		5.41		
Seed material		0.87		
Total primary energy required	GJp/ha		11.63	15.68
Total GHG emissions	kg CO2/ha		1459	1977
N2O emissions	kg N2O/ha		4.36	5.96
Total for farming				
Primary energy	GJp/ha		16.38	20.43
GHG emissions	kg CO2eq/ha		3108	4100
B2. Grain handling and storage				
Diesel for drying	GJ/ t dwg	0.66		
Primary energy	GJp/ t dwg	0.77		
GHG emissions	kg CO2/ t dwg	58		
Storage(electricity)	GJe / t dwg	0.042		
Primary energy (EU-mix)	GJp/ t dwg	0.13		
GHG emissions	kg CO2/ t dwg	7		
B3. Dried grain and straw transportation				
Mode		Road/diesel fuel		
Distance (one-way)	km	50		
Diesel consumption for road transp	MJ/t.km	0.97		
Requirement per tonne transported				
Primary energy	GJp/t	0.056		
GHG emissions	kg CO2eq/t	4.2		
Total for dwg at ethanol plant gate				
Primary energy	GJp/ t dwg		3.32	3.90
GHG emissions	kg CO2/ t dwg		517	661

Table 3. Energy and GHG figures for grain production and supply

Heat for drying of the grain is assumed to be produced from diesel fuel. A small allowance of electricity is made for storage. Average transport distance for the grain and straw is assumed to be 50 km.

The total energy and GHG emissions associated with the production and transport of the dried wheat grain to the ethanol plant are shown at the bottom of ***Table 3***. The higher figures for the 'all straw removed' case reflect the higher fertiliser inputs and also transport of the wheat straw to the plant.

7.3. Ethanol Production & Distribution

The basic energy requirements for the ethanol production process, excluding by-product credits are shown in ***Table 4***. Note that these are expressed as heat or electricity - the primary energy needs are calculated later.

Energy requirement		
Milling (electricity)	GJe / t dwg	0.20
Hydrolysis/fermentation/distillation		
As heat	GJ / t dwg	1.80
As electricity	GJe / t dwg	0.28
Dehydration (electricity)	GJe / t dwg	0.01
DDGS drying (heat)	GJ / t dwg	1.41
Total energy requirement		
As heat	GJ heat / t dwg	3.22
	GJ heat / t EtOH	9.75
As electricity	GJe / t dwg	0.48
	GJe / t EtOH	1.45
Ethanol yield	t dwg / t EtOH	3.03

Table 4: Energy requirement for ethanol production

Electricity is required for milling of the grain as well as for the other steps to power rotating equipment, provide lighting etc. However, steam heat provides the bulk of the energy needs for hydrolysis, fermentation, distillation and dehydration of the ethanol, and drying of the DDGS. Note that the latter represents a significant portion of the total energy input (credits for DDGS are calculated later).

The amount of primary energy needed to supply these basic requirements depends on the different scenarios represented by the various models. The potential efficiencies for steam and electricity generation and heat extraction have been studied in some depth, taking account of latest industry experience [18]. Details of the data used, including efficiencies, are given in ***Appendix 1***. A summary of the results is given in ***Table 5*** below.

Model		Basic Energy Inputs	a NG boiler + grid	b1 NG boiler + BPSTG	b21 NG GT+ unfired HRSG+ BPSTG	b22 NG GT+ fired HRSG+ BPSTG	c1 Straw boiler + BPSTG	c2 Straw boiler + BP/cond STG
Energy supply								
Recoverable enthalpy of steam at :	MJ/t	2194						
Required steam for process	t/t EtOH	4.4						
Steam heat content at boiler outlet	MJ/t		3116	3366	3366	3366	3366	3366
Required HP steam production	t/t EtOH		4.0	4.4	4.4	4.4	4.4	4.4
Heat from condensate recovery (5(	MJ/t steam	292						
Net heat required at boiler outlet	GJ/t EtOH		11.19	13.66	13.66	13.66	13.66	13.66
GT elec / heat ratio	GJe/GJ				0.56	0.26		
GT electricity production	GJe/t EtOH				7.66	3.57		
Straw intake	t/t EtOH		0.00	0.00	0.00	0.00	1.42	1.42
	GJ/t EtOH						20.79	20.79
Boiler efficiency			95%	95%			88%	88%
Heat produced at boiler outlet	GJ/t EtOH						18.30	18.30
	t/t EtOH						5.4	5.4
Electricity from backpressure turbir	GJe/t EtOH	0.65		2.88	2.88	2.88	3.52	2.88
Electricity from condensing turbine	GJe/t EtOH	1.20						1.19
Overall requirement for manufacture								
NG consumption	GJ/t EtOH		11.78	14.38	27.21	18.20		
Electricity import	GJe / t EtOH		1.45					
Primary energy	GJp / t EtOH		16.96	15.24	28.85	19.29	20.79	20.79
GHG emissions	kg CO2 / t EtOH		948	874	1655	1107	0	0
Heat surplus	GJ / t EtOH						4.64	0.00
Electricity surplus	GJe / t EtOH		0.00	1.43	9.09	5.00	2.07	2.62
	GJe/GJEtOH			0.08	0.34	0.19	0.08	0.10
Overall efficiency on primary energy			66.1%	82.9%	70.3%	84.0%	63.8%	60.8%

Table 5. Energy consumption and GHG emissions in the ethanol plant.

Model a is relatively inefficient as it uses electricity from the grid. Taking advantage of the combined heat and power opportunity boosts the efficiency of fossil fuel usage & power generation, even when using a conventional boiler scheme (Model b1).

The introduction of a gas turbine appears to have the paradoxical effect of increasing fossil fuel usage (Model b21). This is because this model produces a lot more electricity. Introducing co-firing in the HRSG (Model b22) decreases again the electricity to heat ratio and the efficiency increases.

Straw burning is somewhat less efficient partly because of a less efficient boiler but also because of the assumption that all straw is burned. In Model c1 some heat is wasted whereas in Model c2 it is used to generate electricity without the benefit of CHP for this marginal production.

The above considerations show how the final efficiency figures result from an array of assumptions, and how direct and simplistic comparisons can be misleading. It should also be noted that, in practice, schemes are likely to be selected more on the basis of economic profitability than maximum energy or GHG savings.

7.4. By-product credits

When surplus electricity for export is produced, it is assumed that it will replace the same amount otherwise produced according to the UK-mix (see ***Table 2***). The credit for DDGS has been evaluated as explained in *section 4.1*.

If DDGS is used as animal feed it could substitute soya meal imported into the EU from the USA. The credit associated to this has been calculated in the JEC study. From the same data and after correction for the use of a slightly different DDGS yield, figures of 0.12 GJ and 15.3 kg CO_2 per GJ ethanol have been adopted for illustrative purposes in this study.

A similar calculation for substituting maize gluten from US maize ethanol is reported in [5], where the DDGS credit is given as 13115 BTU/USgal, which is equivalent to 3.66 GJ_p/t_{EtOH}, or 0.14 GJ_p/GJ_{EtOH}. Calculations by Reinhardt [17] for rape seed meal are estimated by us to give a figure equivalent to 4.70 GJ_p/t_{EtOH} or 0.18 GJ_p/GJ_{EtOH}. Hence the figures based on soya protein and could be regarded as conservative. More research would be welcomed in this area.

If DDGS is used as energy source it will substitute UK-mix electricity and the primary energy available is assumed to be equal to the lower heating value of DDGS. Existing studies of energy content of DDGS [eg 16] have concentrated on its food energy value, and we could only find limited data on the thermal energy content [16]. Because the elemental composition is broadly similar, we have assumed that the LHV of DDGS is the same as for wheat grain, and have used this figure with a correction for water content (see ***Table 2***). More research would be welcomed in this area.

7.5. Revenues and costs

Within the scope of this study, a detailed cost evaluation was not possible; however indicative figures have been produced.

An attempt has been made to evaluate the economics of ethanol production from the point of view of a 100 kt/a ethanol plant. This evaluation assumes that the prices of all materials (feedstocks, process materials and products) behave like commodities i.e. are determined by an international market. No tax or subsidy schemes are taken into account.

The overall cost of ethanol production is dependant upon: costs of the feedstocks and other process materials, the value of the products, plant operating costs and the capital costs associated with building the plant. These have been assessed in order to give a ranking of the scenario's in terms of cost effectiveness for carbon reduction.

Dwg	GBP/t	75
Straw	GBP/t	25
DDGS	GBP/t	75
NG	p/th	32
	GBP/GJ	3.03
Electricity	GBP/MWh	29.5
	GBP/GJ	8.2
Gasoline	GBP/GJ	5.1

Table 6. Commodity prices

The commodity price for DDGS reflects its value as animal feed. Its value as fuel should normally be lower, however the market created by the Renewable Fuels Obligations will influence this. No attempt has been made to predict the eventual value for this application.

The capital and operating costs for the ethanol plant have been estimated as follows:

Model			a NG boiler + grid	b1 NG boiler + steam turbine	b21 NG GT+ steam gen+ steam turbine	b22 NG GT+ fired steam gen+ steam turbine	c1 Straw boiler + steam turbine	c2 Straw boiler + steam turbine + condensing turbine
Capex	MGBP		40	43	50	52	70	75
Capital charge	MGBP/a	15%	6.0	6.5	7.5	7.8	10.5	11.3
Opex	% of capex /a		2.5%	4.0%	4.0%	4.0%	4.0%	4.0%
	MGBP/a		1.0	1.7	2.0	2.1	2.8	3.0
Annual cost	MGBP/a		7.0	8.2	9.5	9.9	13.3	14.3

Table 7. Ethanol plant capital and operating costs

The increasing capital cost reflects the increasing complexity of the plant, particularly when it comes to handling and burning straw. The 15% capital charge corresponds, under typical

European economic circumstances, to an Internal Rate of Return of 8%, but may not reflect the real risks to the investor in this emerging industry.

For operating costs, the figure of 2.5% of CAPEX is fairly standard for usual process plants. This has been increased to 4% for all b and c models to reflect the relative complexity of these plants.

Results of the calculation are shown in Section 8.

8. WTT Results

With the assumptions described above and the data given in *section 7*, all calculations can now be completed. The gross energy and GHG balances, before credits, are shown in ***Table 8.*** This picture without credits is incomplete, but shows the starting point in a transparent manner.

For **Model a**, the basic plant fuelled by natural gas and grid electricity, the total energy input is slightly higher than the energy contained in the produced ethanol. This decreases to 95% of the ethanol energy in the more efficient model b1 where CHP is used.

Model b2, using a gas turbine, at first looks less efficient, requiring more input energy. The reason for that is the much larger surplus of electricity that is exported to the grid.

Model c1 and **c2** clearly show the reduction in fossil energy inputs due to the use of straw in the production plant. Total energy used is again higher than for scenario a, but again the exported electricity needs to be considered to see the whole picture.

Model		**a** **NG boiler + grid**	**b1** **NG boiler + steam turbine**	**b21** **NG GT+ steam gen+ steam turbine**	**b22** **NG GT+ fired steam gen+ steam turbine**	**c1** **Straw boiler + steam turbine**	**c2** **Straw boiler + steam turbine + condensing turbine**
Overall gross balance							
Total fossil energy input	**GJf/GJ EtOH**	1.02	0.95	1.46	1.11	0.45	0.45
Primary Total Energy Input	**GJp/GJ EtOH**	1.02	0.95	1.46	1.11	1.23	1.23
	GJp/t Et OH	27.2	25.5	39.1	29.5	32.9	32.9
Farming		7.2	7.2	7.2	7.2	8.9	8.9
Transport + drying		2.9	2.9	2.9	2.9	3.0	3.0
Manufacture		17.0	15.2	28.8	19.3	20.8	20.8
Distribution		0.2	0.2	0.2	0.2	0.2	0.2
GHG emissions	**kg CO2eq / GJ EtOH**	94.7	91.9	121.2	100.6	75.7	75.7
	kg CO2eq / t EtOH	2529	2455	3235	2687	2020	2020
Farming (CO2)		795	795	795	795	1021	1021
Farming (N2O)		564	564	564	564	772	772
Transport + drying		208	208	208	208	214	214
Manufacture		948	874	1655	1107	0	0
Distribution		13	13	13	13	13	13

Table 8. Gross energy and GHG balances (without by-products credits)

N_2O emissions play a major role in the total representing 40% of the agricultural GHG emissions and about 20 to 30% of the total depending on the Model. The results are therefore sensitive to a change in assumptions regarding these emissions.

Table 9 shows the net balance including credits for surplus electricity and DDGS use as animal feed.

Model		Basic Energy inputs	a NG boiler + grid	b1 NG boiler + steam turbine	b21 NG GT+ steam gen+ steam turbine	b22 NG GT+ fired steam gen+ steam turbine	c1 Straw boiler + steam turbine	c2 Straw boiler + steam turbine + condensing turbine
Overall net balance								
Credit for surplus electricity								
Primary energy credit	**GJp/ GJ EtOH**		0.00	-0.16	-1.05	-0.58	-0.24	-0.30
	GJp/ t EtOH		0.0	-4.4	-28.0	-15.4	-6.4	-8.1
GHG credit	**kg CO2 / GJ EtOH**		0.00	-8.55	-54.47	-29.95	-12.41	-15.69
	kg CO2 / t EtOH		0	-228	-1454	-800	-331	-419
Net balance: DDGS as animal feed								
DDGS credit								
Primary energy credit	**GJp/ GJ EtOH**	-0.12						
	GJp/ t EtOH	-3.13						
GHG credit	**kg CO2eq / GJ EtOH**	-15.3						
	kg CO2eq / t EtOH	-407						
Total fossil energy input	**GJf/GJ EtOH**		0.90	0.67	0.30	0.41	0.10	0.03
Fossil energy saved			21%	41%	74%	64%	92%	97%
Primary Total Energy Input	**GJp/GJ EtOH**		0.90	0.67	0.30	0.41	0.87	0.81
	GJp/t EtOH		24.0	17.9	7.9	11.0	23.4	21.7
Farming			7.2	7.2	7.2	7.2	8.9	8.9
Transport + drying			2.9	2.9	2.9	2.9	3.0	3.0
Manufacture			13.8	7.7	-2.3	0.8	11.3	9.6
Distribution			0.2	0.2	0.2	0.2	0.2	0.2
GHG emissions	**kg CO2eq / GJ EtOH**		79.5	68.1	51.4	55.4	48.0	44.7
GHG avoided			7%	21%	40%	35%	44%	48%
	kg CO2eq / t EtOH		2122	1819	1374	1480	1282	1194
Farming			1359	1359	1359	1359	1793	1793
Transport			208	208	208	208	214	214
Manufacture			541	238	-207	-101	-739	-826
Distribution			13	13	13	13	13	13

Table 9. Net balance, DDGS as animal feed

Model a attracts no electricity credit, since it is a net consumer of electricity (the debit due to the electricity import is already factored into the gross balance calculation). Note that the electricity credit can be extremely large, particularly in Model b21 where it accounts for more than 2/3 of the gross energy and around 2/5 of the GHG emissions.

The DDGS credit further reduces the net energy requirement and GHG emissions. Its effect is more important on GHG because of the impact of N_2O emissions in the soya meal cycle.

In terms of fossil energy usage the 6 models now range from 90% of the ethanol energy to virtually none for **Model c2**. The ranking is the same for GHG emissions although the savings are lower because of the contribution of N_2O from agriculture.
Comparing with the reference gasoline case, it is possible to calculate the fossil energy saved and the $CO_{2\ eq}$ (or GHG) avoided as a percentage of what would have been used and emitted when using a GJ of gasoline instead of ethanol. These figures are also shown in ***Table 9***.

The alternative use of DDGS considered is as a source of energy for co-firing in power stations for instance as part of the UK renewable electricity obligation. This would mirror a real scenario where a growing volume of bioethanol derived DDGS reduces the value of the animal feed and enhances the attractiveness of biomass (hence DDGS) co-firing. Although this may be less economic, it can produce significant energy and GHG credits. The corresponding net balance is shown in ***Table 10***. It is assumed that DDGS used for power generation substitutes UK grid electricity.

Model		Basic Energy inputs	a NG boiler + grid	b1 NG boiler + steam turbine	b21 NG GT+ steam gen+ steam turbine	b22 NG GT+ fired steam gen+ steam turbine	c1 Straw boiler + steam turbine	c2 Straw boiler + steam turbine + condensing turbine
Overall net balance								
Credit for surplus electricity								
Primary energy credit	**GJp/ GJ EtOH**		0.00	-0.16	-1.05	-0.58	-0.24	-0.30
	GJp/ t EtOH		0.0	-4.4	-28.0	-15.4	-6.4	-8.1
GHG credit	**kg CO2 / GJ EtOH**		0.00	-8.55	-54.47	-29.95	-12.41	-15.69
	kg CO2 / t EtOH		0	-228	-1454	-800	-331	-419
Net balance: DDGS as co-fuel for power plant								
DDGS credit								
Primary energy credit	**GJp/ GJ EtOH**	-0.78						
Primary energy credit	GJp/ t EtOH	-20.8						
Electricity generation	GJe/t EtOH	6.74						
GHG credit	**kg CO2eq / GJ EtOH**	-40.4						
	kg CO2 / t EtOH	-1079						
Total fossil energy input	**GJf/GJ EtOH**		0.24	0.01	-0.36	-0.25	-0.56	-0.63
Fossil energy saved			79%	99%	132%	122%	150%	155%
Primary Total Energy Input	**GJp/GJ EtOH**		0.24	0.01	-0.36	-0.25	0.21	0.15
	GJp/t EtOH		6.4	0.3	-9.7	-6.6	5.7	4.0
Farming			7.2	7.2	7.2	7.2	8.9	8.9
Transport + drying			2.9	2.9	2.9	2.9	3.0	3.0
Manufacture			-3.8	-9.9	-19.9	-16.9	-6.3	-8.0
Distribution			0.2	0.2	0.2	0.2	0.2	0.2
GHG emissions	**kg CO2eq / GJ EtOH**		54.3	43.0	26.3	30.3	22.9	19.6
GHG avoided			37%	50%	69%	65%	73%	77%
	kg CO2eq / t EtOH		1450	1148	702	809	610	523
Farming			1359	1359	1359	1359	1793	1793
Transport + drying			208	208	208	208	214	214
Manufacture			-130	-433	-878	-772	-1410	-1498
Distribution			13	13	13	13	13	13

Table 10. Net balance, DDGS as energy source for power generation

Use of DDGS as an energy source generates larger credits. In fact in Models b21/2 and c more than 100% of the ethanol energy can be saved. This simply means that, through the use of by-products as energy sources, large amounts of additional fossil energy can be saved. Whether the benefit of this saving should be solely attributed to the ethanol is an issue, since ethanol is not the only output, but the total fossil energy saved is not in question. The CO_2/GHG reductions are large but less impressive, again because of the emissions from agriculture.

An analysis was conducted on cost to assess the relative ranking of the scenario's with regards 'cost of avoiding GHG emissions'. The data presented follow a simplified economic model, and are not meant to be used for financial decisions. In order to look into cost it is convenient to fix a typical installation size. The example of a 100 kt/a ethanol plant has been used, which is a typical capacity envisaged in current studies and projects. The calculations are based on the figures presented in *section 7*.

Table 11 shows the plant margin calculation as well as the cost of CO_2/GHG avoided for the case where DDGS is used as animal feed. The cost calculation for the case where DDGS is used as energy is not presented here, since predicting the economic value of DDGS as a fuel is difficult. Costs for adapting power plants to burn this type of feedstock would also need to be considered.

The calculation credits the ethanol with the value of an equivalent amount of gasoline, on an energy basis. In reality, of course, ethanol is more costly than gasoline, so the calculation generates a net loss for the process: the size of the deficit is an indicator of the relative costs for the different models.

In none of the configurations does the plant produce a positive net or gross margin. In other words, with the price scenario envisaged which represents today's commercial reality, and without subsidies, ethanol production for road fuel is not profitable.

Model		Basic Energy inputs	a NG boiler + grid	b1 NG boiler + steam turbine	b21 NG GT+ steam gen+ steam turbine	b22 NG GT+ fired steam gen+ steam turbine	c1 Straw boiler + steam turbine	c2 Straw boiler + steam turbine + condensing turbine
Ethanol plant margin								
DDGS as animal feed (Soya meal substitution)								
Total in	MGBP/a							
DW grain			-22.7	-22.7	-22.7	-22.7	-22.7	-22.7
NG			-3.6	-4.4	-8.3	-5.5	0.0	0.0
Grid electricity			-1.2	0.0	0.0	0.0	0.0	0.0
Straw			0.0	0.0	0.0	0.0	-3.6	-3.6
Total out								
EtOH			13.6	13.6	13.6	13.6	13.6	13.6
DDGS			8.6	8.6	8.6	8.6	8.6	8.6
Electricity			0.0	1.2	7.4	4.1	1.7	2.1
Gross margin			-5.4	-3.8	-1.4	-2.0	-2.5	-2.0
Capex	MGBP		40	43	50	52	70	75
Capital charge	MGBP/a	15%	6.0	6.5	7.5	7.8	10.5	11.3
Opex	% of capex /a		2.5%	4.0%	4.0%	4.0%	4.0%	4.0%
	MGBP/a		1.0	1.7	2.0	2.1	2.8	3.0
Annual cost	MGBP/a		-7.0	-8.2	-9.5	-9.9	-13.3	-14.3
Net margin	MGBP/a		-12.4	-12.0	-10.9	-11.9	-15.8	-16.3
	p/l		-9.8	-9.4	-8.6	-9.4	-12.4	-12.8
	EUR/l		-14.6	-14.2	-12.9	-14.1	-18.7	-19.3
Cost relative to b1			1.03	1.00	0.91	1.00	1.32	1.36
GHG avoided	**kt/a CO2eq**		17	47	92	81	102	110
Cost of GHG avoided	**GBP/tCeq**		2662	927	435	537	569	540
	EUR/t CO2eq		1089	379	178	220	233	221
Relative cost of GHG avoided			2.87	1.00	0.47	0.58	0.61	0.58

Table 11. Economic margin and cost of GHG avoided (DDGS as animal feed)

Too much should not be read into the absolute cost figures - a more detailed economic assessment is needed before commercial decisions are taken. However, they do show relative rankings.

In terms of cost per tonne carbon, model b21 has the best profile, indicating that even though the straw burning models (c1 and c2) have higher emission reductions, the additional costs may not be justifiable. Model a has very poor cost effectiveness due to its low level of carbon savings.

Table 12 and Figures 4, 5 and 6 summarise the main figures.

Model		Basic Energy inputs	a NG boiler + grid	b1 NG boiler + steam turbine	b21 NG GT+ steam gen+ steam turbine	b22 NG GT+ fired steam gen+ steam turbine	c1 Straw boiler + steam turbine	c2 Straw boiler + condensing turbine	Gasoline
Fossil energy balance	GJf/GJ road fuel								
Gross			1.02	0.95	1.46	1.11	0.45	0.45	1.14
Net of credits									
DDGS as animal feed			0.90	0.67	0.30	0.41	0.10	0.03	
DDGS as energy			0.24	0.01	-0.36	-0.25	-0.56	-0.63	
GHG emissions	kg CO2eq/GJ road fuel								
Gross			94.7	91.9	121.2	100.6	75.7	75.7	85.8
Net of credits									
DDGS as animal feed			79.5	68.1	51.4	55.4	48.0	44.7	
DDGS as energy			54.3	43.0	26.3	30.3	22.9	19.6	
GHG avoided	kg CO2eq/GJ road fuel								
DDGS as animal feed			6.4	17.7	34.4	30.4	37.8	41.1	
DDGS as energy			31.5	42.9	59.5	55.5	63.0	66.3	
Cost parameters (DDGS as animal feed)									
Economic margin deficit	p/l		-9.8	-9.4	-8.6	-9.4	-12.4	-12.8	
Cost relative to b1			1.03	1.00	0.91	1.00	1.32	1.36	
Cost of GHG avoided	GBP/t Ceq		2662	927	435	537	569	540	
Relative cost of GHG avoided			2.87	1.00	0.47	0.58	0.61	0.58	

Table 12. Summary of main results and indicators

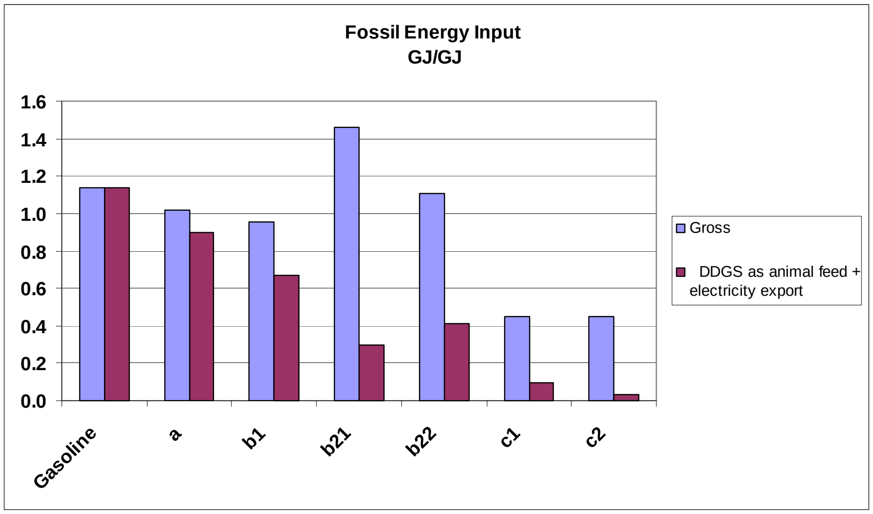


Figure 4. Fossil energy Inputs

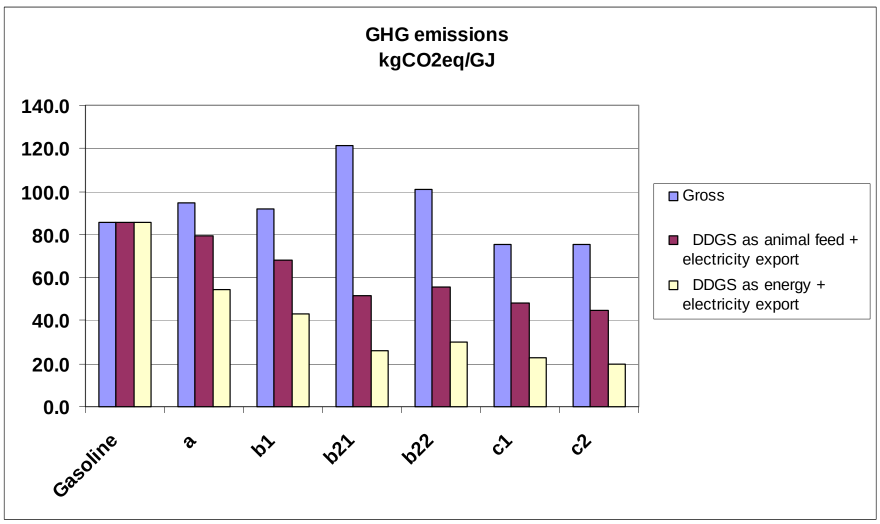


Figure 5. GHG Emissions

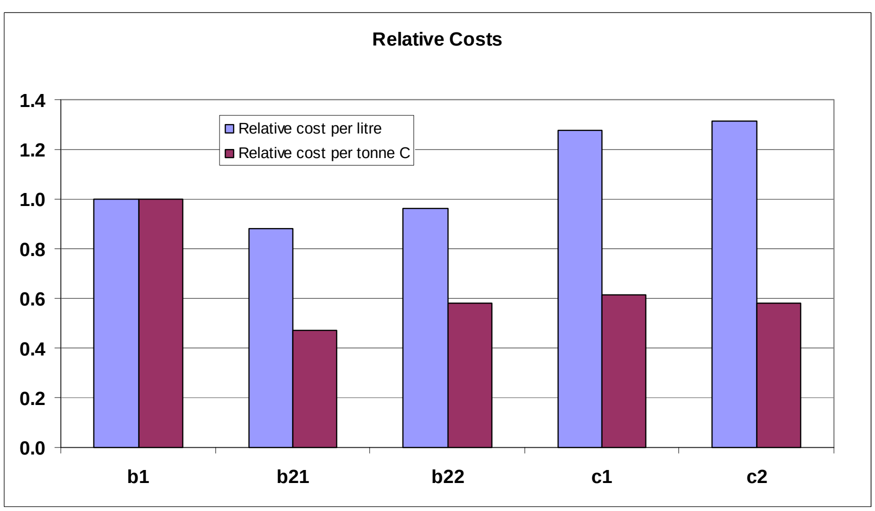


Figure 6. Relative costs

9. Conclusions

1. This study has reached consensus on almost all aspects of the methodology for producing ethanol from wheat. Improved understanding is still needed on N_2O emissions, DDGS credits.

2. All models analysed show lower WTT energy/emissions than gasoline, but how the fuel is made has a big impact.

3. Policy makers should look for these factors to maximise GHG and energy benefits
    a. Incorporation of CHP improves efficiency.
    b. Use of straw as an energy source.
    c. Use of DDGS as energy for power generation.

4. The most efficient models are more costly. Costs should be considered in relation to the environmental savings.

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11. Abbreviations

BPSTG	Back Pressure Steam Turbine Generator - a steam turbine used to generate electricity, but leaving sufficient pressure/heat in the exhaust steam to provide process heat needs
cond STG	Condensing Steam Turbine Generator - a steam turbine used to generate electricity using all the available heat in the steam: the exhaust is effectively hot water.
CHP	Combined Heat and Power - an efficient way of using primary energy, where both electricity and heat are produced and used.
co-firing	Simultaneous combustion of two fuels in the same unit, eg partial substitution of coal by biomass in power generation.
CONCAWE	The Oil Companies' European Organisation for Environment, Health and Safety.
DDGS	Distiller's Dark Grains and Solubles - the residue from the fermentation and distillation process
dwg	Dried Wheat Grain
EUCAR	European Council for Automotive R&D (an organisation of the European car manufacturers)
FAME	Fatty Acid Methyl Ester (biodiesel)
GHG	Greenhouse Gas
LowCVP	Low Carbon Vehicle Partnership
HRSG	Heat Recovery Steam Generator - in this context used to recover heat from the exhaust of a gas turbine, producing steam for process needs.
hwg	Harvested Wheat Grain
ICEPT	Centre for Energy Policy and Technology, Imperial College London
JEC	The JEC Study - abbreviates reference to the joint WTW study of JRC, EUCAR and CONCAWE, 2003.
JRC	Joint Research Centre of the European Commission. JRC Ispra, Institute for Energy Studies contributed to this report
SHU	Sheffield Hallam University
TTW	Tank-to-Wheel, i.e. use of the fuel in a vehicle
WTW	Well-to-Wheels - generic name for the fuel path from primary enrgy to use in the vehicle
WTT	Well-to-Tank - generic name for the fuel production process from primary energy to the vehicle tank.

APPENDIX 1

Ethanol manufacturing plant: Energy generation options

The ethanol manufacturing process requires energy principally in the form of low temperature heat and a relatively small amount of electricity. In the process industry, the common medium to transfer low temperature heat is low pressure steam. Electricity can be either purchased from the grid or generated on site.

Steam can be efficiently produced at high pressure and temperature in a conventional boiler. Various fuels can be used, natural gas being the most popular because of its wide availability, relative cleanliness and a relatively simple hardware requirement. In the case of ethanol production, straw can, in certain cases be available and can also be used as boiler fuel albeit with a rather more complex system (for handling as well as burning the straw).

Steam is also the normal medium to produce electricity in a thermal cycle. Without electricity production the steam is “let-down” to a lower pressure and also “desuperheated” i.e. cooled down by the addition of extra liquid water. The outlet conditions are then suitable for use in the process. Electricity is produced via a steam turbine coupled to an electricity generator (Steam Turbo Generator of STG). A “condensing” STG operates at lower than atmospheric outlet pressure and includes a water-cooled condenser thereby maximising electricity production.

The requirement for low grade heat gives a very good case for “combined heat and power” (CHP). Indeed a so-called “backpressure” or “extraction” STG can be installed with an outlet pressure corresponding to the process steam requirements. The overall efficiency of such a scheme is much better than the combined efficiency of separate heat and power production.

When natural gas is the available fuel, a further refinement of the scheme is to replace the conventional boiler by a gas turbine (GT) coupled to a heat recovery steam generator (HRSG). A gas turbine is in its principle similar to a jet engine. The compressed fuel/air mixture is burned in a chamber and the hot flue gases drive a turbo-generator and an air compressor mounted on a common shaft. The exhausting flue gases are still very hot and are used to generate steam in the HRSG. Additional firing can also be applied in the HRSG to produce additional steam at a very high marginal efficiency. When combined with an STG as described above, the complete scheme is known as “combined cycle” and is the most efficient way of producing electricity today (typically 55% efficiency on natural gas).

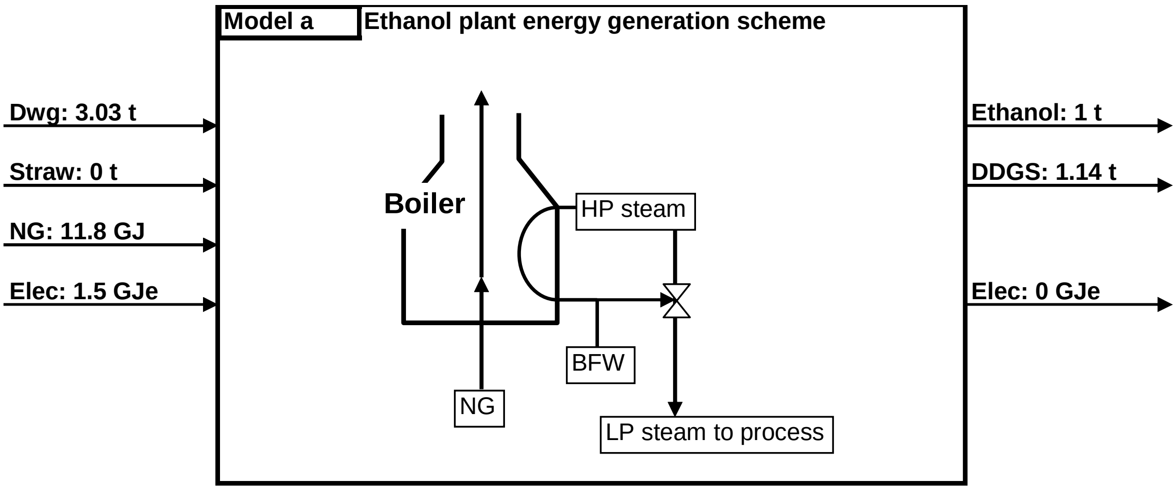
We have considered 6 models covering the range of possibilities described above. They are described below including consumption and production figures expressed for 1 tonne of ethanol produced.

In models a and b, the size of the equipment if determined by the heat requirement of the plant. In models c the determining factor is the amount of straw available.

Only part of the enthalpy of the steam supplied at 3.5 bara and 160°C can be passed on to the process. The recoverable steam enthalpy is assumed to be the difference between the total steam enthalpy and that of liquid water at the same conditions. The actual steam requirement in tonnes is estimated based on the recoverable steam enthalpy. As part of the calculation of the boiler duty it is further assumed that 50% of the hot water heat is recovered when condensate is recycled.

Model a

Conventional natural gas-fired steam boiler + imported electricity



This is the simplest (and cheapest) scheme but also the least efficient. No advantage is taken of the opportunity for co-generation and the electricity is produced at the relatively low average efficiency of the national grid.

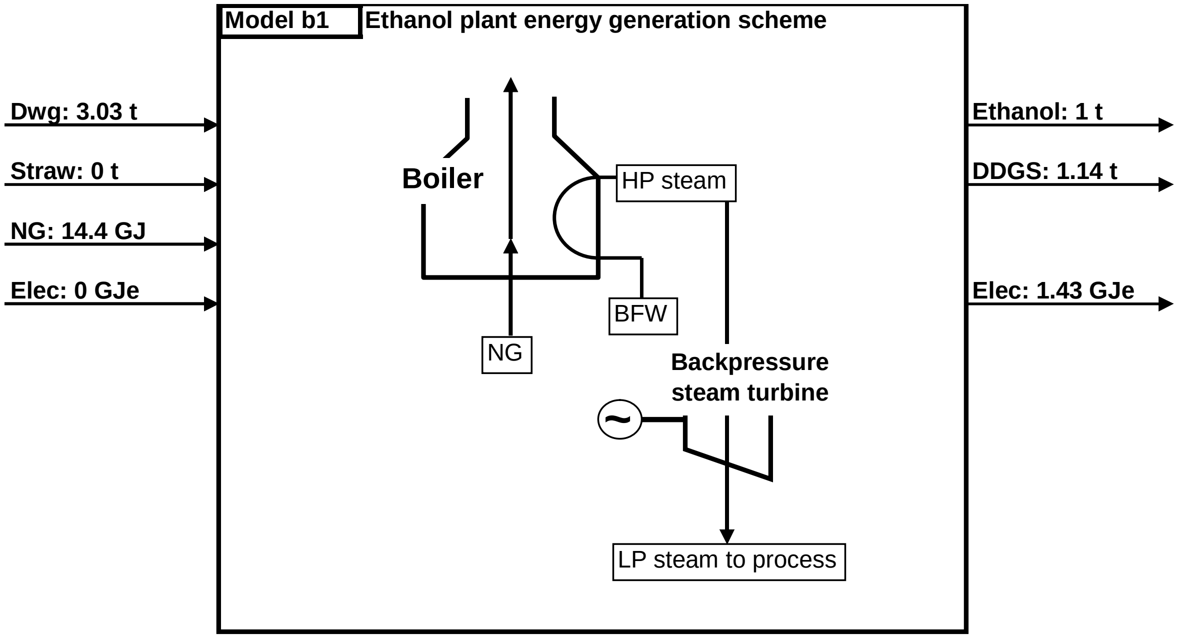
The duty of the boiler is adjusted to produce exactly the amount of steam required by the process.

Main process data:

Boiler		
Steam outlet conditions	bara	68
	°C	520
Steam production	t/t ETOH	4.0
Duty	GJ/t EtOH	11.19
Thermal efficiency		95%
NG consumption		11.78
Steam to process	bara	3.5
	°C	160
	t/t ETOH	4.4
Imported electricity	GJe/t EtOH	1.45
Overall performance		
Total primary energy	GJp/t EtOH	16.96
(including NG and imported electricity production)		
Overall efficiency		66%

Model b1

Conventional natural gas-fired steam boiler
+ Backpressure steam turbo-generator



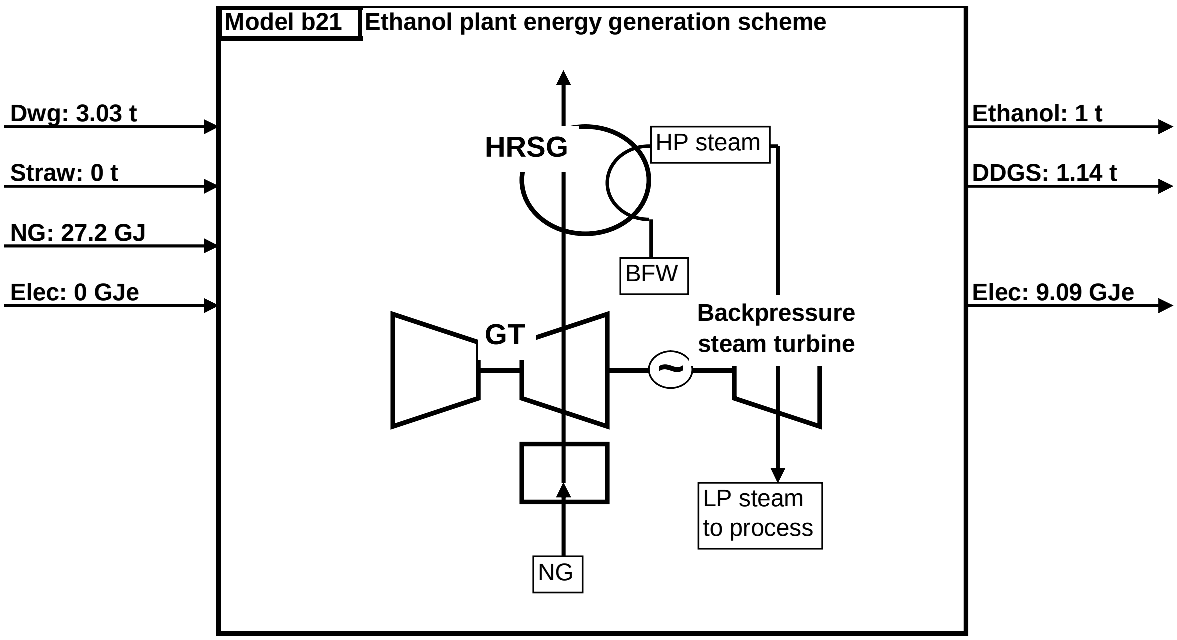
This scheme takes advantage of the CHP opportunity and has a much higher overall efficiency than model a.

Main process data:

Boiler		
Steam outlet conditions	bara	68
	°C	520
Steam production	t/t ETOH	4.4
Duty	GJ/t EtOH	13.66
Thermal efficiency		95%
NG consumption		14.38
Steam to process	bara	3.5
	°C	160
	t/t ETOH	4.4
Backpressure STG		
Efficiency	MWe/t steam	0.18
Electricity generation	GJe/t EtOH	2.88
Surplus electricity	GJe/t EtOH	1.43
Overall performance		
Total primary energy	GJp/t EtOH	15.24
(including NG and imported electricity production)		
Overall efficiency		83%

Model b21

Natural gas-fired gas turbine + unfired HRSG + Backpressure Steam turbo-generator



The gas turbine produces a much larger electricity surplus but also consumes more natural gas (for a 100 kt/a ethanol plant the GT rated electrical output would be in the order of 27 MW).

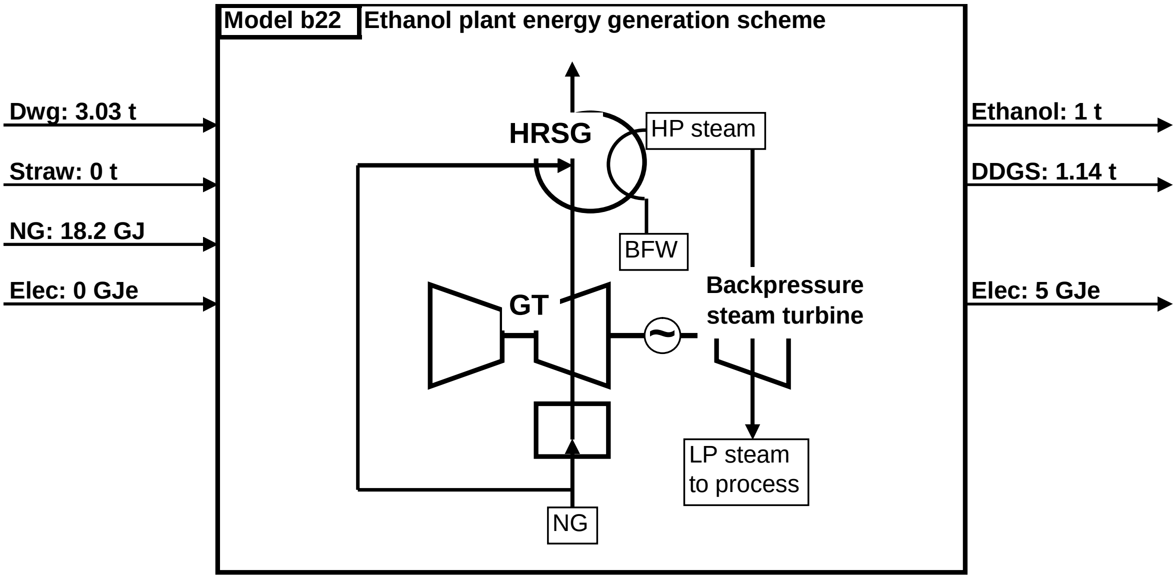
Main process data:

Gas turbine		
Electricity production	GJe/t EtOH	7.66
NG consumption	GJ/t EtOH	27.21
Efficiency		28%
HRSG		
Steam outlet conditions	bara	68
	°C	520
Steam production	t/t ETOH	4.4
Thermal duty	GJ/t EtOH	13.66
Co-firing NG consumption	GJ/t EtOH	0.00
Gas turbine + HRSG		
Thermal efficiency		80%
NG consumption		27.21

Steam to process	bara	3.5
	°C	160
	t/t ETOH	4.4
Backpressure STG		
Efficiency	MWe/t stear	0.18
Electricity generation	GJe/t EtOH	10.54
Surplus electricity	GJe/t EtOH	9.09
Overall performance		
Total primary energy	GJp/t EtOH	28.85
(including NG and imported electricity production)		
Overall efficiency		70%

Model b22

Natural gas-fired gas turbine + co-fired HRSG + Backpressure Steam turbo-generator



The additional firing in the HRSG is extremely efficient. As the system is sized to match the process steam demand, the gas turbine is smaller than in model 21 (for a 100 kt/a ethanol plant the GT rated electrical output would be in the order of 12 MW).

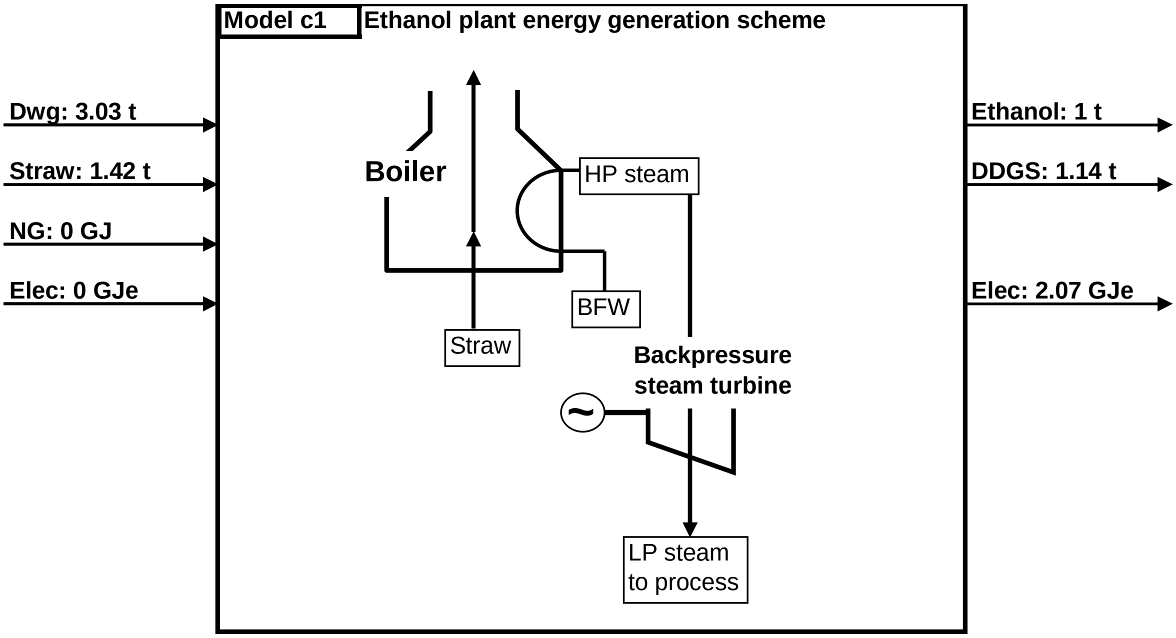
Main process data:

Gas turbine		
Electricity production	GJe/t EtOH	3.57
NG consumption	GJ/t EtOH	12.68
Efficiency		28%
HRSG		
Steam outlet conditions	bara	68
	°C	520
Steam production	t/t ETOH	4.4
Thermal duty	GJ/t EtOH	13.66
Co-firing NG consumption	GJ/t EtOH	5.52
Gas turbine + HRSG		
Thermal efficiency		97%
NG consumption		18.20

Steam to process	bara	3.5
	°C	160
	t/t ETOH	4.4
Backpressure STG		
Efficiency	MWe/t stear	0.18
Electricity generation	GJe/t EtOH	6.45
Surplus electricity	GJe/t EtOH	5.00
Overall performance		
Total primary energy	GJp/t EtOH	19.29
(including NG and imported electricity production)		
Overall efficiency		84%

Model c1

Straw-fired steam boiler
+ Backpressure steam turbo-generator



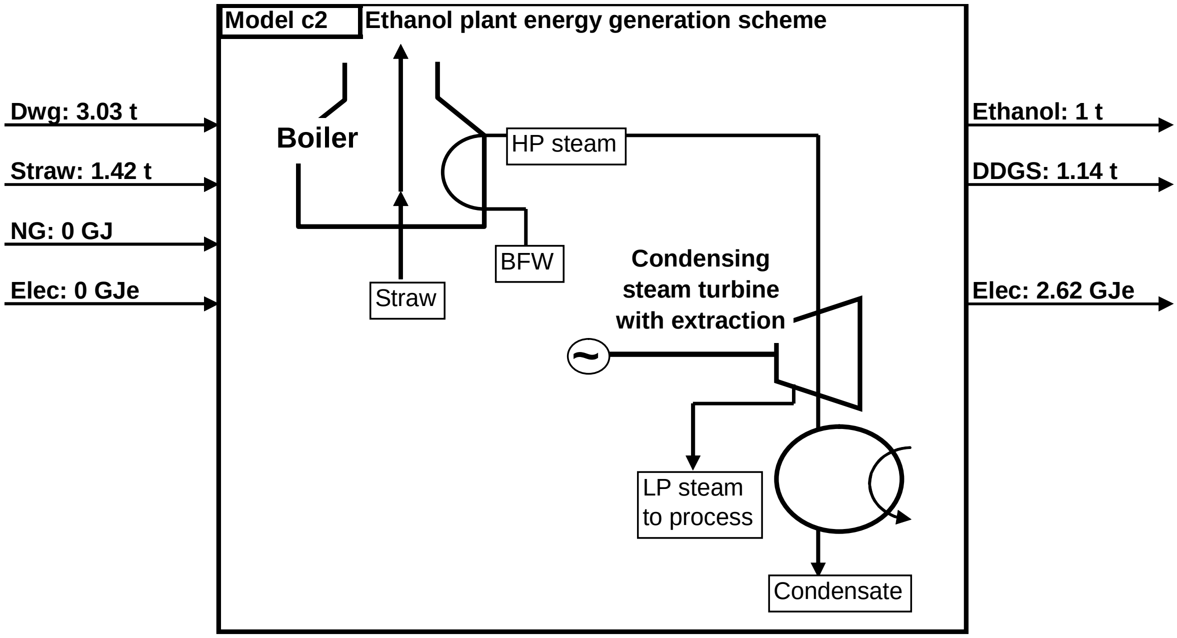
The system is sized to process all the available straw (i.e. in production ratio with the grain used). This is because this would maximise electricity production. As a result the heat generation does not exactly match the requirement. There is a surplus of steam that is not used and assumed to be vented.

Main process data:

Boiler		
Steam outlet conditions	bara	68
	°C	520
Steam production	t/t ETOH	4.4
Duty	GJ/t EtOH	13.66
Thermal efficiency		88%
Straw consumption		1.42
Steam to process	bara	3.5
	°C	160
	t/t ETOH	4.4
Excess steam	t/t ETOH	1.0
Backpressure STG		
Efficiency	MWe/t steam	0.18
Electricity generation	GJe/t EtOH	3.52
Surplus electricity	GJe/t EtOH	2.07
Overall performance		
Total primary energy	GJp/t EtOH	20.79
(including NG and imported electricity production)		
Overall efficiency		64%

Model c2

Straw-fired steam boiler
+ Backpressure and condensing steam turbo-generator



This model represents an extra sophistication of model c1 whereby the excess steam is used for producing additional electricity through a condensing turbine. Although this could be achieved using two separate STG's, they would in practice be combined,since this would be significantly cheaper. This model, of course, avoids wasting part of the available heat, but requires more investment.

Main process data:

Boiler		
Steam outlet conditions	bara	68
	°C	520
Steam production	t/t ETOH	4.4
Duty	GJ/t EtOH	13.66
Thermal efficiency		88%
Straw consumption		1.42
Steam to process	bara	3.5
	°C	160
	t/t ETOH	4.4
Backpressure STG		
Efficiency	MWe/t steam	0.18
Electricity generation	GJe/t EtOH	2.88
Condensing STG		
Efficiency	MWe/t steam	0.33
Electricity generation	GJe/t EtOH	1.19
Surplus electricity	GJe/t EtOH	2.62
Overall performance		
Total primary energy	GJp/t EtOH	20.79
(including NG and imported electricity production)		
Overall efficiency		61%

APPENDIX 2

N2O Emissions from Agriculture

Most of the GHG emissions associated with biofuels production come from farming. The farming emissions are dominated by two sources: nitrogen fertilizer production and emissions of nitrous oxide from the field. Until now, LCA or WTT studies of biofuels have been forced to estimate N_2O emissions either from measurements on individual fields, or from calculations based on IPCC guidelines.

There are enormous variations in N_2O emissions from one field to another, depending on soil type, climate, crop, and fertilizer and manure rates. The revised 1996 IPCC guidelines [IPCC2/1996] only give the possibility to consider nitrogen fertilizer and manure use, and whether or not the crop is nitrogen-fixing. To account for other variables, IPCC specifies a wide error range: the max/min ratio varies from 9 (for direct emissions) to 60 (for leaching effects). But even this range is by far not sufficient to cover the range of values measured on individual fields. For example, a field with wet, peaty, soil may show measured emissions ten times the <u>maximum</u> value from IPCC guidelines.

The soils and waste unit of the Institute of Environment and Sustainability of DG-Joint Research Centre (Ispra) has developed a database-model which we have christened GReenhouse Emissions from Agricultural Soils in Europe (GREASE), which can be used to make a more accurate estimate of greenhouse gas emissions from energy crops, arising from all known sources (direct and indirect). At the heart of GREASE is the DNDC soils model. This is a publicly available program created by the EOS Institute at University of New Hampshire. It simulates carbon and nitrogen soils chemistry in agricultural land. It is universally recognized as the most refined simulation available, and has been extensively validated with field measurements.

GREASE estimates the average emissions per crop for UK by totalling emissions per crop calculated separately for 127 UK regions. To calculate the N_2O emissions from one region on one day, GREASE provides DNDC with 26 items of input data. Calculations are run per day per crop per region for two years. Daily weather data and farming calendar from the JRC-MARS website are combined with soils parameters per region from European Soils Bureau at JRC. EUROSTAT provide crop areas, yields and manure use per region. Average fertilizer use per crop in UK was taken from national averages published by International Fertilizer Association (the average fertiliser rate for UK wheat is 192 kg N per ha).

GREASE ran DNDC for each NUTS3 region of UK (UK contains about 127 NUTS 3 regions, defined by GISCO, part of EUROSTAT). DNDC calculates N_2O emissions each day for a year (1999), using real local weather data provided by the MARS database, (Monitoring Agriculture with Remote Sensing). To establish the starting soil condition, the model is run for a year before the real calculation starts. MARS also provides the calendar of planting and fertilizer application. The nitrogen content of precipitation is interpolated from meteorological station measurements tabulated by EMEP (http://www.emep.int/).

The parameters describing soil type for each NUT are derived from the European Soil Database maintained by the European Soils Bureau at JRC Ispra. This also provides data on %irrigation. The dominant soil of each NUTS3 is characterized by clay fraction, pH, bulk density and soil organic content. The latter has a min. and max. value to account for variations inside the NUT. This range gives minimum and maximum emissions for each NUTS3, but in the UK average the stochastic variation is from this source is negligible. New Cronos database of EUROSTAT provides the land cover data; the area of each crop in each NUTS3 region. Because there is a lack of data on crop rotations, at the moment the model assumes repeated crop years. Furthermore, provisionally, GREASE sets the inputs on plant physiology (which depend on the variety and farming practices) to the DNDC default values. Both give rise to systematic errors, which contribute to the error range of our UK averages.

Uncertainty arises from the coarseness of the available data on N-fertilizer and manure rates. New Chronos provides fertilizer rate data only on a coarse scale (averaged for each of 95 regions in EU instead of the 1700 NUTs in GREASE), and there is no differentiation by crop or soil type. The JRC soils unit used fertilizer-per-crop-per country from the International Fertilizer Association. There are significant discrepancies in the total fertilizers per country reported by IFA/FAO, New Chronos and IPCC.

However, the main problem is the lack of fertilizer rate differentiation by soils type. High-organic soils give high N_2O emissions in general, but require little or no nitrogen fertilizer. If they are assumed to receive the same fertilizer and manure rate as surrounding regions with other soils, N_2O emissions from that NUT are enormously exaggerated: in extreme cases most of the nitrogen applied is predicted to be released as N_2O. The figures from these high-organic soil regions significantly affect the EU average.

CAPPING

The only previous WTW study we know to have discussed the problem of high-organic soils is [GM 2002, ref 7 in main report]. They simply assume that energy crops are not grown on such soil. We think one should consider it, or we are effectively banning energy crops in many parts of UK. In order to avoid the effect of exaggerated N_2O emissions from these regions, we cap the calculated annual N_2O emissions. We made the capping level (for each NUT and crop) proportional to the nitrogen fertilizer rate for as given crop.

We made an upper and lower limit of the proportionality constant, according to the following assumptions:

– *Lower limit*: corresponding to the “max emission factor” for direct N_2O emissions in the revised IPCC guidelines. We can be 95% confident that this assumption underestimates the UK emissions average, because IPCC do not consider high-organic soils: their upper limit is lower than any field measurements on high-organic soils. It is almost like saying “let’s pretend high-organic soils are like normal ones”.
– *Upper limit:* We found three sources that report N_2O emissions from intensive arable cultivation of various crops on high-organic fields in different parts of Finland and Germany. Using our fertilizer data for those crops in those regions, we found the proportionality factors which gave caps at the measured values. Then we averaged the three constants (they differed by less than 25%).

We can be 95% confident that this method overestimates the UK emissions average: it works well with NUTs with very highly organic soils, but does nothing in many marginal cases, where the emissions are already exaggerated but not high enough to reach the cap. In the future GREASE will be refined so that fertilizer rate is also adjusted for soil type: then capping should no longer be necessary.

The best-estimate N_2O emissions from UK wheat (not corrected for reference crop) is 4.36 kg/ha N_2O. Our average N_2O emissions data are likely to be somewhat higher than those of other studies, because:

- We take into account manure use as well as N fertilizer, ([GM 2002], for example, does not)
- We consider both direct and indirect N_2O emissions
- Mostly, because we do not exclude the use of high-organic soil for growing energy crops.

OVERALL ERROR MARGIN

Apart from the uncertainty related to capping, GREASE does not at present consider rotations or the details of crop varieties and farming practice outside those specifically mentioned above.

Using default values set in the USA could give significant systematic errors in the UK average emissions. By experimenting with changing the default values we judge that an error of +/- 25% is possible for a particular crop. If we compound the errors from this source with the errors from capping, we find overall 80% confidence limits of +/-30%.

Despite the difficulties, GREASE has a smaller error margin because it is a sophisticated model averaging 170 regions of UK, whereas most studies use the approximate IPCC guidelines or even extrapolate from measurements on single fields.

Strictly, a correction should be applied for emissions from set-aside land. Results are available from a detailed study of The Wash region, which gives emissions from setaside as 24% of those for wheat, but this is averaged for whatever the farmers were doing with their set-aside (the conditions in The Wash give higher than average N_2O emissions). A UK study, [Brown 2002] confirms modelling at JRC, that the N_2O release during fallow setaside amounts to about 30% of the release from wheat farming. However, their N_2O release figures for wheat in UK amount to about 2.9 kgN_2O/ha/y when direct and indirect emissions are considered, compared with 4.36 from the rather similar JRC model. For fallow land the equivalent figure is about 0.95kg/ha/y

There is also a "background" emission determined by the history of the land use, but not by the current use. This cancels between wheat-growing and set-aside. Note that both studies give higher emissions from fertilizer than IPCC default values (although the UK study has lower emissions from other sectors). An earlier UK study [Salway et.al. 1999] also estimated higher emissions than [Brown 2002].
Investigation of why the JRC N_2O model gives different results than [Brown 2002] proved difficult, because the main author of the IGER-UK study is no longer available. Both studies give a normal distribution of log(N_2O/ha) with about the same median value, but the JRC data has longer tails to both high and low values. For example, at the high end, IGER-UK has no results above 11.6 kgN2O/ha. The high-end tail in the JRC results has a much larger effect in the linear average of N_2O emissions than does the low-end tail.

All these values are higher than in the German studies. Germany has less organic soil, fertilizer use on wheat is lower, and the climate is drier: all of these give less N_2O. Furthermore the Kaltscmitt nitrogen inputs do not, we believe, include manure and rotting crop residues from the previous year (both IGER-UK and JRC include these)

In view of the uncertainties, no correction has been applied for either fallow land N_2O emissions, or for yield reduction from the loss of break crop. For reference, a 30% reduction in N_2O emissions, coupled with a 12% yield reduction would exactly cancel out.

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