Expert Paper on the Global Impacts of Road Transport Biofuels

A Contribution to the Government's Analysis

CLEANER TRANSPORT FORUM

Institute for European Environmental Policy

nsca

NSCA

NSCA brings together organisations across the public, private and voluntary sectors to promote a balanced and innovative approach to understanding and solving environmental problems. NSCA works in the fields of air quality, noise, land quality, local environment management, and industrial regulation. It is a registered charity with over 100 years experience of environmental campaigning, information provision, and policy formulation.

Cleaner Transport Forum

The Cleaner Transport Forum was established in 1997 to bring together organisations with an interest in Transport and the Environment. It has 60 members including representatives from the oil and motor industries, local authorities, retail and distribution interests, environment groups and transport consultancies.

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The following contributors were involved in various ways in the development of this paper. It seeks to set out some key messages and areas of expert consensus on the subject of road transport biofuels, and in particular their merits in terms of reducing greenhouse gas emissions. Any misrepresentations or other errors herein are, however, the responsibility of the editing author, Malcolm Fergusson.

Dr Ausilio Bauen
Head of Bioenergy Group, Imperial Centre for Energy Policy and Technology

Dr Nick Eyre
Director of Policy and Development, Energy Saving Trust

Malcolm Fergusson
Senior Fellow, Institute for European Environmental Policy

Julie Foley
Research Fellow, Institute for Public Policy Research

Dr David Hart
Head of Fuel Cell and Hydrogen Research, Imperial Centre for Energy Policy and Technology

Dr David Martin
Ecovector Consulting

Professor Nigel Mortimer
Resources Research Unit, Sheffield Hallam University

Professor Jim Skea OBE
Director, Policy Studies Institute

Alex Veitch
Senior Transport Policy Analyst, Energy Saving Trust

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Key Messages

What We Know

- The continuing growth in road transport requires effective policy responses which include measures to deliver substantial reductions in future greenhouse gas emissions, if UK commitments under the Kyoto Protocol and longer-term national targets are to be met. Low-carbon road transport fuels could play an important part in this, but both efficiency of fuel consumption and demand management will remain important factors in the overall equation if environmental damage is to be limited.

- Road transport biofuels already available offer greenhouse gas benefits relative to conventional petroleum-based fuels, although the scale of benefit can vary significantly according to the fuel, feedstock and production process.

- Liquid biofuels from wastes, and from lignocellulosic materials, offer potentially greater benefits in the medium term.

- It is an open question whether the UK could sensibly aim to be self-sufficient in transport biofuels, but it is unlikely that this would happen in practice anyway, as imports are likely to occur.

- Imported biofuels are not automatically either better or worse in terms of greenhouse gas emissions than domestically-produced ones, but may well present different issues to be taken into account.

- Biomass is potentially an important 'second front' for renewable energy alongside wind turbines and other electricity generators, and could contribute to the development of either liquid or hydrogen fuel supplies for transport. However, where supplies of biomass are limited, production of liquid biofuels is more complicated and probably less advantageous than burning the feedstock for heat and power, depending on both the prevailing energy mix and the availability of other renewables to produce electricity and heat.

What We Need to Understand Better

- Different allocation methods and other assumptions can make a substantial difference to the estimated greenhouse gas emissions benefits of any given liquid biofuel. This depends in large measure on the likely use of co-products and by-products, particularly from arable crops. A better understanding of how these might evolve in the event of large-scale biofuel production is therefore needed, especially regarding the appropriate allocation procedure for the specific circumstances under consideration.

- The impact of alternative agricultural practices on greenhouse gas emissions is not yet fully understood, and would need to be explored further if these were to be used for biofuel production.

- The technology employed can have a great impact on the associated greenhouse gas emissions from biofuel production, but particularly the technical and economic potential of hydrolysis and gasification based routes needs to be better understood.

- The potential for indigenous biomass production, its competing uses and trade-offs between different uses is subject to significant uncertainties.

- Aviation remains a highly problematic sector. The scope for biofuels remains particularly uncertain, and would only address part of the problem posed by emissions at high altitude.

Policy Implications

- There are significant methodological issues and uncertainties in undertaking life cycle assessments of biofuel greenhouse gas emissions, and in some areas there is no one 'right answer'. Policymakers need to understand this in order to reflect the environmental benefits of biofuels in government policy and policy instruments in a realistic way. In particular, the specific results of life cycle assessments need to address the questions raised in policy-making. Furthermore, it would be useful if simple and robust approaches could be developed to allow the various fuel chains to be compared on the basis of their environmental implications.

- Notwithstanding these methodological problems, it is important for the long term to move towards tax incentives that reflect the environmental outcomes of different biofuels (preferably on the basis of full fuel cycle greenhouse gas emissions).

- As against this, offering a fiscal incentive directly related to the carbon benefit of liquid biofuels may not be sufficient to encourage a major market or industrial development. Additional, integrated measures will probably be needed if it is decided that biofuels are a strategic priority to be encouraged. Different types of policy support are likely to be needed at different stages of the various biofuels' development. For example, fuel duty breaks will at least help to create a market for biofuels from arable crops; many biofuel sources (particularly the ligno-cellulosic options) are some way from being commercially viable, so duty breaks will make little difference at this early stage. These fuels need government support to aid their commercial development, eg through demonstration projects or provision of venture capital funds.

- The development of a market for road transport biofuels can be construed as contributing to a range of policy objectives, such as rural development, agricultural diversification, local environmental benefits, greenhouse gas abatement, or reduced oil dependence. A clear understanding of the importance and specific nature of these different objectives is needed in drawing conclusions as to the desirability or cost-effectiveness of biofuel production. It might also help to determine what type of biofuel production would be most advantageous.

- Some of the most favourable assessments of current biofuels assume production processes which are not currently the norm (eg using straw for process heat). To realise this potential in full might require additional policy incentives, and there may be a cost attached to these.

1 Introduction

This paper has been compiled by a group of academics and other independent experts with experience and interests in the area of road transport biofuel technology and policy. The Department for Transport (DfT) invited the National Society for Clean Air and Environmental Protection (NSCA) and the Institute for European Environmental Policy (IEEP) to facilitate an expert/stakeholder consultation process in support of its own internal work on the issues. The work of this group is one of two main strands to the project as a whole: the other, which is also being facilitated by IEEP, addresses other, more local, impacts of biofuels, such as land use, biodiversity, regional development, agri-cultural practices, etc. The work is overseen by the Cleaner Transport Forum. DfT and the BOC Foundation have kindly agreed to fund the project, which culminates in a conference at the end of March 2004.

Amongst the authors (see page 2) are several who have been involved in major assessments of biofuels in the UK in recent years, including ongoing work at Sheffield Hallam University (SHU) and Imperial College, London (IC). Elements of various sets of results are incorporated in this paper.

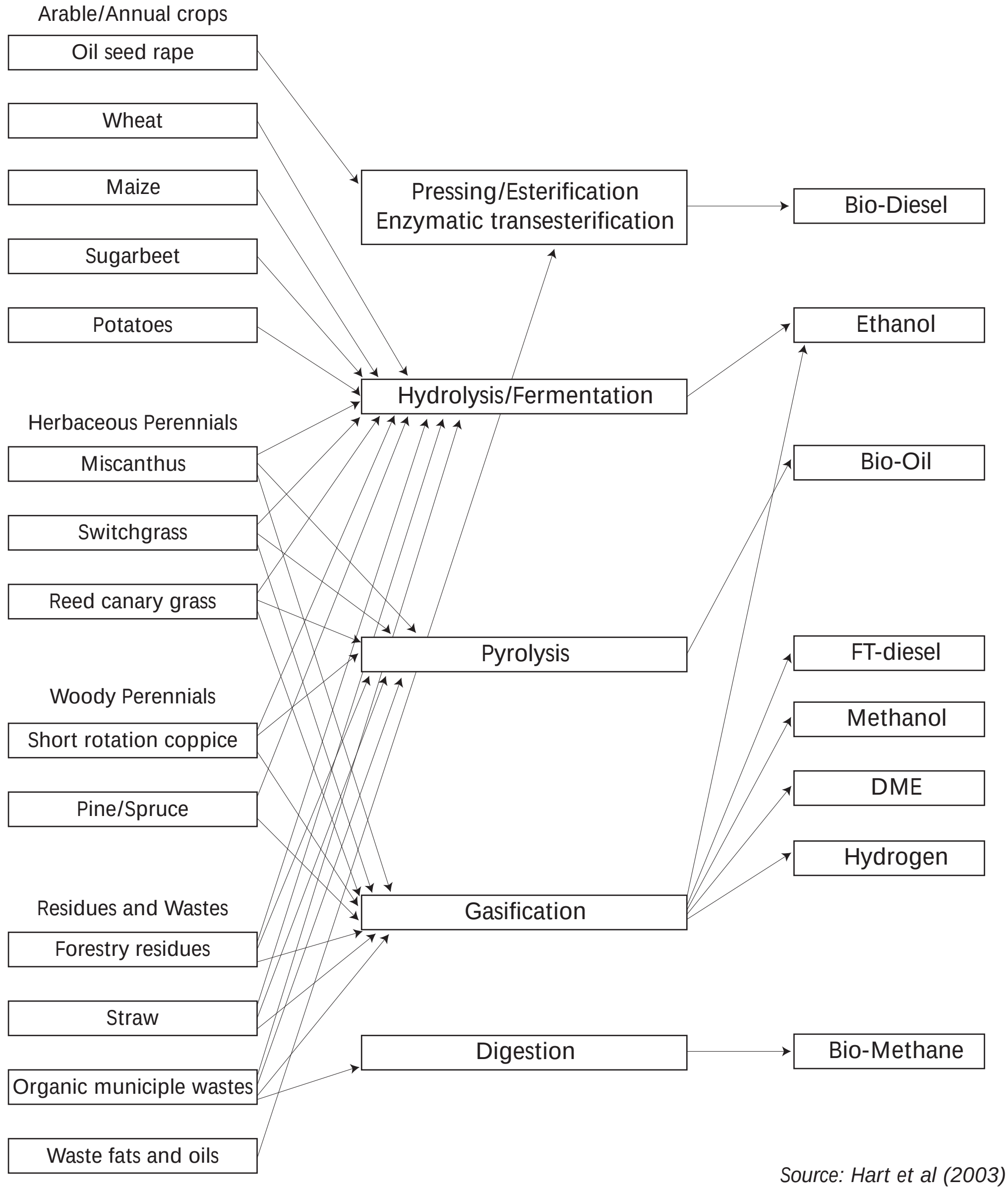
The next section of this paper briefly outlines the main road transport biofuel options which are currently available, and those which appear most likely to come on stream over the coming decades. Section 3 sets out a range of methodological issues and explains their importance in interpreting the various fuel cycle assessments of greenhouse gas emissions which have been undertaken, and in explaining some of the differences between the various analyses. Section 4 sets out a range of these estimates from recent literature in a comparable format, and seeks to identify areas of common ground and to explain or highlight divergences between them. Section 5 addresses the framing of the issues in the policy context, and highlights interlinkages with a range of policy areas, while Section 6 adds some broad conclusions.

2 The Main Fuel and Technology Options

A wide range of biomass feedstocks and processes is available or will soon become available to produce an equally wide variety of biofuels, some of which are useable as motor fuels, and others not. Hart *et al* (2003) characterise the main options diagrammatically as follows in Figure 1.

For the purposes of this exercise, however, we will focus on the most probable options, distinguishing those already available commercially from those which are likely to become available in the coming years.

Figure 1: Pathways to Liquid Biofuels



Source: *Hart et al (2003)*

2.1 Options Available Now

Biodiesel from Oil Crops

Biodiesel is also known as Vegetable Methyl Ester (VME) or Fatty Acid Methyl Ester (FAME), or, when made from rapeseed oil, Rape Methyl Ester (RME). It is manufactured through the esterification of vegetable oils or animal fats, from one of two principal sources: oil extracted from seeds or oil-rich nuts; or recovered waste vegetable oils and animal fats. The latter is highly desirable in environmental terms, although processing requires impurities to be treated or removed before esterification.

For the UK and the rest of Europe, rapeseed and sunflower are the principal potential feedstocks; elsewhere, soya and palm oil are options. Currently rapeseed is by far the most common feedstock globally.

Biodiesel can be used in pure form in diesel engines with some minor engine modifications, or it can be blended with conventional diesel for use in standard engines. All stages of the biodiesel production chain are already commercially available, and industries are established in several European countries.

Bioethanol from Sugar and Starch Crops

Ethanol is currently produced by fermentation of crops high in sugar, or a sequence of hydrolysis/fermentation steps for starch crops. Principal feedstocks for ethanol production in the UK and the rest of Europe are sugar beet and wheat grain. Other possible sources elsewhere are corn (mainly in the US), sugar cane (mainly in Brazil) and sweet sorghum.

Ethanol has been in common use in transport for about 30 years around the world as both neat ethanol and as a blending agent or oxygenate in petrol. A 10% by volume ethanol blend in petrol contains about 97% of the energy of pure gasoline, but this is compensated by increases in combustion efficiency leading to similar volumetric fuel efficiency. If ethanol blends are increased above 20% by volume, a higher compression ratio is needed to produce similar power to that of a same size petrol engine. Alternatively, ethanol could be converted to the ether ETBE (Ethyl Tertiary Butyl Ether) which is added as an oxygenate to petrol.

The fermentation and distillation of sugars obtained from crops such as sugar beet is very well established, and is nearing its efficiency limit, though recent developments may allow further improvements. Ethanol produced from starch is also a commercial process already, but recent R&D has concentrated on improving the hydrolysis process to produce simple sugars and reduce the significant energy requirements of the process.

2.2 Options Potentially Available by 2020

Bioethanol from Lignocellulosic Materials

In the medium term, further improvements in hydrolysis offer the possibility of manufacturing ethanol from a wide range of lignocellulosic materials. These might include straw; wood and wood residues; energy grasses such as miscanthus; human and animal slurries; and the organic fraction of municipal solid waste.

This is an important development as it offers the prospect of recycling a range of waste products and low-value co-products, and of using a wider range of plant feedstocks including high-yielding energy crops.

Ethanol production from lignocellulosic biomass is still at the demonstration stage, however. A key challenge will be ensuring that the cost of future commercial production is competitive, but there is some evidence to suggest that costs could be significantly below those of current sugar and starch-based processes (Woods and Bauen, 2003).

Gasification Products

As Figure 1 above illustrates, gasification provides an alternative route to conversion of a wide range of biomass feedstocks, via a range of processes, into various end products. These are not all described here. However, gasification may in the medium term offer a more robust process than those currently available, offering greater flexibility in the range of feedstocks and of products.

The Fischer-Tropsch Process

One attractive option is use of the Fischer-Tropsch (FT) process to convert gasified material to diesel, with additional outputs of kerosene, naphtha and some gaseous hydrocarbons. A particular attraction of this process is that biokerosene could be used to help address the intractable emissions problems of the aviation sector, while naphtha could be used as a chemical feedstock, and the gases as process heat or to generate electricity. FT-biodiesel is chemically similar to mineral diesel and can be used as a direct mineral diesel substitute.

FT process technology is already mature, having been used for some time to make liquid fuels from coal, and more recently from natural gas. Biomass gasification technology is at the demonstration stage, as is the integration of biomass gasification with the FT process. In Europe, a single pilot plant in Germany currently produces FT-biodiesel.

Dimethyl Ester

Dimethyl ester (DME) can be used as a clean and efficient direct substitute fuel in diesel engines. It has the advantage that all biomass gasification products can be converted to DME in a dedicated plant, as opposed to the FT process that results in a range of fractions in the output.

However, DME requires dedicated infrastructure and on-board storage, as opposed to synthetic diesel that can be integrated into the fossil diesel infrastructure. Also, the technology is as yet still at the demonstration stage, and seems unlikely to capture a major share of the market.

Hydrogen

The use of hydrogen as a road transport fuel offers a number of potential attractions. Hydrogen can be produced from a variety of different sources, especially renewable energy resources including biomass. When renewable energy resources are used to provide the hydrogen, potentially low total greenhouse gas emissions can be realised. The range of possible sources of hydrogen also adds to diversity of supply. Hydrogen is generally expected to be deployed in conjunction with fuel cells, which are significantly cleaner and more efficient than internal combustion engines. Furthermore, the use of hydrogen in road transport is usually foreseen as an essential component for the ‘hydrogen economy’ which is put forward as a comprehensive alternative to the current ‘fossil fuel economy’ (see for example ippr, 2001). This would offer benefits in terms of avoiding energy resource depletion and reducing greenhouse gas emissions by increasing reliance on renewable energy sources. Direct emissions of harmful pollutants could also be reduced, thereby protecting urban air quality.

However, these prospective benefits must be set within the context of the fundamental and extensive changes which would be necessary to implement a hydrogen economy. For its use to become widespread, a large hydrogen storage and distribution infrastructure, capable of replacing the existing system based on fossil fuels, would have to be developed. This would take considerable time and require extensive capital investment. Prototype hydrogen fuel cell vehicles are already in operation, but large scale deployment is expected to be instituted over a number of decades, and is not a mainstream option for the immediate future.

3 Well-to-Wheel Greenhouse Gas Emissions: Some Methodological Issues

Given the appropriate policy context, total greenhouse gas emissions for the production of transport biofuels can be compared with conventional transport fuels so that net savings can be determined. This assists with evaluating the likely impact on global climate change mitigation of policies that are intended to promote the replacement of conventional transport fuels with biofuels. However, some important methodological issues need to be borne in mind.

Well-to-tank and Well-to-Wheels Assessments

With conventional road fuels and engine technologies, emissions have historically been measured at the exhaust tailpipe of the vehicle. For carbon dioxide, this measurement would reflect the amount of fuel (and hence carbon) which is consumed in moving a vehicle a given distance. In this case such an approach is adequate for most purposes; although there are additional emissions which result from the production of the fuel at the refinery, these are relatively small and proportionate to those from tailpipe emissions, at least if the fuels are derived from conventional sources of crude oil.

For liquid biofuels, however, such an approach would be completely misleading: they too emit carbon dioxide from the vehicle exhaust in significant quantities, but they offer benefits because this carbon was absorbed from the atmosphere as the source plants grew, rather than being released from underground storage as is the case with fossil fuels. Hence the requirement is to assess the emissions incurred from all stages of the life cycle of the fuel – moving from a 'tank-to-wheels' to a 'well-to-wheels' (WTW) analysis. For a petroleum-based fuel this mainly involves adding in the emissions from refineries and transportation of the fuel to the filling station, but for a biofuel it may be much more complex, as described below.

Particularly where there is a change in vehicle technology as well as fuel involved (eg in switching to hydrogen fuel cell technology), then a full WTW analysis is necessary to give comparable results. Liquid biofuels, however, are likely to be used initially in normal petrol or diesel engines as a blend with the conventional fuel, and in this case the calculation can be simplified by ignoring the engine part of the equation. The result is then a 'well-to-tank' calculation, which can be used to compare the emissions per unit of useful energy of any two fuels which can be used interchangeably. Since the Sheffield Hallam work has concentrated on liquid biofuels of this sort, a well-to-tank methodology was used, whereas other studies covering a wider range of fuels use the WTW approach. The work at Imperial College is also well-to-tank. This is not a problem, except in that the well-to-tank results need to be modified to reflect the relative efficiencies of petrol and diesel engines in order for results to be fully comparable between the two fuels as they are in a WTW analysis.

Scope of Assessments

In the context of climate change policy, assessment of the impact of producing liquid transport biofuels focuses on weighted total greenhouse gas outputs from the whole production cycle, and principally those of carbon dioxide, methane and nitrous oxide. Total greenhouse gas outputs equal the *direct* emissions from the combustion of fuels and the *indirect* emissions due to the production of these fuels, the generation of electricity and the manufacture of materials, equipment, etc for use in the process. In addition, other sources of greenhouse gas outputs *may* be taken into account in any analysis, as follows:

- Changes in the storage of carbon in soil can result in net increases or decreases in greenhouse gas emissions for the cultivation of crops of transport biofuels. However, due to the many uncertainties over the evaluation of net carbon balances for particular crops, associated greenhouse gas emissions are not included in the results presented here.

- In contrast, other greenhouse gas emissions, particularly carbon dioxide emissions from the manufacture of cement and nitrogen fertiliser, may be significant and are commonly taken into account, as they are in the results presented here.

- Reflecting greenhouse gas emissions from feedstocks must be treated with care:

whether carbon originally derived from fossil fuels used in the production process actually leads to carbon dioxide emissions will depend on the ultimate fate of this carbon. If the carbon always remains stored in the feedstock, then it should be excluded from calculations, but if the feedstock is eventually burnt or decomposes naturally, the carbon dioxide (and possibly methane) released must be included.

- Additionally, the carbon in fossil fuels used as feedstocks in chemical processes may be released as carbon dioxide emissions as a result of chemical reactions. This is an important consideration for the production of nitrogen fertiliser from natural gas. In this case, carbon dioxide is a by-product of nitrogen fertiliser production, emitted in sufficient quantities to be recovered for subsequent sale as an industrial gas. Uses for the latter include the manufacture of soft drinks and injection into oil reservoirs for enhanced oil production, and the likelihood of the eventual release of this carbon dioxide into the atmosphere depends on the particular application. In most instances, though, it is assumed that the carbon dioxide ultimately reaches the atmosphere and contributes to global warming. Hence, this must be reflected in this case in the calculations relating to the initial production of nitrogen fertiliser.
- Similarly, nitrous oxide emissions from the application of nitrogen fertiliser to cultivated land are also taken into account here as elsewhere.

Global Warming Potentials

Assessments of the emission of individual greenhouse gases can be combined together using factors which reflect the global warming potential (GWP), which relates other greenhouse gases to an equivalent amount of CO_2. This is important in this context, as methane and nitrous oxide, although emitted in much smaller quantities than carbon dioxide in some biofuel production processes, have higher warming potentials. In the work of SHU, for example, it is assumed that the 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.

It should be noted that standard values of global warming potential depend on the period considered for policy deliberations due to the different times which each greenhouse gas remains in the atmosphere (IPCC, 2001). Appropriate values for GWPs must be selected and applied depending on the period of the policy scenario under investigation. The standard values used reflect the GWPs over a hundred-year time horizon, which is the recommended practice. However, this is arguably rather a long perspective for a medium-term policy scenario, and a 20-year horizon might be preferable. This is significant in calculating the impact of methane in particular, as its GWP over 20 years is substantially higher than that for 100 years.

The Range of Factors to be Considered in Calculations

Although there are differences between the sources of biomass and the types of processes used to produce transport biofuels, a core of key considerations affects calculations of the greenhouse gas emissions associated with their production. These key considerations include:

- cultivation practices
- crop yields
- fertiliser application rates
- fertiliser manufacturing
- the use of co- and by-products, and
- the utilisation of renewable and other energy sources in biofuel production.

Cultivation practices, crop yields and fertiliser application rates are, of course, interrelated issues.

Potential Impact of Alternative Agricultural Regimes

Most studies (including those reflected in this report) reflect conventional cultivation practices and do not, for example, address organic agriculture or farming based on genetically-modified crops. The effects of other cultivation practices would need to be investigated separately, but such an investigation would need to be based on reliable data which can be extrapolated on a national scale to obtain results that are both reliable and comparable. Notwithstanding this, it can be argued that alternative cultivation practices might not necessarily cause dramatic reductions in the greenhouse gas emissions associated with transport biofuel production. For example, organic agriculture would reduce artificial fertiliser application rates, which would be beneficial, but direct fuel consumption might rise owing to additional field operations and average crop yields might fall. Similarly, additional field operations, the use of specialised pesticides, herbicides and fungicides, and the complexity of seed preparation may increase the direct and indirect fuel consumption of agriculture based on genetically-modified crops despite decreases in fertiliser use and improved crop yields. It should be noted that preliminary work involving the sensitivity analysis of biodiesel production from oilseed rape suggests that the negative impact of falling crop yields on greenhouse gas emissions is more important than that of increasing crop yields with conventional cultivation practices (Mortimer *et al*, 2003).

Fertiliser Application Rates

Apart from the link with crop yields, the fertiliser application rate has a direct and significant influence on the greenhouse gas emissions of transport biofuel production through the manufacture of the fertiliser. Significant amounts of primary energy use are associated with ammonium nitrate production in particular, despite strenuous and successful efforts to improve the efficiency of the industry in recent times, because a fossil fuel feedstock, typically natural gas, is unavoidably used in production. Furthermore, carbon dioxide and nitrous oxide are produced during manufacture. Also, very large quantities of carbon dioxide are produced which are recovered for subsequent use, and as explained above, this may or may not be eventually released into the atmosphere. Nitrous oxide emissions from soil treated with ammonium nitrate are also significant, and have to be included. Hence, even leaving aside the relationship between crop yields and fertiliser application rates, it can be seen that future trends in greenhouse gas emissions associated with transport biofuels depend, to an important degree, on the operation of the global fertiliser industry, and on the subsequent use of carbon dioxide as a significant by-product.

Treatment of Products, Co-Products and By-Products as Renewable Fuel Sources

The actual use of co- and by-products from the production of most transport biofuels is a key consideration for estimating associated greenhouse gas emissions. The importance of allocation procedures is discussed below, but it must also be emphasised that the chosen approach must reflect the reality of actual production. One particular feature of the majority of co- and by-products derived from transport biofuel production is that they can, potentially, be used as fuels. In fact, it can be argued that if transport biofuels are produced in substantial quantities then there would be a significant glut of co- and by-products that would result in their re-classification as waste products, some of which are simply ploughed back into the soil. The only realistic and acceptable alternative in this case might be use as fuels, most obviously in the processing of the biofuels themselves, which requires significant amounts of heat and electricity. A number of co- and by-products could be used in this way, and since they all derive, ultimately, from biomass sources, they could displace most or all of the fossil fuels that would otherwise be used in the conversion and processing of transport biofuels.

If this were to happen, it would result in very large reductions in greenhouse gas emissions, to the point where the biofuels could become ‘carbon neutral’ or even ‘carbon negative’. This results from avoiding the significant use of fossil fuels in the biofuel production plant and the ‘exporting’ of surplus electricity which displaces conventional supplies derived mainly from fossil fuel sources. However, positive action is needed to realise this particular potential: co- and by-products would have to be recovered and used as standard practice, and biomass heating systems and combined heat and power systems would have to be incorporated into actual transport biofuel conversion and processing plants. This is not common practice at present, however; gas or oil heating is widespread because it is simple to use, well understood and cheap. In addition to proving the technical possibility of recovering and burning certain co- and by-products, therefore, serious economic consequences would have to be accommodated to change this. However, without such commitment, these significant benefits for reductions in energy resource depletion and greenhouse gas emissions cannot be claimed automatically for transport biofuels.

A similar point relates to the potential use of liquid biofuels in the tractors and other machinery used for biofuel production. If this were to displace the diesel fuel currently used, it too would improve the environmental performance of the production cycle. However, the extent of the improvement is limited because using liquid biofuels in agricultural operations effectively reduces the amount of saleable product for other users. Furthermore, the ‘red diesel’ currently used enjoys a very low rate of duty, and is therefore far cheaper than any foreseeable biofuel substitute. There is therefore currently no incentive for this to happen.

The Need for Allocation of Emissions and Other Impacts

The Rationale for Allocation

The production of transport biofuels almost invariably involves the generation of co-products and by-products, and these may indeed be essential to the economic viability of the crop as a whole. For example, rape straw, rape meal and glycerol are produced during the production of biodiesel from oilseed rape. Although rape straw is often regarded as a waste product, it has potential as a material or a heating fuel. Rape meal is usually prepared as an animal feed and glycerol is sold for use in the chemical and pharmaceutical industries. Bioethanol production from wheat provides wheat straw, which can be used as a potential material or heating fuel or as bedding for animals, and distillers' dry grains, which are the basis for animal feed. Apart from displacing conventional heating fuels such as natural gas or burning oil, the use of co-products and by-products as fuel can generate surplus electricity which can be sold to other users, either directly or through public electricity networks.

In all these instances it is necessary to allocate greenhouse gas emissions in a logical way between the biofuel and its associated co- and by-products. Allocation is essential so that co- and by-products, which by definition have other uses, carry their share of the greenhouse gas emissions involved in their joint production with the biofuel. Otherwise, not only does the main product carry the entire burden of greenhouse gas emissions, but also the co- and by-products would then carry none of these implications, and might incorrectly appear in a favourable light compared with alternative products. In either case, this could lead to inappropriate policy choices. It is also important to understand the principles and practice of allocation in order to be able to interpret different greenhouse gas emission results appropriately.

Allocation Methods

Allocation procedures are important, and options for their application are set out in the International Standard ISO 14040 Series (European Committee for Standardisation, 1998). There are several possible rules to follow for allocation, and there is no one 'right answer' to the problem.

The method which appears to be favoured in ISO 14040 and recommended by many practitioners is based on ***substitution***. This involves applying effective greenhouse gas emission 'credits' for co- and by-products derived from the analysis of their main means of production. This is the approach used in the major European-level study completed recently, and which is discussed below. 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 is that a considerable amount of 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 itself, and unfortunately, this is often the case with transport biofuel production. For example, soya meal could be regarded as an alternative for the rape meal obtained during the production of biodiesel from oilseed rape, but it is always jointly produced with soya oil, so the substitution approach simply transfers the problem to the analysis of soya meal and oil production. In cases such as this, the substitution approach becomes a circular non-solution, even though it is still possible to derive a mathematically-correct 'result'. The use of credits in this context assumes that a by-product can be and actually is replaced by another main product; but where both are by-products, then the assumption is, in effect, that they are substituting each other simultaneously, which is clearly not credible.

One by-product that can, in theory, be addressed reasonably well by the substitution approach is surplus electricity. In this case, it can be assumed that surplus electricity displaces a given source of electricity, such as an ageing fossil fuel-fired power station, or average supplies of electricity available from the public network. Even here, however, the mix of electricity supply sources can change significantly over time, so the results only give a 'snapshot' and might be a poor guide to the future environmental performance of the biofuel production system.

When substitution cannot be used, ***mass*** or ***energy content*** are often suggested as an alternative basis for allocation. These physical characteristics are superficially attractive because they can usually be measured quite accurately and easily for all the joint products under consideration, and they do not vary over time. However, they do have important drawbacks.

The main problem with using mass is that some co- or by-products may be produced in much greater quantities than the main product. This would result in the majority of the emissions being allocated to the co- or by-products rather than the main product, which implies, in effect, that the co- or by-products were more important that the main product, which is by definition incorrect. This creates logical inconsistencies, especially when the co- or by-products are actually waste products: here the majority of the greenhouse gas emissions would be allocated to a product which is simply thrown away. This situation might well occur with transport biofuels.

Using energy content as an alternative might be realistic if all the joint products are actually used for energy purposes. Even here, though, care is needed as the term 'energy content' can refer either to the amount of heat released when a fuel product is burned, or to the amount of metabolic energy derived by an animal when a food product is eaten. These two types cannot be added together since the energy in fuels is hardly ever a substitute for the energy in food or vice versa. This approach is also inconsistent if some of the joint products are used for entirely different purposes, such as materials, where it is quite unlikely that they will ever be converted into useful energy. These factors are significant because some transport biofuels are commonly associated with by-products used for animal food and other purposes.

Another method is clearly needed in the many cases where allocation by substitution, mass or energy content would not be applicable, and here allocating on the basis of the respective ***value*** of outputs (ie unit price multiplied by quantity) is commonly used. The main attractions of this approach are that prices can normally be found for all the joint products if they are sold in the market, and the resulting monetary values are directly comparable because they are, quite literally, expressed in a 'common currency'. They also presumably provide some measure of the relative usefulness of the various products.

However, these advantages of market prices also lead to the main drawback of this approach. Unlike allocation procedures which are based on fixed characteristics of the joint products, partitioning on market prices depends on factors which can and do change over time. Transport biofuels offer highly pertinent examples of this, because if production is significant, then the supply of co-and by-products will also increase proportionately. In these circumstances, it is very possible that an oversupply of any given co- or by-product could occur, leading to a dramatic fall in its market price, or it even becoming a waste product. In these circumstances, greenhouse gas emissions would be increasingly allocated to the main product, ie the transport biofuel, and this takes us back to the 'no allocation' case which was the point of departure for this discussion. In this sense, no allocation can be viewed as the limiting, worst case variation of allocation by price.

In summary, allocation by price must be regarded as a valid approach in the many cases in this field where the alternatives cannot be used. However, results based on present-day prices could well be a poor guide to future performance. Complementary economic assessments should be used as an indication of the robustness of such assessments, and the no allocation method provides a worst case scenario.

The Effect of Different Allocation Methodologies

The effect of using different allocation approaches on results for transport biofuels has been investigated in a number of studies (eg Kaltschmitt and Reinhardt, 1997), albeit not in detail in the United Kingdom. However, some indication of the effect of allocation can be demonstrated by comparing the relative savings in greenhouse gas emissions for some transport biofuels relative to conventional transport fuels using allocation by mass and price, or without allocation. The basic assumptions involved in this exercise are set out in the relevant study (Elsayed *et al*, 2003).

As the Table overleaf illustrates, the allocation assumptions can make a significant difference to the supposed benefit of the biofuel in net greenhouse gas terms, especially for biodiesel. However, it can be seen that allocation by price tends to fall in the mid-range between the (not very realistic) allocation by mass and the (possibly over-pessimistic) no allocation case. As such, allocation by price could be regarded as reflecting the current situation most accurately. In contrast, no allocation might represent the extreme case in which biofuel production was a major activity in which the by-products became surplus to requirements and, hence, had no value so that all greenhouse gas emissions would be allocated entirely to the biofuel as the main product.

Table 1 The impact of allocation method on greenhouse gas results

Biofuel	Net Carbon Savings (%)	Net Methane Savings (%)	Net Nitrous Oxide Savings (%)	Net Total Greenhouse Gas Savings (%)
Biodiesel from Oilseed Rape	79 ± 1	32 ± 4	- 226 ± 27	72 ± 1
- with allocation by mass	71 ± 1	12 ± 8	- 639 ± 80	53 ± 2
- with allocation by price	59 ± 2	- 68 ± 12	- 1188 ± 147	25 ± 5
- without any allocation				
Bioethanol from Sugar Beet				
- with allocation by mass	63 ± 4	59 ± 5	- 320 ± 36	60 ± 4
- with allocation by price	58 ± 4	41 ± 5	- 642 ± 71	51 ± 4
- without any allocation	56 ± 4	36 ± 4	- 820 ± 107	46 ± 4
Bioethanol from Wheat				
- with allocation by mass	81 ± 1	18 ± 1	- 213 ± 36	78 ± 1
- with allocation by price	70 ± 2	27 ± 14	- 428 ± 36	64 ± 2
- without any allocation	59 ± 4	- 73 ± 18	- 642 ± 71	52 ± 2

Note: Net savings are relative to the corresponding conventional fuel (petrol or diesel).

Source: Elsayed *et al*, 2003

4 Various Estimates of Well-to-Wheel Emissions

Comparison of GHG Emission Calculations from Different Studies

This section seeks to present three recent sets of results of life cycle analyses in a comparable and simple format. Two (SHU and IC) are aggregations of various work by some of the authors of this paper, and the third (CEJ) is of a major recent European study. These studies and their key characteristics (which differ in some important respects) are summarised in Table 2 below.

Table 3 sets out a range of representative results from the three studies for comparison. Here, total fuel-cycle weighted greenhouse gas emissions of various biofuels are measured relative to those of a corresponding conventional fuel obtained from crude oil. This approach allows well-to-tank and well-to-wheels results to be compared on a similar basis, and the resulting percentages reflect the degree of reduction (or occasionally increase) in greenhouse gas emissions achieved by the substitution of a biofuel for all or part of the conventional fuel. Note however that the results do not fully reflect the absolute benefit in terms of greenhouse gas emissions per unit of distance driven, since the latter are also influenced by vehicle and engine efficiency, and in this respect, diesels are typically more fuel-efficient than a petrol equivalent.

Although there appears at first to be a significant divergence between the different sets of results, in some cases there is reasonably good agreement, and elsewhere some of the differences are easily explained.

Table 2 Some recent studies of greenhouse gas emissions

Provenance/authorship	Acronym	Coverage	Scope	Allocation Method
Sheffield Hallam University	SHU	Liquid biofuels	WTT	Price
Concawe/Eucar/JRC	CEJ	All major	WTW	Substitution
Imperial College	IC	All major	WTT	None

Table 3 Comparison of relevant SHU, IC and CEJ Results

Feedstock	Process	Range	GHG % of Conventional Equivalent		
			SHU	CEJ	IC
Oilseed Rape	Esterisation	Low	45%	38%	20%
		Mid	**47%**	**62%**	**36%**
		High	49%	84%	52%
Recycled Vegetable Oil	Esterisation	Low	13%		2%
		Mid	**15%**	**n/a**	**10%**
		High	17%		18%
Lignocellulosics	Fermentation/ Hydrolysis	Low	14%	22%	5%
		Mid	**16%**	**25%**	**27%**
		High	19%	34%	49%
Sugar Beet	Fermentation	Low	46%	56%	37%
		Mid	**49%**	**59%**	**74%**
		High	53%	63%	111%
Wheat	Fermentation	Low	33%	57%	32%
		Mid	**36%**	**85%**	**64%**
		High	38%	106%	95%

Notes
lignocellulosics = wheat straw in SHU, wood in CEJ and IC
Percentages are relative to conventional fuel (ie esterisation: diesel, fermentation: petrol)
Percentages are of fuel-cycle total weighted greenhouse gas (GHG) emissions
IC mid-points are mathematical mid-point of Low and High

First, some general remarks on the various studies can be made:

- The SHU studies give only a narrow range of results for each technology, reflecting the fact that they are intended as a 'snapshot' of current UK practice reflecting specific conversion processes, They do not, for example, reflect possible future developments.
- The IC results, in contrast, show a much broader range, as they reflect the results of a literature review of a number of earlier studies. Typically, therefore, the more pessimistic end of the range might reflect rather obsolete processes or technologies with strong reliance on fossil fuels, whereas the optimistic end reflects state-of-the-art technology with most inputs of heat or electricity coming from renewable sources. In reality current UK practice tends to fall in the middle of this range, ie with quite efficient production processes, but with energy inputs typically provided by natural gas.
- In addition to methodological differences from the above, the JEC study seeks to reflect European rather than UK circumstances. In some cases this may account for differences in underlying assumptions, eg over crop productivities or process efficiencies.

Other key points to emerge on the specific technologies are as follows:

- Oilseed rape offers significant greenhouse gas benefits at the more optimistic end of the range (ie possibly halving the overall emissions, but this assumes *inter alia* that the rape straw is utilised in the process, or sold on in the case of SHU). SHU's baseline results fall within the wide uncertainty band of the CEJ results, but fall close to the low end of the IC range (at 22% – not shown in the Table) if the straw is utilised in the process. Results from the top end of the CEJ band suggest a significantly lesser benefit. The low value in the IC report reflects literature estimates attributing low emissions from agricultural inputs and N_2O emissions, and rape straw use as fuel at the conversion plant – ie a fairly optimistic scenario – but the mid-point is reasonably close to SHU.
- Manufacturing fuels from waste vegetable oils (and in the future possibly also other organic wastes) offers substantial greenhouse gas (and other) benefits. The very low IC values at the bottom end of the range refer to literature estimates that assume the use of straw or pulp as fuel at the conversion plant.
- Manufacture of bioethanol from sugar or starch crops appears to offer broadly comparable benefits to those of RME. The much less positive result for wheat in the CEJ study is accounted for in part by the fact that there is no allocation applied for wheat straw, which seems inconsistent and unduly pessimistic. However there appear to be other differences as yet unresolved.
- Lignocellulosic sources offer much greater benefits in the medium term, probably reducing net greenhouse gas emissions by three-quarters or more. There is reasonably close agreement on this conclusion. Low energy inputs to lignocellulosic crops and more efficient/renewable-based processes are key to achieving the greatest emissions reduction.

Some Observations on the Recent Concawe/Eucar/JRC Study

The recent CEJ study referred to above was a major collaborative effort produced during the period over which this paper was drafted. It was led by the oil and motor industries in collaboration with the European Commission's Joint Research Centre. Given its broad scope, high level of resources and expert contributors, it is likely that this will be viewed as the 'definitive word' on biofuels for some time to come.

However, even with a major study such as this, it is unwise to take all its conclusions uncritically. For example, it was noted above that it uses what seems to be a rather inconsistent and unfair approach to use of wheat straw, which gives an unduly unfavourable result in this case. Beyond this, in spite of having access to the working spreadsheets which underlie the CEJ results, we have been unable to interpret these fully, and have as yet not been able to account for all the differences between these and the results of the two UK studies. In some cases, however, it may be that the CEJ study uses average figures from across Europe which are not fully applicable to the UK situation, and in such cases, divergences are to be expected.

Nonetheless, the exercise of comparing the studies has been useful, and has allowed some relatively robust conclusions to be drawn. Given greater time and effort, it is likely that further progress could be made in developing a shared understanding of results and the differences between them.

5 Framing the Answers and Refining the Questions

The Economic and Policy Context

The economic context of biofuel development is mainly governed by a range of commercial interests which see new opportunities in possible future demand for alternative road transport fuels. These interests chiefly consist of companies involved in agriculture, food processing and petrochemical production. Incentives for the mainstream petrochemical industry to consider alternative sources of oil are currently weak, but some specialist distributors are already developing and marketing ‘green’ diesel blends. The most important driver for agricultural enterprises and food processing companies is probably the need to diversify their operations in the light of imminent uncertainties. Given recent adverse experiences in the UK, farmers are now fully aware of diversification as a basic economic necessity. Apart from providing a means to insure against over-dependence on single crops, products or customers, the farming community is particularly concerned about the expected impact of fundamental changes to the Common Agricultural Policy and, more generally, the prospect of future removal of tariff barriers by the World Trade Organisation. The precise impacts of these forces are as yet poorly understood, but could well be adverse from the perspective of conventional farming practices. Liberalisation, in the broadest sense, is expected to threaten some areas of conventional food production in the European Union, and this threat is also perceived by those food industries which are strongly connected to European agriculture. Consequently, the opportunity of switching production from food to biofuels (and other non-food crops) is seen as a sound strategic option by some sections of the agricultural and food processing industries.

From the farmers’ perspective, there are clear attractions in considering biofuels which require few or no alterations to existing farming patterns and practices, and limited modifications and additions to subsequent processing. This probably explains current interest in the possible production of bioethanol from sugar beet and wheat using fermentation, and the production of biodiesel from oilseed rape. However, the companies involved also understand the financial risks associated with such diversification. The most prominent risks include basic economic prospects of biofuels in relation to cheap oil; the need for significant capital investment in new plant; and the lack of strong market demand for the product. Underlying these risks is general uncertainty over future Government policy on the promotion of and support for biofuels in the United Kingdom and the rest of Europe, as this is still an emerging area.

A recent report from the Environmental Audit Committee (2003) highlighted the very different perspectives on biofuels in different Government departments. There are several competing policy issues involved in developing a domestic biofuel industry, each of which has economic, environmental and social aspects. Although understanding of biofuels is growing and controversy diminishing, policy appears still to be driven by interest groups rather than sound and independent analysis. It is important that a future policy on biofuels should be based on a robust assessment of all the relevant costs and benefits.

To assist in this process, the impacts of a UK bioethanol industry could for example be summarised in a multi-criteria presentation. The main policy issues covered here are:

- the overall production cost of bioethanol compared with conventional petrol;
- the level of added value that a UK bioethanol industry makes to the national economy (ie the contribution to national GDP);
- the extent of the net financial costs to the Treasury;
- the extent to which rural economic development could be enhanced by a bioethanol industry;
- the potential additional employment in the main sectors of agriculture, feedstock conversion, fuel supply and distribution and in the manufacturing sector;
- the potential levels of greenhouse gas avoidance available by substituting bioethanol for petrol, and the cost-effectiveness of public support (ie £/t carbon abated) within the UK Climate Change programme;
- local environmental impacts.

Quantification of all these impacts is complex and subject to considerable uncertainties. For illustration, however, Table 4 below provides a summary of these impacts in a qualified manner for selected potential bioethanol production routes in comparison with petrol.

The Energy Supply and Demand Context

No source of energy supply, including renewable ones, offers a 'free lunch' in financial or environmental terms. We therefore reiterate the observations made in Eyre *et al* (2002) and Hart *et al* (2003) that demand management and efficiency of energy use will remain vital for the transport sector in the future. By no means all of the environmental impacts of the transport sector could be mitigated by alternative fuels. Also, if alternative fuels are to be deployed in the transport sector, controlling total energy demand will allow any given quantity of biofuels to have a larger impact by meeting a larger share of the total market.

There is a growing consensus that the future 'dream ticket' power source for the surface transport sector is fuel cells driven by hydrogen, and this leads some to conclude that liquid biofuels represent a technological cul-de-sac which is best avoided. However, it is a false dichotomy to portray biofuels as being a competitor to hydrogen, for several reasons. First, there is no certainty that the hydrogen economy will emerge as quickly or as fully as enthusiasts may suggest, and in any realistic scenario liquid biofuels are likely to remain the best renewable option for the transport sector for some time to come. Second, hydrogen only offers decisive environmental benefits if it is produced from a renewable source, and Eyre *et al* (2003) demonstrate that it would not make environmental sense to use indigenous renewable electricity for this purpose for at least some decades to come. Instead, biomass production and processing offers a number of possible routes to hydrogen, and could well comprise a key element of the path to a hydrogen economy, rather than a rival to it.

It may well make more sense in the near future to use much of the available biomass for heat or electricity generation rather than transport. This could easily change as technologies develop, however. Eyre *et al* (2002) concluded that using woody biomass to manufacture hydrogen (or alcohol) for use in an efficient fuel cell vehicle has comparable carbon-saving benefits to using biomass for CHP, and probably larger benefits than using biomass for either heat of power generation below. By this argument, stimulating biomass production would be a 'no regrets' strategy even if a major market for liquid biofuels did not emerge or were not needed.

Domestic Production and Imports

Although both Eyre *et al* (2002) and Hart *et al* (2003) produce estimates of the UK land area which would be required to power the road transport sector, this is purely for illustrative purposes and does not imply that all biofuels would be sourced domestically. On the contrary, if biofuels become a major market, then it will be a global one, and the UK is likely in these circumstances to import some at least of its biofuel requirements.

In terms of fuel life cycle, the additional greenhouse gas emissions incurred by long distance bulk transportation of fuel or feedstock by ship would be minimal, and could easily be offset by the efficiency gains of growing more productive crops elsewhere.

Table 4 Multi-Criteria Presentation of Impacts of Bioethanol from UK-Sourced Crops

	Bioethanol			
	Set aside crops		Existing crops*	Petrol
	Wheat/ sugar beet	Lignocellulosics		
Pre-tax fuel cost	Expensive	Very Expensive	Expensive	Cheap
Value added to UK economy	High	Moderate – Low	Low	Moderate
Additional employment	Good	Good	Moderate	Low
Impact on the Treasury	Moderate	Poor	Moderate	Good
Greenhouse gas avoidance	Good	Very Good	Good	No
Cost of greenhouse gas avoidance	Moderate	Moderate	Moderate	N/a
Local environmental impacts	Variable	Variable	Low (?)	Low

* NB There could be additional costs due to changes in land-use and land values

On the other hand, the production processes used could give rise to significantly different environmental characteristics than those set out above. For these reasons, it cannot be assumed that the environmental balance sheets of imported biofuels will automatically be either better or worse than those of domestic products; but it will certainly be more difficult to assess or accredit them.

Uncertainty in the Policy Context

Estimates of net savings in total greenhouse gases from the production and use of transport biofuels relative to conventional fuels from crude oil are an essential basis for informed policy debate. Such estimates are necessary to ensure that the prospective savings from policy options are calculated correctly. Whilst it is now generally appreciated that biofuels are not necessarily wholly 'carbon neutral', in most cases they can deliver significant greenhouse gas savings in the very near future. However, the extent of these savings depends, crucially, on the chosen biofuel and its production technology, including its original source and means of cultivation or recovery. Hence, the basis for such estimates needs to be explained in detail so that they can be used properly within the policy context. In particular, it is recommended that estimates comply with the requirements of the International Standard for Life Cycle Assessment, the ISO 14040 series (European Committee for Standardisation, 1998). This ensures clarity and comparability in subsequent estimates by providing a framework for establishing the nature of the biofuel, the basis for its measurement, the details of its production and the methods of calculation used, especially the allocation procedures. The most important aspect of this is transparency so that estimates can be used with confidence in the appropriate policy context. In particular, relevant values of global warming potentials must be adopted for the timescale under consideration and, crucially, relevant allocation procedures must be applied to reflect the reality of the circumstances under investigation.

It is, of course, vital that subsequent estimates answer the specific question which has been asked by policy makers. It is necessary to appreciate that no one estimate can answer all the questions which might be asked. The estimates discussed here answer questions relevant to greenhouse gas emissions within the foreseeable future within the policy context of immediate responses to global climate change. Such estimates do not, in themselves, address fossil fuel resource depletion (for which properly based calculations of primary energy are required) or land use (for which suitable analysis of productivity, land type, etc, is needed). Similarly, current estimates do not resolve concerns about biodiversity and other environmental impacts, or security of oil supply. Significantly, unless combined with inherently consistent economic analysis based on an agreed perspective (private company, government or society), such estimates cannot simply indicate which biofuel option is the most cost-effective in reducing greenhouse gas emissions. Obviously, complex questions of this sort require a collection of estimates which are specifically devised to address given facets of the issue under consideration. Although the evaluation of net greenhouse gas emissions is a key concern, estimates only provide insight into one aspect for policy makers.

The Need for a New Tax Basis for Biofuels

The development of incentives to promote biofuels, including a graduated fuel duty reflecting greenhouse gas emissions, will clearly be important if production is to flourish. At the same time the rationale for current fuel duties is opaque to many people, and basing a fuel duty on the carbon content of a fuel, or the CO_2 or greenhouse gas emissions produced over the fuel chain, may be a way of making this more transparent. A recent report by the cross-party Environmental Audit Committee criticised the Government's fuel duty policy for lacking a clear long term strategy linked to environmental benefits. It argued that:

> 'The Treasury could do far more to set out a coherent long term strategy for fuel duties, and demonstrate how the current incentives for biofuels, road fuel gases (such as LPG), and hydrogen fit into this.' (Environmental Audit Committee, 2003)

Accordingly, the Government's commitment in the 2003 pre-Budget Report to develop a new framework for the taxation of biofuels is important and very welcome. Some important observations can be made, however. The discussion above illustrates that, even for a single product such as bioethanol, the full life cycle greenhouse gas emissions can vary enormously according to the feedstock and conversion processes used. Also, in the nature of a biofuel, its carbon content is no guide to its net carbon impact. For these reasons, it is essential that the tax basis should reflect well-to-tank assessment rather than simply the carbon content of the end product. This requirement will be a substantial challenge to current practice.

Linkages to Other Policies

A range of policies, or very likely a combination of policy instruments, might be needed in order to support the development of a transport biofuel industry. One recent study (EEDA, 2003) identified the following as possible means to support the development of a UK bioethanol industry.

- An excise duty reduction so that the retail price of gasoline/bioethanol blends was equal to that of gasoline.
- An excise duty reduction capped at 20p/litre with additional support in the form of capital grants in order to offset some of the initial expenditure on bioethanol processing infrastructure. The level of capital grant might need to be varied in order to accommodate different technologies.
- A Transport Renewable Fuels Obligation applied to all UK fuel suppliers under which they would be required to supply a minimum percentage of bioethanol fuel, would be a novel means to meet national targets that comply with the Biofuels Directive (if substantial targets are set).
- A combination of capital grants and staged excise duty reductions.

In addition, venture capital funding could be specifically targeted at the development and commercialisation of biofuels technologies. Venture capital grants could be channelled through the Low Carbon Innovation Programme run by the Government-funded Carbon Trust which already provides similar support for other low carbon energy but currently has little funds for transport applications. Demonstration projects might also be funded through the Energy Savings Trust.

A high level of duty reduction would be a simple way forward to stimulate the market, but there is a danger that this would encourage cheaper imports rather than a domestic industry. In contrast, capital grants might be especially attractive to the bioethanol industry, as these would help with the relatively high capital costs of the necessary plant and equipment. If the main requirement were to achieve a given target such as those set out in the Biofuels Directive, however, a Transport Renewable Fuels Obligation might be an option, since although this would require administrative effort in setting up and verification, there is a high level of certainty that the targets would be met.

Furthermore, linkages to other policies must be taken into account. For example, WTO rules will shape the way in which a global market in biofuels might develop, and it will probably not be possible to discriminate against potentially cheaper imports in order to encourage domestic production, Equally, care will be needed to ensure that any financial support to UK biofuel production facilities does not fall foul of EU rules on state aids.

The reform of the Common Agricultural Policy agreed in June 2003 has a number of implications for biofuel production. Central to the agreement is the decoupling of support payments for farmers from agricultural production. This is expected to make farmers more responsive to market forces and more open to diversification into new products and opportunities. An additional aspect of the agreement was a new aid payment of EUR 45/ha for energy crops that will be paid on top of the new Single Farm Payment on an area of up to 1.5 million ha in the EU as a whole. It is not yet clear what the UK share of this area will be, but the ceiling for these payments is not high. Set-aside provisions are also relevant. However, the overall impact of these developments for biofuel production is as yet far from clear.

The biofuels Directive (Directive 2003/30/EC) of May 2003, is also relevant, as it requires Member States to take action to promote the use of biofuels and other renewable fuels in the transport sector. However, it is significantly weaker than the text originally proposed, and it is far from clear how vigorous an approach a number of governments, including that in the UK, will take. Nonetheless, there certainly are some enthusiastic supporters, and an increase in demand across the EU can be envisaged which may well have significant effects on the global supply and demand for liquid biofuels and their feedstocks.

The transport sector is currently excluded from plans for implementation of carbon emissions trading systems at both UK and EU levels, although it could be included under future reviews. The future inclusion of transport could be an important development, but its effects would be complex and merit further study. Amongst other issues, the likely effect of such a change on the development of liquid biofuels would be an area requiring further consideration.

Aviation

There are and will continue to be major grounds for concern over the future environmental impacts of aviation. It appears very likely that demand for aviation fuel will continue to grow strongly, with air travel demand in the UK and worldwide significantly outstripping improvements in aircraft technologies. There has been a five-fold increase in air travel since the 1970s. Government forecasts suggest demand could be two and a half times current levels by 2030. Emissions from international flights fall outside of the Kyoto Protocol and aircraft fuel is exempt from any tax. The Government has committed to putting the UK on a pathway to cutting carbon dioxide emissions by 60 per cent by 2050, but if emissions from international aviation continue to grow unchecked, then by 2050 the impact of emissions from international flights from UK airports could exceed the UK's entire emissions quota (ippr, 2002).

The energy efficiency of aircraft has improved steadily in recent years, but it will be difficult in future to maintain this pace of improvement, far less to increase it significantly. As noted above, biokerosene may become a realistic prospect in the coming decades. A more radical switch to hydrogen-based propulsion is conceivable in the very long term. This would require a very radical departure from current aircraft designs to accommodate the volume of fuel which would be needed, but this could probably be accommodated over the long timescales envisaged.

A further difficulty arises from the fact that the global warming impact of aviation arises not only from the carbon dioxide emissions of aircraft: NOx and water vapour emitted at high altitude are a potentially even greater problem (IPCC, 1999), and one that switching to a renewable fuel does not solve. Indeed in some circumstances a shift to all-hydrogen fuel could exacerbate the problem, in that the exhaust gases would then be almost entirely water. It thus seems virtually unavoidable that, if current increases in air travel demand continue, aviation will contribute an ever-larger share to the atmospheric processes that give rise to climate change.

6 Broad Conclusions on Road Transport Biofuels

The continuing growth in road transport requires policy responses that deliver substantial reductions in future greenhouse gas emissions, if the UK is to meet its commitments under the Kyoto Protocol and its longer-term targets. Low-carbon road transport fuels may contribute to this end, but fuel efficiency and demand management will also remain important if environmental damage is to be limited.

Road transport biofuels already offer greenhouse gas benefits relative to conventional petroleum-based fuels, although the scale of benefit can vary significantly according to the fuel, feedstock and production process. In addition, these fuels can assist in the longer-term transition to a low-carbon transport strategy. In the longer term, biofuels from wastes and from lignocellulosic materials offer greater benefits, but in practice a range of feedstocks and processes are likely to be deployed in parallel at any one time and with significant overlaps in time, rather than in series.

Biomass is also a potentially important 'second front' for renewable energy alongside wind turbines and other electricity generators, and could contribute to the development of either liquid or hydrogen fuel supplies for transport. However, production of liquid biofuels is probably less advantageous than burning the feedstock for heat and power, depending on both the prevailing energy mix and the availability of other renewables to produce electricity and heat.

However, some of the most favourable assessments of current biofuels assume production processes which are not currently the norm (eg using straw for process heat). To realise this potential in full might require additional policy incentives, and there may be a cost attached to these.

We doubt that a significant industry will develop on the basis of the levels of duty reduction currently offered, and a much larger discount might not have the desired effect. If a sustained biofuel industry is to be fostered, therefore, the UK needs to develop a more sophisticated industrial strategy and a package of policy measures in order to encourage key developments.

Allocation methods and other assumptions can make a substantial difference to the estimated greenhouse gas emissions benefits of any given liquid biofuel, and different approaches may be needed to answer different policy questions. There are also a range of uncertainties over productivity, likely efficiencies of future processes, etc. The impact of alternative agricultural practices would also need to be explored further if these were to be used for biofuel production.

We consider that this exercise and others like it are important to help develop a shared understanding of the costs and benefits of the range of biofuel options available for road transport, but that more work would be needed in order to reduce uncertainties further.

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