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THE POTENTIAL FOR BIOETHANOL PRODUCTION FROM WHEAT IN THE U.K.

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by

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SUMMARY

Chapter 1

Ethanol can be manufactured from petroleum derivatives (synthetic ethanol) or by the biological fermentation of carbohydrate (bioethanol). Most of the ethanol produced in the UK is synthetic ethanol. Ethanol is currently used in cosmetic, chemical and pharmaceutical applications. At present bioethanol has to compete with synthetic ethanol in these markets. Ethanol has been used as a motor fuel since the turn of the century. Recent interest in the use of bioethanol as a fuel has arisen due to environmental concerns as it has potential as a clean burning, renewable energy source.

Chapter 2

Ethanol has been used as a petrol additive, a petrol substitute and has potential as a diesel substitute. As a petrol additive, ethanol extends the fuel and increases the octane number and oxygen content. Ethanol is therefore suitable for use as an octane enhancer in unleaded petrol. Increasing the oxygen content of the fuel reduces polluting emissions. The EC maximum limit for blending ethanol with petrol is 5% (but may be increased to 10%). Ethanol petrol blends can be used in unmodified engines. Some engine modification is required for the use of ethanol as a petrol substitute. Advantages of ethanol as a fuel compared to petrol are that it is safer, has a higher octane rating and lower emissions of some pollutants. Work has been carried out in several countries on the use of methanol as a substitute fuel in diesel engines. Due to the similar characteristics of methanol and ethanol, developments in the technology for the use of methanol as a fuel could easily be transferred to ethanol. The low cetane number of ethanol means that either the fuel or the engine must be adapted.

Ethanol has been considered as a feedstock for the production of ethyl t-butyl ether (ETBE). ETBE is used as a petrol additive which substitutes for lead as an octane enhancer. ETBE has similar properties to ethanol when blended with petrol but is more favoured by oil companies because it is easier to handle.

Ethanol has been proven to be suitable for fuel use in terms of its chemical characteristics. Its viability will depend on cost and energy ratio.

Chapter 3

Three categories of substrate for ethanol production are sugar, starch and cellulosic/lignocellulosic (or woody) feedstocks. Sugar crops require minimal

treatment before fermentation. The only sugar crop with potential in the UK is sugarbeet.

Cellulosic/lignocellulosic feedstocks include waste materials such as straw and woody materials grown specifically for ethanol production such as short rotation coppice or conventional forestry products. Cellulosic/lignocellulosic feedstocks have received a lot of attention, due to their potential as a cheap feedstock for bioethanol production, but require more pretreatment than starchy or sugary feedstocks. Starchy feedstocks, such as cereal grains and potatoes have been used extensively for ethanol production via the alcoholic drinks industry. Maize, barley and wheat have all been used previously as bioethanol (for industrial/fuel use) feedstocks in the USA, Finland, Austria and Sweden. A high protein animal feed (distillers' dried grains with solubles, DDGS) is produced as a by-product of ethanol production from cereals. Potatoes are a less favourable feedstock than cereal grains because their high water content makes storage difficult, and the low protein content means that high value by-products are not available. Starchy feedstocks require more processing than sugar feedstocks but less than lignocellulosic feedstocks. This technology is well developed. There are two basic approaches to bioethanol production from starchy feedstocks. The first approach is to have a plant dedicated to production of ethanol and animal feed. The second approach is to produce bioethanol as one product of an integrated starch plant. In the USA, starch plants produce bioethanol and high fructose syrups for the soft drinks industry.

Chapter 4

The production of ethanol from wheat already accounts for some 450 000 tonnes of wheat per year in the UK, through its use as a raw material for the production of grain spirit, which is the basis of vodka, gin and blended whisky. The qualities required from wheat for bioethanol production would be the same as those presently identified as important by distillers, ie soft wheat with a high thousand grain weight, low grain nitrogen percentage and protein content.

Two bioethanol plants in Sweden and France using wheat as a feedstock are operating using the "Biostil" system which was originally developed for production of bioethanol from sugarcane in Brazil. As two plants are operating using this system, energy balance and costings in this report are based on Biostil specifications. The plant which operates in Sweden has been adapted to integrate starch production.

Chapter 5
An energy ratio is the ratio of energy used during production to the energy obtained from the products and by-products. Energy inputs include direct use of energy, for example fuel used by tractors, and also indirect use of energy, for example the energy

used in the manufacture of fertilisers and pesticides. If the energy ratio is less than one, more energy will be used in production than is gained, and there will be no benefit in producing ethanol as a renewable energy source. Energy ratios were calculated to take into account a range of conditions from good to typical to poor. The range of inputs included factors such as variations in yield, different fertiliser and pesticide applications and variations in grain moisture content at harvest. When ethanol is the only output considered, the energy ratio is less than one under all conditions. Where DDGS are also considered in the calculation, the energy balance becomes positive under good conditions. If the use of straw as a fuel is considered in the energy balance, the energy ratio is positive under all conditions, but is still poor.

Chapter 6

Costings were carried out based on a quote from Chematur Engineering for a 30 million litre per annum Biostil plant. The net cost of ethanol from wheat was calculated to be 38.1p per litre. The cost of wheat is by far the largest single cost in the production of fuel ethanol. At 38.1p per litre fuel ethanol from wheat is not directly competitive with synthetic ethanol, fossil fuels or MTBE. Growing wheat on set aside offers the opportunity to reduce the cost of bioethanol to as low as 21p/litre. At this cost bioethanol could compete with synthetic ethanol, and fossil fuels if duty concessions were applied.

Chapter 7

Ethanol has been previously used as a petrol additive and petrol substitute.
Brazil initiated its bioethanol programme, using sugarcane as a substrate in the wake of the energy crisis of the 70's in an attempt to reduce dependence on imported oil. From this point of view, the programme has been successful, but as oil prices have fallen the future of the programme is uncertain. The programme received heavy government support, but had advantageous knock on effects in other manufacturing industries, and provided employment for the rural population. The use of the by-products bagasse (to generate electricity) and vinasse (as a fertiliser) were also important in determining the viability of the programme, and improved the energy ratio.

The bioethanol fuel programme in the USA has been based on ethanol production from maize. Like the Brazilian programme, the USA programme was set up to reduce dependency on oil imports, but its continuation has been closely linked to agricultural policy and the utilisation of surplus maize. The programme has been heavily supported by the government, and ethanol petrol blends are taxed at a lower rate than petrol. Recent clean air legislation has given a boost to the programme, but it is still very controversial due to the high level of government subsidy required for its operation.

Chapter 8

It is concluded that use of bioethanol as an oxygenate could become a feasible option before use as a fuel. Bioethanol faces competition from other oxygenates but as there is increasing interest not only in renewable energy sources but in renewable sources of a range of industrial feedstocks, an improvement in the energy balance might give bioethanol an advantage over other oxygenates. If the price of oil increases in the future then the price of competing oxygenates may also increase.

The cosmetics and toiletries markets may be the best option for development in the short term but the potential size of this market is unclear. The industrial ethanol market has been estimated to be approximately 400 000 tonnes/year in western Europe, and the cosmetics and toiletries sector is the biggest user of ethanol. A UK bioethanol industry would have to secure 10% of this market in order to match the current area of high erucic acid rapeseed (16 000 ha) grown for industrial use. Therefore, if wheat is to be developed as a major industrial crop, this must be linked to the establishment of new markets for ethanol such as a fuel additive or substitute. Alternatively the co-production of ethanol with starch may offer scope for greater utilisation of wheat.

Bioethanol from wheat does not have an overall cost advantage over other sources of ethanol and/or other fuels, though cheaper raw material from set aside may help keep it competitive. With this background bioethanol depends on securing markets or price premiums as a result of its environmental benefits for its viability. The most successful areas of development are therefore likely to be those which allow the natural image of bioethanol to be used as a marketing tool.

Recommendations

1. Fuel use. Exploratory talks with the government with respect to reduction of excise duty on fuel bioethanol would be required before any development of wheat bioethanol can be considered. Experience to date with RME indicates that such an excise duty reduction is unlikely. The attitude of vehicle manufacturers would also have to be determined. The development of bioethanol as a motor fuel in the near future seems unlikely unless the energy balance is improved and/or the price of oil increases considerably. The use of bioethanol as a fuel is not considered a viable option in the foreseeable future.

2. Oxygenate. For use of bioethanol as an oxygenate on an extensive scale, oil company backing would have to be established. In the USA warranties cover vehicles for the use of ethanol/petrol blends. A survey of manufacturers to determine whether a similar scheme could operate in the UK would be of benefit prior to any development of bioethanol as an oxygenate. Current concern over inner city air quality indicates that there are moderate prospects for bioethanol as an oxygenate in the medium term.

3. Cosmetics and toiletries. There may be some opportunity for development of a niche for bioethanol within this market. A major cosmetics and toiletries manufacturer has stated that they would use bioethanol in preference to synthetic ethanol if it were available at a competitive price because they like to use natural products. The potential size of this market is unclear. Market research is required to determine the potential market size. This area provides the best prospects for bioethanol in the short and medium term.

4. Co-production with starch. Co-production of ethanol with starch seems to be a promising approach to reducing the cost of the feedstock because the wheat starch is split into high and low value fractions, and only the low value starch is used for ethanol production. It has been suggested that this approach could also improve the energy balance. However, this is a route which depends entirely on the viability of starch production from wheat. Further work is required to determine whether production from starch in the UK is viable, and to quantify the effect that co-production would have on the cost and energy balance of bioethanol.

GLOSSARY

Bioethanol Ethanol produced by the fermentation of sugars derived from biological raw materials.

Biomass Plant and animal matter that may be used as a source of energy and/or chemicals.

By-products A product formed in the process of making something else.

Cellulose The chief component of cell walls of plants and of wood.

Cetane number A measure of the ignition quality of diesel engine fuels, based on cetane ($C_{16}H_{34}$).

Co-products Two or more equally important products produced from the same process.

DDGS Distillers' dried grains with solubles. The solid fraction of grain based fermentation stillage which is separated from the liquid and dried to about 90% dry matter, with the syrup produced from the liquid portion of the spent grains added back.

Ethanol (C_2H_5OH) The next simplest alcohol after methanol.

lignocellulosic Composed of lignin and cellulose, eg wood.

Methanol (CH_3OH) The simplest alcohol.

LFA Less favoured area.

MJ Megajoules (10^6 Joules).

Octane number An indication of the anti-knock quality of a motor fuel. The percentage by volume of iso-octane in a mixture of iso-octane and normal heptane which has the same knocking characteristics as the motor fuel under test.

Oxygenate An organic compound containing oxygen and having properties as a fuel which are comparable with petrol. Includes alcohols and ethers.

Renewable fuel An energy source which is produced without depleting a finite resource.

RON Research octane number. The octane number of a motor fuel determined in a single cylinder laboratory test engine under mild "engine -severity" conditions. Gives an indication of low-speed knock properties of the fuel.

SSF Simultaneous saccharification and fermentation.

Synthetic ethanol Ethanol produced by catalytic hydration of ethylene derived from natural gas or by-products of petroleum refining.

Volatility The ability of a liquid to evaporate.

CHAPTER 1 INTRODUCTION

1.1 Bioethanol and fossil fuel derived ethanol

There are two ways to manufacture ethanol

1. by the biological fermentation of carbohydrates using yeasts or bacteria

2. by catalytic hydration of ethylene derived from petroleum or from natural gas.

Ethanol manufactured from ethylene is called **synthetic ethanol**. The UK is a major producer of synthetic ethanol, accounting for sixty percent of synthetic ethanol production in the EC (Marrow *et al.*, 1987).

Ethanol manufactured by the biological fermentation of carbohydrate is known as **bioethanol**. Biological fermentation of carbohydrate to produce ethanol is best known as the basis of the alcoholic drinks industry, but ethanol also has a range of industrial uses. Ethanol for use in the alcoholic drinks industry is termed potable ethanol. Ethanol for industrial uses is referred to as industrial ethanol.

Seventy percent of the industrial ethanol manufactured in the EC is produced by fermentation, but most of this is produced from surplus wine and not directly from agricultural feedstocks (Marrow *et al.*, 1987). However, this ethanol production from surplus wine has required heavy subsidies and may be discontinued, while production from agricultural feedstocks such as wheat may be increasing.

1.2 Current uses of ethanol in the UK

The largest market for industrial ethanol at the moment is in the cosmetics and toiletries industries. For example ethanol is used in the production of hairsprays and

bodysprays. Another major use is in the printing industry. Ethanol is used in printing ink due to its quick drying properties. Ethanol can be used as a solvent, and this market is expected to increase as ethanol is being used to substitute for more toxic organic compounds (Anon, 1993). Synthetic ethanol is not used for human consumption and therefore "bioethanol" has no competition from synthetic ethanol in the alcoholic drinks industry, or for food uses. However, for all other potential uses bioethanol has to compete with synthetic ethanol and often with methanol, an alcohol with similar characteristics. Although some sources state that the cosmetics industry prefers synthetic ethanol to bioethanol because bioethanol tends to have a stronger odour, it has also been reported that there is strong competition between fermentation and synthetic ethanol in the cosmetics and toiletries sector (Anon, 1993), and one manufacturer has stated that they would prefer bioethanol to synthetic if it were available at a competitive price, because they prefer natural products.

A potential market for bioethanol in which synthetic ethanol and methanol produced from natural gas could not compete could come from its use as a renewable fuel. Although bioethanol, synthetic ethanol and methanol can all be used as fuel, and are all cleaner burning than petrol, synthetic ethanol and methanol cannot compete with bioethanol as a renewable energy source as they are themselves derived from fossil fuels.

1.3 History of use as a fuel

The use of ethanol as a transport fuel is not a new idea. Ethanol was used as a motor fuel for the first time in 1890 (Lewis, 1983). In the 1920s, Henry Ford's Model T was designed to run on alcohol, petrol or any mixture of the two (Ward, 1989) and during the 1920s and 1930s, alcohol or petrol/alcohol (usually ethanol) blends were used in Argentina, Australia, Cuba, Japan, New Zealand, the Philippines, South Africa and Sweden. Vehicles were manufactured to run on 100% alcohol fuel for export to New Zealand and the Philippines (Lewis, 1983; Houghton-Alico, 1982). Ethanol was also used during the first and second World Wars but after the second, interest in ethanol as a fuel declined (Houghton-Alico, 1982), due to the availability of cheap oil.

The energy crisis which followed the quadrupling of world oil prices in 1973 renewed interest in the use of ethanol as a fuel, largely for economic and political reasons. In order to reduce dependency on imported oil, Brazil initiated a national fuel ethanol programme (proalcohol) in 1975, to produce ethanol to blend with petrol and a similar programme was set up in the USA in 1979. While decreasing oil prices may have threatened the continuation of these programmes, recent environmental concerns with respect to pollution and global warming have increased interest in "environmentally friendly" alternatives to fossil fuels.

CHAPTER 2   ETHANOL AS A FUEL

2.1 Ethanol as a petrol substitute

2.1.1 Modifications to conventional spark-ignition engines

Ethanol is used as a petrol substitute in Brazil. However, the use of ethanol as a petrol substitute requires some modification of conventional spark-ignition engines due to the fuel's characteristics.

Volatility. Ethanol is less volatile than petrol. This means that engines running on ethanol are difficult to start in cold weather, and conventional spark-ignition engines require some adjustment to overcome this problem. For example, it may be necessary to provide a more volatile fuel to start the engine and/or a system for heating the intake manifold in climates where the temperature drops below 4.4 ^{o}C (Houghton-Alico, 1982).

Corrosion. Ethanol is corrosive, and therefore imposes some limitations on the materials that can be used in engine manufacture for ethanol run cars.

2.1.2 Advantages of ethanol

The use of ethanol as a fuel has several advantages over petrol.

Safety. Unlike petrol, burning ethanol can be extinguished with water.

Octane quality. Octane quality is expressed as the research octane number (RON). Ethanol has a high RON, in the range 91 - 105 (Houghton-Alico, 1982). The

standard European RON for unleaded fuel is 95 RON (Anon, 1989). A high octane number is advantageous because the higher the octane number of the fuel, the better the engine can resist knocking and the more efficiently it can run.

To gain the maximum efficiency from fuel ethanol, it should be used in engines with a high compression ratio. Use of pure ethanol increases the specific power output of a vehicle by 5 - 10% compared to a petrol fuelled car. In theory a vehicle's efficiency can be increased by 30% if run on ethanol and optimised for that fuel (Holman *et al.*, 1991).

Environmental factors. Homewood (1993) states that studies carried out in the USA and University of Sao Paulo show that ethanol pollutes less than petrol. The relative emissions from ethanol run engines are illustrated in Fig 2.1. Sulphur dioxide and aromatic emissions from ethanol run engines are insignificant, carbon monoxide emissions have been reported to be up to 30% lower, and nitrogen oxides up to 15% lower than from petrol run engines. A potential disadvantage of using ethanol as a fuel is that formaldehyde and acetaldehyde emissions are dramatically increased in comparison to emissions from petrol (Holman *et al.*, 1991). These aldehydes are sometimes categorised as unburned fuel emissions. Acetaldehyde is less toxic than formaldehyde, which is a potential carcinogen, but the effects of increased emissions of these substances are not clear. Reports on the environmental effects of the aldehyde emissions vary. Some reports state that acetaldehyde is less photochemically active than formaldehyde, while Holman *et al.* (1991) state that it is also involved in photochemical reactions forming ozone and other photochemical oxidants and Homewood (1993) states that unburned ethanol is unreactive and does not contribute to the formation of photochemical smogs.

Fig. 2.1 Relative emissions from ethanol fuelled engines
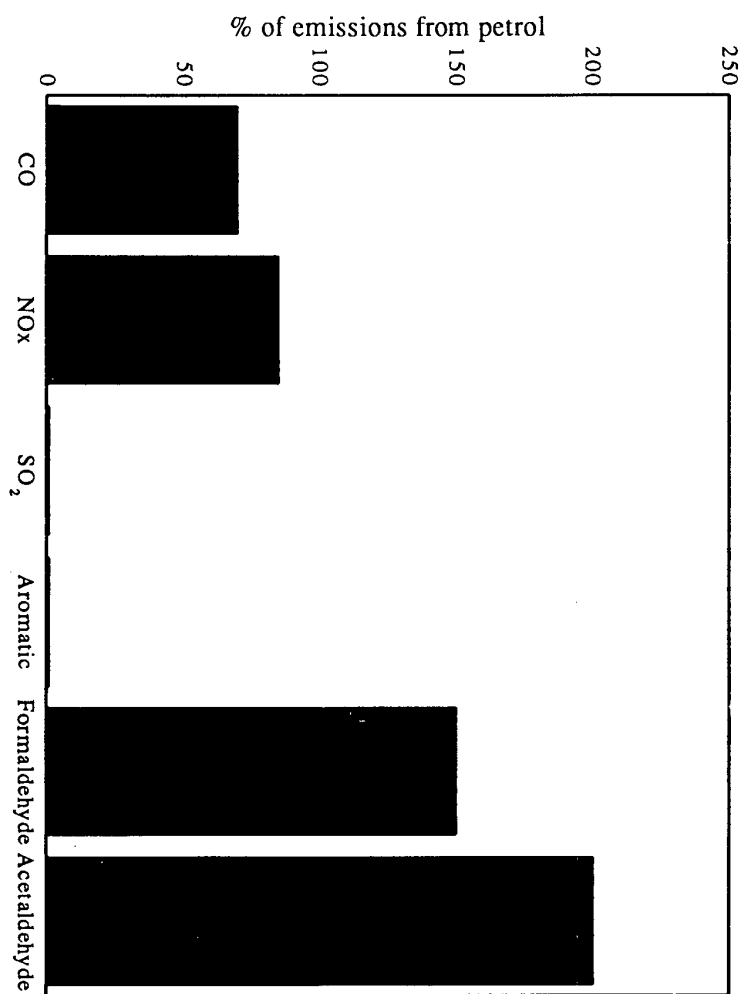
Carbon dioxide. Holman *et al.* (1991) refer to studies in the USA which suggest that when bioethanol is produced, the reabsorbtion of carbon by the vegetation can balance its emission from the use of the fuel, and therefore in theory there would be no net increase in carbon dioxide emitted to the atmosphere. However, Holman *et al.* (1991) also quote studies which conclude that taking into account emissions during the production and use of ethanol, an ethanol fleet would increase carbon dioxide emissions by 23% compared to an equivalent petrol fleet due to the very high energy inputs of modern agriculture, and the carbon dioxide produced during the fermentation process. The carbon dioxide produced during fermentation could be captured and bottled for use, for example in the soft drinks industry. However, the value of the carbon dioxide is quite low, so there is little incentive for distilleries to do this, unless perhaps there was a nearby buyer.

2.2 Ethanol as a petrol additive

2.2.1 Advantages of using ethanol as an additive

Using ethanol as a petrol additive allows some of the fuel's benefits to be exploited in unmodified spark ignition engines. When added to petrol, ethanol acts as an octane enhancer and increases fuel oxygen content. Houghton-Alico (1982) states that the use of blends usually results in increased power and efficiency, although a slight decrease in mileage may occur because of the lower volumetric heating value of ethanol whereas Goodger (1980) reports that with suitable engine adjustment the 10% blend on road testing showed improvements in fuel economy of about 2% in terms of distance travelled per unit volume of fuel and 5% in distance per unit of energy.

2.2.2 Amount of ethanol in blends

There is no clear agreement on the level to which ethanol can be acceptably blended for use in unmodified engines. There is general agreement that below 5%, the EC maximum limit (which may be increased to 10%), ethanol will not cause any problems. However, in the USA blends containing up to 10% are sold and covered by the warranty of all USA car manufacturers (Lynd *et al.*, 1991). Some reports state that up to 20% anhydrous ethanol can be used in existing engines without major engine modification and in Brazil blends of up to 22% are used.

2.2.3 Environmental factors

Vehicles running on 10% ethanol blends have been found to produce 25 - 30% less carbon monoxide than those running on petrol (Goodger, 1980; Holman *et al.*, 1991). Data for nitrogen oxide and unburnt fuel emissions are inconclusive (Goodger, 1980).

2.3 Ethanol as a feedstock for ethyl t-butyl ether

Lead was traditionally added to petrol to boost the octane quality. Concern about the effect of lead on public health and the introduction of catalytic converters (lead deactivates the catalyst) has resulted in the widespread use of unleaded petrol. When lead is reduced or removed the octane number of petrol must be raised by other means (Anon, 1992a). The octane number can be raised by more intensive refining of the petrol or by blending with high octane components, called oxygenates. Ethanol falls into this category of compounds but has to compete with others including methanol, t-butanol (TBA), methyl t-butyl ether (MTBE) and t-amyl methyl ether. The decision whether to use oxygenates or more intensive refining is based on cost, and when crude oil prices are low, it is usually more cost-effective to

use other refining processes (Anon, 1989). However, the use of oxygenates also reduces levels of some polluting emissions, and because of this property their addition is necessary to comply to air quality standards in parts of the USA.

The use of alcohols has some disadvantages compared to other octane enhancers. For example, petrol/alcohol blends will absorb water and if the water content reaches a critical level (around 0.5%), two layers separate resulting in petrol sitting on top of a water/alcohol mix (Goodger, 1980). Thus care must be taken to ensure that water does not enter the distribution system.

MTBE is the more popular of the ethers and is made from isobutylene (2-methyl propene) and methanol by the chemical industry. MTBE is now accepted as a normal, though expensive petrol component. Ethyl t-butyl ether (ETBE) manufactured from ethanol has the same properties as MTBE and better anti- knock properties than ethanol (RON = 118). Considering the disadvantages of ethanol, both as a petrol substitute and additive, the use of ethanol in the form of ETBE as an octane enhancer may be seen as more acceptable by car manufacturers and oil companies than the use of ethanol itself. A recent report commissioned by the French government has suggested that total or partial replacement of MTBE by ETBE is a feasible way to utilise bioethanol. The French oil companies Elf Aquitaine and Total both have ongoing ethanol development programmes. Elf has favoured integrating ethanol as a 10% ETBE additive in unleaded petrol. Total has tested direct incorporation of 5% ethanol, but is now also turning attention to ETBE manufacture (Todd, 1993).

2.4 Ethanol as a diesel substitute

2.4.1 Methanol versus ethanol

Methanol has been extensively studied as an alternative fossil based fuel for diesel engines. As ethanol and methanol have similar combustion characteristics, the technology that has been developed for the use of methanol in diesel engines is applicable to ethanol. The main problem with the use of ethanol as a fuel for diesel engines is that it has a low cetane number, which means that ethanol has poor auto-ignition characteristics. Delayed ignition may result in too much fuel being injected before ignition, causing a rapid increase in engine pressure, and diesel knock. Because of the low cetane number, if ethanol is to be used in a diesel engine either the ethanol or the diesel engine must be adapted.

2.4.2 Adaptation of the fuel

Ethanol can be modified for use in diesel engines by the addition of ignition improving agents or through emulsification of the alcohol fuel in diesel oil to increase the cetane number. Ignition improving agents (organic nitrate esters) are already commonly added to low quality diesel oils to improve the cetane number.

2.4.3 Adaptation of diesel engines

Diesel engines can be adapted for the use of straight alcohols in the following ways:
- development of a two fuel system to use diesel oil as pilot fuel to start the combustion and ethanol as main fuel (75 - 95% replacement of diesel)
- ignition of injected ethanol by glow plugs.

These modifications were originally developed for use with low quality diesel fuels.

A disadvantage of dual fuel systems is the increased cost of production, but overall the cost may be lower than for unmodified engines using fuels with ignition improvers.

In summary, diesel engines require more development work than spark ignition engines for the adaptation to fuel ethanol use. Several different technical routes have been studied. Field testing of diesel engines for use with methanol is underway in the USA, Canada, Germany, Japan, New Zealand and Sweden.

2.5 Factors affecting viability of ethanol as a fuel

2.5.1 Physical characteristics

The viability of ethanol as a fuel is determined by many factors such as its suitability for use in engines, handling characteristics, calorific value and performance. These factors have been well studied and ethanol has been proven to be suitable as a fuel in terms of its chemical characteristics. Two additional factors that are central to determining the viability of the fuel are the financial cost and the energy ratio.

2.5.2 Cost

As a substitute fuel, ethanol must be available at a price at which it can compete with conventional fuels and other alternative fuels such as methanol and liquified natural gas. As a petrol additive bioethanol has to compete with other oxygenates. At present all these fuels would be taxed at the same rate. It could be argued that environmental benefits of using bioethanol increase its value. However, other fossil-based alternative fuels, including synthetic ethanol, share some of bioethanol's advantages as a clean burning fuel. In order to have any competitive advantages over other clean burning fuels bioethanol must be available at a competitive price to these

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fuels and/or must be found to have an energy ratio greater than one.

2.5.3 Energy ratio

This is the ratio of the energy used in the production of bioethanol to the energy gained from its use as a fuel and the energy value of its by-products. If more energy is used in production than is gained from the use of the fuel and by- products then the energy ratio will be less than one and bioethanol will not have the advantages of a renewable fuel. If this is the case then it will, arguably, have no advantages over fossil-based alternative fuels which share its clean burning properties such as synthetic ethanol and methanol.

CHAPTER 3   SOURCES OF BIOMASS FOR ETHANOL PRODUCTION

3.1   Fermentation ethanol production

Over 96% of fermentation ethanol is produced using strains of the yeast
Saccharomyces cerevisiae or species related to it. The theoretical reaction is:

1 kg glucose ---> 0.51 kg ethanol + 0.49 kg carbon dioxide.

However, in practice approximately 10% of the glucose is used for growth of the
yeast and yields of ethanol may be 90% of theoretical values (Ward, 1989).

Although the overall reaction for fermentation ethanol indicates that glucose is the
substrate for the reaction, yeast can utilise a range of sugars and more complex
carbohydrates can also be used as feedstocks for fermentation, with some pretreatment
to break them down to sugars. The major potential feedstocks for bioethanol
production can be divided into three categories: sugar-based sources, starchy sources
and cellulosic/lignocellulosic (woody) sources.

Fermentation processes based on sugar and starch are well established and therefore
these are the feedstocks likely to be used for fermentation ethanol production in the
short term.   However, in addition to processing technology, selection of the feedstock
for ethanol production requires consideration of economic, agronomic and
environmental factors.   A potential crop must be inexpensive to cultivate and harvest,
provide a high yield of fermentable carbohydrates and be adapted to the scale of
technology chosen for processing.   If available, public sector incentives, including tax
credits, subsidies and low interest loans, may also influence the choice of feedstock
(Meo, 1985).

3.2 Sugar-based sources

The three main sugar crops are sugar cane, sweet sorghum and sugar beets (Worley *et al.*, 1992). Other sugary crops which have been considered for ethanol production include fodder beets and fruits (Houghton-Alico, 1982). Processing sugar feedstocks for fermentation generally involves a simple mechanical process of pressing or crushing and extracting the juice. The advantages of using sugar crops for bioethanol production include low equipment, labour and energy costs, whilst the difficulties of storing the juice without contamination may be a disadvantage (Houghton-Alico, 1982).

Fruit crops are unlikely to be used as a feedstock for alcohol fuel production because of their high market value for human consumption (Houghton -Alico, 1982).

Sugar beet is the main sugar based feedstock with potential for use in the UK for ethanol production. Advantages of using sugar beet as a feedstock for ethanol production are that it produces high yields of sugar per hectare and high yields of beet pulp and beet top co-products (Houghton-Alico, 1982). Pretreatment of sugarbeet for fermentation involves cleaning and slicing (Mouris, 1984) or pulping (Houghton-Alico, 1982) followed by extraction of the raw juice. Sugar beet has been used for ethanol production in Japan (although the principal feedstock for ethanol production in Japan is molasses) and some work has been carried out in Australia (Houghton-Alico, 1982). In the past sugar beet has been bred for the sugar industry, and it may be possible to improve ethanol yields by breeding sugar beet specifically for fermentation (Doney & Theurer, 1984).

Fodder beets are agronomically similar to sugar beets. Their advantages include high yields of sugar per hectare, resistance of loss of fermentable sugars during storage and lower fertiliser requirements than sugar beets (with consequent energy balance implications).

3.3 Cellulose/lignocellulose-based sources

3.3.1 Advantages of cellulosic/lignocellulosic feedstocks

It has been argued that if bioethanol is to become a major alternative fuel at an attractive cost, production must be based on cellulosic feedstocks, as opposed to sugar or starch (Anon, 1990a).

Lignocellulosic and cellulosic materials may represent a large potential resource available at a low cost. Lynd *et al.* (1991) claim that cellulosic materials potentially available from energy crops, wastes and conventional forestry in the USA could provide an amount of ethanol commensurate with current consumption of liquid transportation fuels in the USA. Another advantage of using cellulosic materials for ethanol fermentation may be the energy available from residues remaining after fermentation. It is thought that burning these residues may provide more energy than is required for processing a wood feedstock to produce ethanol, and may be used to produce electricity (Lynd *et al.*, 1991).

Sources of cellulosic materials can be divided into waste products such as agricultural residues, forestry residues and municipal solid waste, and materials grown specifically for fuel production, such as woody or herbaceous high productivity energy crops or trees produced by conventional forestry.

3.3.2 Pretreatment of lignocellulosic/cellulosic materials

Cellulosic materials must be hydrolysed to sugar before they can be fermented to ethanol. This can be done by acid or enzymatic hydrolysis. Although there has been a lot of recent interest in cellulose to ethanol technology, the process dates back to at least 1900, with early work being based on wood. On average wood contains 45% cellulose, therefore 100 kg of dry wood contains 45 kg of cellulose which may be converted to 50 kg of glucose, and 25.6 kg of ethanol or 34 litres of 95% ethanol. In the Southern USA between 1910 and 1922, two plants produced 19 000 - 26 500 litres of 95% ethanol per day from sawmill waste. However the yield was 9.2 litres of 95% ethanol per 100 kg of wood; less than one third of the theoretical yield. The low yield was due to the breakdown of sugar before it was converted to ethanol. Development of a process which removed sugars from the reaction zone as soon as they were formed, preventing their breakdown, increased the yield to 21.7 - 24.2 litres of alcohol/100kg oven dried wood. This process (the Scholler process) was used extensively in Germany before the second World War. Towards the end of the second World War, the USA forest products laboratory further refined the Scholler process improving alcohol yield to 26.9 litres of 95% alcohol per 100 kg of dry bark free Douglas fir wood. A full scale saccharification plant based on this process was built at Springfield in Oregon, with an estimated capacity of 15 million litres of ethanol per year, but it never operated commercially. At the end of the war the advent of cheap naptha and synthetic ethanol from ethylene derived from petroleum and natural gas led to the closure of the plant (Franzidis & Porteous, 1981).

Although, in the last 20 or 30 years there seems to have been a great deal of work carried out to develop commercially viable cellulose hydrolysis processes, it seems the process has only been established at the industrial level in the former USSR (Franzidis

& Porteous, 1981).

Estimated costs for ethanol produced from cellulose by acid hydrolysis are similar to those for enzyme based processes. However, although enzymatic processes are at a much earlier stage of development, the long term prospects may be better than for acid hydrolysis (Lynd *et al.*, 1991).

Simultaneous saccharification and fermentation (SSF) has been under development for some time, and is based on enzymatic hydrolysis. This process has five basic steps: feedstock handling and pretreatment, enzyme production, yeast production, simultaneous saccharification/ fermentation and ethanol recovery. SSF simultaneously converts the pretreated cellulose slurry to glucose and glucose to ethanol in the same vessel in a continuous or semi-continuous mode. SSF can result in 25-40% increases in ethanol yield compared to saccharification followed by fermentation (Emert & Katzen, 1981).

Biotechnological techniques are being applied to improve the microorganisms and the enzymes they produce, which are critical to the conversion process (Anon, 1990a). Cellulosic hydrolysis processes have been run recently on pilot scales. In 1990, Marrow & Coombs stated that although lignocellulosic materials are available at prices which mean that the cost of fermentable sugars is potentially lower than for sugar or starch feedstocks, at present there are no methods available to liberate the sugars in an economic way. Lynd *et al.* (1991) also conclude that research to improve conversion processes and to develop cellulosic energy crops is necessary to reduce costs and to increase production potential.

3.3.3 Wheat straw

Waste materials considered as a feedstock include wheat straw (Jimenez *et al.*, 1991). There may therefore be potential for the use of both the grain and straw for ethanol fermentation.

Wheat straw is 30% cellulose, 50% hemicellulose and 15% lignin. Hemicellulose is much more easily hydrolysed than cellulose. Wheat straw has a higher hemicellulose content than other cellulosic materials (Franzidis & Porteous, 1981). As with cellulose, hemicellulose can be converted into sugars (mainly xylose) by either acid or enzyme hydrolysis. However the use of acid hydrolysis results in the formation of degradation products which may inhibit subsequent fermentation. Hence the development of effective enzyme systems (hemicellulases) is important. Such enzyme systems are similar to but more complex than those associated with cellulose hydrolysis. Marrow & Coombs (1990) assessed the potential for ethanol production from cereal straw. They estimated the cost of straw for industrial use to lie in the range £23-29/tonne (variation related to transport costs). They calculated that where transport distances are short, straw could be supplied at a delivered price of about £23/tonne. If both the hemicellulose and cellulose are used, 4.25 tonnes of straw are required to produce one tonne of ethanol and if only cellulose is utilised 6.25 tonnes are required. This results in relatively low costs of raw material for 1 tonne of ethanol of £145 for cellulose only and £100 for cellulose and hemicellulose (in comparison to a cost of £379/tonne of ethanol for wheat purchased at £115/tonne - see Chapter 6). However, it is important to note that the price of straw can be very variable, and a high demand for straw may push the price up.

3.4   Starchy sources

An advantage of using starchy feedstocks is that storage is easier than for sugar juice. Starch has to be broken down into sugar before fermentation, but the cost of this process is relatively small (Houghton-Alico, 1982).

3.4.1 Choice of starchy feedstock

Maize has been used on a large scale for bioethanol production in the USA. Potential starchy feedstocks in the UK are wheat, barley and potatoes. An important factor in the choice of starchy feedstock is the starch content. The relative starch contents of maize, wheat and potatoes are shown in Table 3.1.

Although potatoes have a comparable starch content/dry weight to cereals, they are difficult to handle in bulk. The high water content of potatoes makes storage difficult and high value by-products are not available (Marrow *et al.*, 1987).

Table 3.1 Typical composition (% dry weight) of starch sources. (Borglum, 1981)

	maize	wheat	potato
starch	71.5	74.4	75
protein	9.9	14.5	10.0
fat	4.8	1.9	0.3
ash	1.4	2.0	4.5
other	12.4	7.2	10.2

Ethanol has been produced from cereal crops on an extensive scale in the USA and on a limited scale in Western Europe (Anon, 1990b). However, ethanol fermentation from grain has been considered as a way to utilise surplus wheat in, for example, Austria (Houghton-Alico, 1982) and Sweden (Ringblom, 1985). Barley has been put forward as the best prospect for ethanol fermentation in Finland (Josephson, 1992) as it is the cheapest grain (Leppanen & Oksanen, 1993).

3.4.2 Processing

There are two basic approaches to producing ethanol from cereal grains. Either ethanol is produced as the main product, with a protein animal feed as a by- product, or ethanol is produced as a co-product with other starch products, and protein animal feed as a by-product in an integrated starch plant. In a plant where ethanol is the main product, whole crushed grain can be used as a feedstock, with recovery of protein and fibre after the fermentation process. In an integrated starch plant the grain must be milled and starch fractions separated before fermentation. The lower quality fraction called B-starch is used for ethanol production. This combined starch and alcohol production allows higher value starch to be sold, with the less valuable starch fraction being used for fermentation. This process requires a larger initial investment and therefore whether it is economic depends on the returns obtained on the sale of by- products or co-products.

Whether ethanol is produced as the main product or the co-product the starch must be converted to sugar by hydrolysis. Theoretically, the starch can be converted to glucose by acid or enzymatic hydrolysis. Acid hydrolysis is a one step process, whereas enzymatic hydrolysis is a two step process. However, problems with acid

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hydrolysis include the breakdown of the newly formed glucose, resulting in reduced yields, corrosion, and lower recovery (Lewis, 1983), so enzymatic hydrolysis is more commonly used.

The two steps of enzymatic hydrolysis are liquefaction (or cooking) and saccharification. Liquefaction involves mixing the prepared feedstock with water to form a slurry, and adding the liquefying enzyme alpha amylase. Calcium hydroxide may be added to improve the heat stability of the enzyme (Murtagh, 1986). The slurry is agitated continuously and gelatinised by heating to temperatures high enough to cause the cells to absorb water and expand. In a batch atmospheric cooker, the mash may be held at 100^oC for 1 hour, whilst in a continuous pressure cooker, the mash may be retained at $150 - 160^oC$ for 2 - 10 minutes. A second dose of alpha amylase is added after cooling to about 90^oC (Murtagh, 1986). The alpha amylase can then break down the starch molecules into dextrins (non-fermentable sugars). The second step, saccharification, breaks down the dextrins to fermentable sugars, and requires different conditions of temperature and pH, and the addition of a second enzyme (Houghton-Alico, 1982).

The liquefaction stage is equivalent to malting in the whisky industry. Malting utilises the natural enzymes produced by germinating barley to convert the starch in the barley to fermentable sugars. However, this is an expensive and energy intensive process which is suitable for the production of high value beverages but not for the production of fuels (Marrow *et al.*, 1987).

Dehydrated potatoes can be treated in a similar way to grains, with the use of fungal amylase for saccharification (Houghton-Alico, 1982). Potatoes are processed as soon

as possible after harvesting. The washed tubers are disintegrated by rasping, and the starch washed and recovered by centrifugation. By-products are not important and the yield is low due to the high water content of the tubers. As a result, 1 tonne of potatoes only yields 150 - 230 kg of starch.

CHAPTER 4 ETHANOL PRODUCTION FROM WHEAT

4.1 Industrial ethanol production versus potable ethanol

The production of alcohol from wheat already accounts for some 450 000 tonnes of wheat per year in the UK (about 370 000 tonnes of which comes from Scotland) (Taylor *et al.*, 1993) through its use as a raw material for the production of grain spirit, which is the basis of vodka, gin and blended whisky. Prior to 1981, when grain purchased from within the EC and used in the production of alcohol became eligible of export refunds, the most common choice of raw material was imported maize. The change in regulation resulted in the Scottish grain distillers replacing maize with grain of community origin, and many started using wheat when it became available at a significantly lower net cost to the industry (Entwistle & Kinloch, 1989).

The malt whisky industry relies on traditional methods which are important in giving whisky its distinctive flavour. For example, malt whisky is made in batches, and the type of barley, the strain of yeast, the shape of the still and the use of copper stills have all been identified as factors which affect the flavour (Johnson, 1991). Malt whisky is a high value product and the emphasis is therefore on the development of flavours rather than the efficiency of the process.

The process used to distil grain whisky, however, is a continuous process, which is designed to be more efficient than the traditional pot still process and therefore, like industrial ethanol production, requires raw substrate which will be selected for high ethanol yield and convenience of processing.

4.2 Crop selection

Since distillers have started using wheat as a feedstock, work has been carried out to determine the qualities of wheat required for distilling. Initially, wheat used for distilling had the same quality specifications as feed wheat (Taylor *et al.*, 1993). Varieties of wheat which are grown for their food and bread making value are not the best for ethanol production as they have been bred for high protein content and hard endosperm.

The quality requirements for wheat for bioethanol production would be the same as those required for potable alcohol production. The quality requirements specified by grain distillers are summarised in Table 4.1.

Table 4.1 Quality requirements - Grain Distillers

Type	soft wheat
specific weight	min 72 kg/hl
Moisture	16% maximum
Admixture	2.0% maximum
Screening	2% maximum through a 2.0 mm screen.

(Entwistle & Kinloch, 1989)

Distillers found that hard grained wheats gave a lower spirit yield than soft grained varieties and the industry introduced a hardness value of less than 10 on a calibrated Near Infrared Reflectometer as a specification for wheat. In contrast, collaborative work carried out by SAC and the Invergordon distillers group found no indication that the hardness of grain affected ethanol yield (Taylor & Roscrow, 1990). However, the determination of alcohol yield was carried out in the laboratory, whereas on the

commercial scale there are processing problems with hard wheat varieties. The reason for this is that breakdown of starch cells from hard endosperm varieties is not easy to achieve (Taylor *et al.*, 1993). Rifkin (1989) concluded that while soft endosperm textured varieties were preferred, some hard wheats will yield well provided the total N content is low.

Work by Taylor & Roscrow (1990) and Taylor *et al.* (1993) also examined the importance of other parameters on the ethanol yield from wheat. It was found that there was no significant relationship between percentage grain passing through a 2 mm sieve and alcohol per tonne of grain (Taylor & Roscrow, 1990). Nor did a high specific weight give much indication of a high spirit yield (Taylor *et al.*, 1993) although as it is an indication of a clean, plump, well filled and healthy grain (Fenwick, 1990) it is desirable to most processors. There was, however, a relationship between thousand grain weight and alcohol per tonne of grain, presumably larger grains having a lower proportion of husk and a higher proportion of starch than small grains. Grain nitrogen % has been found to be an important factor in determining alcohol yield. Variety trials indicated that for 0.1% increase in grain nitrogen there was a 5.8 litre/tonne decrease in alcohol yield (Taylor & Roscrow, 1990).

Benzian and Lane (1979) found that as optimum nitrogen application rates were approached grain yield tended towards a plateau whilst grain nitrogen content continued to increase. Although in southern England grain nitrogen was found to be highest when nitrogen applications were made late (Holbrook & Ridgman 1989), Taylor & Roscrow (1990) found no consistent effect of N timing on grain nitrogen content or alcohol per tonne of grain.

Data gathered from trials carried out in 1991 and 1992 as part of the Scottish

Recommended List Series including the varieties Admiral, Beaver, Estica, Haven,

Hereward, Hornet, Hussar, Mercia, Norman, Riband and Talon showed that spirit

yield was negatively correlated with grain protein (Taylor *et al.*, 1993) (Table 4.2).

Higher protein reflects lower starch in the grain. The response of spirit yield to grain

quality parameters within each site and within each variety was examined by regression

analysis. For any given value of grain hardness, grain protein or grain yield, spirit

yields per tonne of grain were significantly different at each site, suggesting that spirit

yield might depend on environmental factors as well as certain grain quality parameters

(Taylor *et al.*, 1993).

There were significant differences between varieties for grain yield and all

of the quality parameters. The SAC cereal recommended list for 1993 lists varieties

Riband, Beaver, Norman, Admiral and Hunter as suitable for distilling.

Table 4.2 Mean grain yield and quality parameters from 4 trials (Taylor *et al.*, 1993)

Variety	Hard/soft difference	Grain protein %	specific weight kg/hl	Grain yield t/ha	Spirit yield l/t	Spirit yield l/ha
Admiral	5	9.0	76.0	9.07	388	3482
Beaver	3	9.5	73.4	8.83	379	3319
Estica	10	9.6	75.4	8.4	367	3052
Haven	11	9.0	73.6	8.94	386	3419
Hereward	11	10.2	79.8	7.69	378	2883
Hornet	3	9.2	74.9	8.87	383	3372
Hussar	11	9.3	77.0	8.78	381	3318
Mercia	11	9.9	79.1	8.45	379	3171
Norman	4	9.4	73.4	8.40	382	3179
Riband	4	9.1	72.6	9.18	387	3524
Talon	13	9.8	77.0	8.48	382	3208

4.3 Processing technology

Two existing bioethanol plants are operating in Sweden and France using the Biostil fermentation process. Biostil is a process for ethanol manufacture which was initially developed for the production of fuel ethanol in Brazil from sugar cane feedstocks.

The system has since been developed for use with wheat. The Swedish farmers' co-op built the first fuel alcohol plant which utilises excess grains in 1983. The Skaraborg plant produces 20 000 litres/day anhydrous fuel ethanol (marketed as a 4% gasoline blend). Another plant has since been set up which utilises Biostil for ethanol production from wheat in Sica-Brie (France), which produces 100 000 litres/day of potable and technical grade ethanol.

Co-products from the ethanol production are protein rich feed, bran and carbon dioxide. The animal feed is used by the farmers' co-op in the cattle feed mix where it partly replaces imported soy protein. The CO_2 can be liquefied and used by the beverage industry (although it has a low value). The Skaraborg plant is promoted as having demonstrated a number of new developments. The plant was first to apply a yeast recycle step (where yeast slurry is separated out from the fermented "beer" and returned to the fermenter) to a continuous whole grain mash fermentation and to utilise part of the distillation heat to dry the animal feed product. The stillage drier was designed to work at low temperature to ensure good digestibility of the dried protein rich feed. A basic feature of the fermentation concept is the ability to accept very concentrated feedstocks. In the Skaraborg plant, every tonne of wheat processed requires only 0.5 t of process water. This reduces the cost of the process as less energy is required for effluent treatment and drying of the animal feed byproduct. The reduction in process water requirement permits the recovery of dried animal feed product which avoids the need for separation and evaporation of a grain solubles fraction. The plant produces no liquid effluents.

A typical product pattern from Swedish wheat is :

2.8 kg wheat -> 0.8 kg CO_2, 1 litre ethanol 99.8% wt, 0.3 kg bran and 0.8 kg protein rich feed.

The Biostil process can be adapted to produce ethanol as a co-product with starch. In mid 1984 the plant was extended with a process line for A-starch recovery. The effluent from the starch line is routed to the fermentation section (Ringblom, 1985).

CHAPTER 5   ENERGY BALANCE

5.1 Background to energy balance theory and techniques

The energy crisis which followed the quadrupling of world oil prices in 1973 highlighted the political problems of dependency on imported oil and drew attention to the finite nature of fossil fuel reserves.   At this time energy analysis was used by agrochemical companies to justify the energy consumed in pesticide manufacture, by comparing the energy use with the energy gained in terms of increased yield (Chapman & Colthurst, 1975) and to compare the efficiency of different agricultural production systems.

Energy analysis was a new approach to interpreting the costs of goods and services. Energy analysis data are often used to calculate an energy ratio or energy balance. An energy ratio is the ratio of energy used during production : the energy obtained from the product and by-products. The energy balance is the energy obtained in the form of product and by-product minus the energy used in production.

There do not appear to be any universally followed conventions for energy analysis work. One reason for this is that the number and type of inputs included in an energy analysis vary between different studies and are dependent on the system being studied, and the aims of the study. The inputs included in energy analysis calculations must therefore be specified in order for comparisons between individual energy balances to be possible. Where energy balances are used to assess the viability of a biofuel, the concern is generally with the amount of non-renewable energy used to produce renewable energy. In order for a biofuel to be viable as a renewable energy form it is important that the non- renewable energy input is less than the total energy output. If

the energy balance is negative or the energy ratio is less than one there will be a net loss of energy in the production of the fuel, thereby negating its status as a renewable energy source.

Energy inputs can be divided into direct energy inputs such as fuel or power consumption, and indirect energy inputs the such as chemicals and equipment. These inputs can be assigned an energy value (MJ), which may be expressed per unit of final product, eg MJ/kg ethanol, or per hectare, ie MJ/ha.

5.2 Attributing energy values

5.2.1 Range of inputs and outputs

A range of values for inputs and outputs was used in the energy balance to account for a range of conditions with respect to factors such as yield, different fertiliser and pesticide applications and variation in grain moisture content at harvest. The range of values allows calculation of energy ratios for best case, good-intermediate, poor-intermediate and worst case scenarios.

5.2.2 Direct on-farm energy inputs

For wheat production, direct on-farm energy inputs include the energy used as a result of fuel consumption for field operations such as ploughing, discing, harrowing, drilling, rolling, fertiliser application, pesticide application and combining and for grain drying.

The energy inputs used for fuel consumption were obtained from Bockman *et al.* (1990) (who quote Breirem *et al.*, 1984) and Dickson & Ritchie (1993). Both sets of data are for barley, but it is assumed for this calculation that the energy used for field

cultivation of barley is representative of the energy used in the cultivation of wheat. The data given by Dickson & Ritchie (1993) are used as the basis of the energy input for "best conditions". They used a Bomford chisel plough and a Lely Roterra for primary and secondary cultivation in their measurements which were undertaken on a clay loam soil in Midlothian. The use of more traditional techniques, for example, Mouldboard ploughing would result in a higher fuel consumption. The higher energy consumption given by Bockman *et al.*, (1990) was used for the energy input under intermediate conditions and this value was multiplied by a factor of 1.5 to obtain the "worst case" value which accounts for extreme conditions of heavy and wet soils .

The energy input for grain drying was calculated from product information provided by Alvan Blanch and Master Drier. It was assumed that the grain was dried to 15% from 17% under good conditions, from 20% under typical conditions and 30% under very poor conditions.

5.2.3 Indirect on-farm energy inputs

The indirect on-farm energy inputs include energy required for the manufacture of pesticides and fertilisers, machinery and field equipment.

Nitrogen fertiliser energy input. Energy values given by Leach (1975), ICI (Tatchell, 1974) and Norsk Hydro (Bockman *et al.*, 1990) were used in conjunction with SAC and ADAS recommended fertiliser rates to calculate the total energy input per hectare for N fertiliser. A range of energy requirements have been published for nitrogen fertiliser manufacture. The range is a reflection of the improvement in the efficiency of manufacturing nitrogen fertilisers. It is not clear to what extent energy saving processes have been adopted. For example, it has been suggested that the

efficiency of Eastern European factories, from which the UK imports fertiliser, might be less than that of Western European factories. Because of the uncertainty of the energy used for manufacturing nitrogen fertiliser from different sources, a wide range of energy inputs was calculated. The range of energy inputs calculated accounted not only for the different application rates and differences arising from the energy efficiency of factories, but also differences that arise from the type of fertiliser used, for example, urea manufacture is generally more energy intensive than ammonium nitrate manufacture. Leach (1975) gives energy values of 83.5 MJ/kg N for urea bagged and delivered to the farm and 76 MJ/kg N for ammonium nitrate. This is in contrast to data given by Bockman *et al.* (1990) which gives an energy value of 41.2 MJ/kg N for ammonium nitrate bagged and delivered to the farm.

Autumn nitrogen application is not recommended as profitable responses are rare and most will be lost in the environment. Spring nitrogen application is best applied as a split dressing. It is recommended to apply up to a third at the start of spring growth and the rest at Zadoks growth stage 30-31. A 50/50 split is recommended to reduce grain N% for distilling.

SAC and ADAS recommended N applications are calculated using different soil classification systems, and show some variations in the range of N application. The range of energy inputs have been calculated to take account of both SAC and ADAS recommended applications.

P and K fertiliser input. The energy value attributable to P and K fertiliser is dependent on the rate of application. There are slight differences in the energy input from different types of P and K fertiliser, but less variation than there is for N fertiliser

manufacture. Leach (1975) gives values of 13.7 - 15.2 MJ/kg P bagged and delivered to the farm depending on product and 7.9 - 9.0 MJ/kg for K. Similar energy values have been published by ICI (Tatchell, 1974), Mudahar & Hignett (1987) and Norsk Hydro (Bockman *et al.*, 1990).

The values given by Leach (1975) were used in conjunction with the SAC and ADAS recommended fertiliser guide to determine the energy input for P and K fertiliser. The range of values given reflect variation in soil status. It was assumed that straw was removed. Ploughing in straw reduces the recommended P & K application and therefore the energy input, but the resulting reduction in the total energy input is relatively small and does not greatly alter the energy ratios. SAC and ADAS use slightly different soil classification systems and there are some differences in the highest and lowest recommended applications, but recommended intermediate applications are similar.

Pesticide energy inputs. Farm management handbooks describe a typical pesticide application for winter wheat as one application of herbicide and 2 applications of fungicide for eyespot and leaf diseases. Values for the energy required to manufacture pesticides have been published by Green (1987) and Pimental (1980). However, the list is fairly limited, and does not include new chemicals.

Most pesticides are produced by a series of chemical reactions. Their production requires direct inputs of energy such as electricity, gas, steam or petroleum and indirect energy inputs in the form of materials. The total energy input is the sum of direct and indirect energy inputs.

In addition to the energy required for manufacturing the active ingredient, energy for formulation, packaging and transport must also be included to give the final energy value.

The "best conditions" energy value was calculated for one application of herbicide and two applications of fungicide. This gives a total of 537 MJ/ha. Further applications of fungicide may be used depending on the season and the system of production. For the intermediate energy figure, energy for a further fungicide application was added giving a total of 587 MJ/ha.

For "poor-intermediate" conditions, an additional fungicide application was considered. Adding this energy input to previous energy inputs gives a total energy input from pesticides of 605 MJ/ha. For "worst conditions" an additional insecticide treatment was considered, with an energy input of 288 MJ/ha. Adding this on to the previous total gives a energy input of 893 MJ/ha.

5.2.4 Direct ethanol processing inputs

Energy inputs were calculated from the list of consumptions given for a 30 million litres per year fuel ethanol plant producing two products, fuel alcohol and DDGS, by Chematur Engineering AB of Karlskoga, Sweden. Direct energy inputs are power and fuel.

5.2.5 Indirect ethanol processing inputs

Capital costs. The energy input to account for machinery and equipment in the factory was calculated from the capital costs calculated in Chapter 6 using a monetary to energy conversion factor of 18 MJ/£. This conversion factor was calculated by

dividing the total consumption of commercial energy in the UK for 1988 (Anon, 1990c) by the gross domestic product for the same year (Anon, 1990d) and is a recognised method for calculating energy input for capital costs.

Other indirect energy consumptions. Other indirect energy consumptions include steam and chemicals. Previously published data were used to assign energy values to these inputs.

5.2.6 Outputs

The energy outputs accounted for in the calculation were ethanol, DDGS and straw. Chematur Engineering give an output of 370 - 385 litres of ethanol per tonne of wheat and an output of DDGS of 0.9 kg DDGS/litre of ethanol. DDGS is sold as an animal feed and has an energy content of 12.6 MJ/kg (Anon, 1992b). The range of energy outputs attributable to ethanol were calculated to account for range in wheat yields per ha (from 10 tonnes/ha under the best conditions and 6 tonnes/ha under the worst conditions), and some variation in the yield of ethanol per tonne of wheat. The energy output was calculated from the calorific value of ethanol and does not take into account the theoretical 30% increased efficiency of vehicles run on ethanol as compared to those run on petrol as described in section 2.1.2. The energy value attributed to straw was calculated from the calorific value, and gives an indication of the maximum energy value that could be obtained from straw if it were used as a fuel in, for example a straw burning furnace on the farm. If the straw was used for electricity generation, the "usable" energy would be reduced due to factors such as energy used in transporting the straw and energy lost during electricity generation and transmission (about 75% is lost).

5.3   Energy balance

Input	energy value (MJ/ha)			
	best case	intermediate		worst case
Field inputs				
nitrogen	2 060	5 768	13 300	23 013
phosphate	0	1 120	1 642	2 204
potassium	0	796	971	1 305
pesticide	537	587	605	893
field operations	2 558	3 340	3 340	5 010
field equipment	3 103	3 103	3 103	3 103
grain drying	987	1 974	2 044	4 598
drying/storage equipment	130	130	130	130
Processing inputs				
fuel	25 357	19 904	21 495	15 821
power	30 462	23 910	23 910	17 600
capital costs	6 369	4 999	4 999	3 680
chemicals	152	173	173	167
steam	31 845	27 080	27 080	22 998
Total input	103 560	92 884	102 792	100 522

Outputs

ethanol	81 228	63 740	63 740	46 929
DDGS	43 614	34 224	34 224	25 197
straw	60 000	60 000	60 000	60 000

Total output

ethanol + DDGS	124 842	97 964	97 964	72 126
ethanol + DDGS + straw	184 842	157 964	157 964	132 126

Energy ratios

output	energy ratio			
ethanol	1:0.784	1:0.686	1:0.620	1:0.467
ethanol +DDGS	1:1.206	1:1.055	1:0.953	1:0.718
ethanol +DDGS + straw	1:1.785	1:1.701	1:1.537	1:1.314

When ethanol is the only output considered, the energy ratio is less than one under all conditions. Where DDGS are also considered in the calculation, the energy balance becomes positive under good conditions, but is still low. If the use of straw as a fuel is considered in the energy balance, the energy ratio is positive under all conditions, but the highest ratio is only 1: 1.79. Straw could be used in other ways to improve the energy balance, for example as a feedstock for paper and cardboard manufacture, or as a feedstock for ethanol, but the exact effects of these uses on the energy ratio are difficult to quantify at present.

5.4 Methods of improving the energy ratio

The energy ratio for ethanol production from wheat is not very good. It is less than one where the only product considered is ethanol, and just above one when DDGS are included, under good conditions. This is in contrast with an energy balance of 1:5 for mineral oil. There are two approaches to improving the energy balance: one is to modify the inputs, for example by reducing inorganic fertiliser inputs; the other is to increase the energy output. Accounting for the use of straw as a fuel has the potential to improve the energy ratio to 1:1.31. - 1:1.79. In Sweden, straw is used as a fuel in small ethanol producing facilities, operated by farmers on a co-operative basis. The biggest energy input is in the industrial processing, so improvement in the energy ratio will be dependent on improvements on the efficiency of the industrial process. Chematur state that there is some potential for improving the energy balance for example by producing ethanol as a co-product with starch.

5.5 Previously published energy ratios

Energy balance figures given by Shell (Anon, 1992b) give an input output ratio of 1:1.37 for ethanol and DDGS, and 1:2.37 when straw is included. The biggest single input in their calculation is also the process energy.

CHAPTER 6   ETHANOL COSTING

6.1   Introduction

To allow a comparison with synthetic ethanol and other fuels this section aims to calculate the cost of producing a litre of ethanol from a commercial facility. Environmental aspects are not considered.

The costings are based on a quote from Chematur Engineering AB of Karlskoga, Sweden. This company markets the Biostil technology, originally developed by Alfa Laval, which is operated in more than 30 plants worldwide. Most of these use sugar based raw materials while only two operate on starch products.

6.2   Plant specification

Annual production 30 million litres anhydrous fuel grade ethanol and 27 000 tonnes DDGS (distillers dried grains with solubles).

DDGS is produced at 11% or less moisture and 27-30% protein and is sold as a highly digestible animal feed.

The plant operates 24 hours per day, 300 days per year using the Biostil continuous fermentation rather than batch or cascade systems.

The plant requires approximately 24 employees (8 of which are shiftworkers).

Daily mass balances:

Wheat 260 tonnes per day
- 100 000 litres anhydrous ethanol
- 90 tonnes per day DDGS
- 80 tonnes per day CO2

Yearly mass balances:

Wheat 78,000 tonnes
- 30 million litres anhydrous ethanol
- 27 000 tonnes DDGS
- 24 000 tonnes CO2

The process is fairly simple including only four major steps: milling of the wheat, hydrolysis and fermentation, distillation and finally drying of the distillers dark grains. An approximate costing for this facility (as at August 1993) has been provided as follows:

6.3   Plant capital cost

Unit	Cost	
	$US	£UK
Wheat handling, milling	3 054 000	2 036 000
Hydrolysis, fermentation	9 760 000	6 506 667
Distillation	6 021 000	4 014 000
Dryer, DDGS, storage, pelleting	5 200 000	3 466 667
Utilities (water, air etc)	2 138 000	1 425 333
Chemical and ethanol storage	1 595 000	1 063 333
Waste water treatment	1 624 000	1 082 667
Miscellaneous (site preparation roads, laboratory, control room etc)	1 992 000	1 328 000
	31 384 000	20 922 666 @ $1.50 per £

Note that these costs include all engineering, installation, insurance and site costs (although not the cost of the land or of commissioning company management)

6.4   Production cost for 30 million litre ethanol plant

	Annual Cost (£)	Cost per litre of Ethanol (pence)
1. Capital cost 15 year life. 10% interest rate. Annual charge (interest and capital repayment) on £20 922 666	2 749 000	9.2p
2. Purchase of wheat: 78 000 tonnes at £115/t (including £5/tonne haulage)	8 970 000	29.9p
3. Energy for processing	1 400 000	4.7p
4. Staff: 24 at average £22 000	528 000	1.8p
5. Maintenance 1% of capital cost per annum	200 000	0.7p
6. Admin. & general overheads	200 000	0.7p
7. Working capital interest: approx £10m at 10% for 6 months average	500 000	1.7p
TOTAL ANNUAL COSTS	13 947 000	48.7p
8. By-product income Distillers' dark grains and solubles 27 000 tonnes at £110/tonne	2 970 000	9.9p
Carbon dioxide 24 000 tonnes at ? (see notes on costings)		
NET COST OF ETHANOL FROM WHEAT	10 977 000	38.8p

This is the cost of producing a litre of ethanol from this size of plant. It does not include:

- Fuel taxes

- Marketing and distribution costs

- A profit margin

This cost compares to:

Car petrol (at pumps) 57 p/litre

Car diesel (at pumps) 51 p/litre

Synthetic ethanol priced at approximately 39p/litre (£500 per tonne)

MTBE production cost approximately 16 p/litre (USA estimate)

The above fuel prices include motor fuel duty of around 28 pence per litre for unleaded petrol and diesel, as shown below.

Breakdown of UK diesel price

	p/litre
composite price (June '93)	7.2
distribution	6.57
excise duty	27.70
	41.47
	———
VAT @ 17.5%	7.26
Subtotal	48.75
retail margin	3.52
VAT on retail @ 17.5%	0.62
Total	52.86

If bioethanol was used as a petrol additive, it may have to compete with other oxygenates including synthetic ethanol, methanol, MTBE and ETBE. The cost to produce MTBE has been estimated at 91 cents/gallon (Hall, 1991) (assuming a price of $19.50 per barrel for West Texas Intermediates crude oil in 1992; the current price for west Texas Intermediate crude oil is $15.85). This works out at approximately 16.10 p/litre which is well below the net cost of bioethanol, and Marrow *et al* (1987) state that MTBE is the highest valued oxygenate.

Notes on the costings:

Life of the plant. Most studies suggest a life of 10 to 15 years, e.g. Marrow *et al.* (1987).

Energy costs. Our figures are based on energy consumption figures of 550 kwh of electricity and 1500 m Cal of fuel oil power per 1000 litres of ethanol produced.

Carbon dioxide. The viability of collecting carbon dioxide produced during fermentation is likely to vary depending on the proximity of an end user.

Biostil also quote energy figures for a 90 million litre US plant compared to more traditional technologies.

Staff costs are based on Biostil data

Working capital interest is largely on stored wheat.

The DDGS price is based on the current market price of traditional distillery dark grains.

6.5 Sensitivity

Price of wheat and other cereals. The cost of the raw material is by far the largest single cost (29.9 pence per litre) in the production of bioethanol. This cost alone makes bioethanol from wheat uncompetitive.

A reduction in wheat price of £20 per tonne would reduce the cost of ethanol by just over 5 pence to 31.5 pence per litre. At this cost of production bioethanol could compete with synthetic ethanol if the price was set close to the production cost. However, BP, the largest producer of synthetic ethanol in Western Europe, more or less has a monopoly in the UK and therefore currently controls the price of synthetic ethanol. It is possible that the cost of synthetic ethanol is set well above the production cost and therefore if bioethanol was brought onto the market at a competitive price, synthetic ethanol manufacturers could drop their price.

Growing wheat on set-aside at a discount of £20 per tonne for this industrial use might provide a considerably higher margin than pure set-aside (see table below). Using set-aside for growing industrial cereals would be more attractive than using set-aside for growing industrial rape if the rape were then allocated to the rotational land. The reason for this is that if rape is grown on set-aside the very substantial rape area payment is substituted for a much smaller set-aside area payment. When wheat is grown on set-aside the area payment received is actually greater than that paid on ordinary arable land.

Gross margins per hectare

	Wheat on normal land	Wheat on set-aside	Set-aside alone
Output			
Grain 6.9 t at £110	761		
6.9 t at £ 90		623	
Straw 3.2 t @ £15	49	49	
Area payment (1995/96)	232	304	304
	——	——	——
	1042	976	304
Variable costs	198	198	0
	——	——	——
Gross margin	844	778	304
Variable element of fixed costs (fuel, overtime, repairs)	74	74	12
	——	——	——
Margin	770	704	292

The break even price for wheat grain on set-aside based on the above assumptions is only £30 per tonne. This means that contracts for wheat grain on set-aside would provide a margin better than bare set-aside if the price offered was greater than £30 per tonne. For most farmers it would need to be well over £30 per tonne to justify the extra management involved and to cover the risk of a poor year which might result in yields well below 6.9 tonnes per ha. It is interesting to note that contracts for industrial cereals have been offered and taken up by some farmers at a price of only £45 per tonne. Considering the risk and extra management involved this is little more than a break-even price.

Raw material prices at this level should transform the economics of bio-ethanol production. A fall in wheat price from the £115 per tonne budgeted to £45 per tonne would cut production costs by 18 pence per litre, resulting in a net cost of ethanol from wheat of 21p. This is probably not as low as the production cost of synthetic ethanol, but is well below the current ethanol market price of 39p per litre.

Rotational considerations may make this development less attractive. Farmers are using set-aside to provide an early entry for oilseed rape or a clean entry for winter wheat to maximise the area of high yielding first wheats.

It is worth noting that there has been an overshoot of the eligible crops base area in "non LFA Scotland" for 1993 of 5.4%. This would normally result in an increase in the set-aside requirement to 20.4%. Recent changes in CAP rules have reduced the penalty by 90% to only 0.54%. Any overshoot penalty in 1994 will be reduced by 80% and by 50% in 1995. However in 1996 full penalities will apply. It is likely that "non LFA Scotland" will continue to overshoot its base area resulting in revised set-aside percentages.

The net effect of this is to reduce the general profitability of cereals and especially the returns from set-aside (as the extra set-aside requirement receives no area payment). This makes industrial cereals, even at very low contract prices, more attractive. In some regions there is an added advantage of cereals on set-aside in the value of straw for nearby livestock regions. Straw in non LFA Scotland (and similar livestock areas of England and Wales) could be priced at £30 rather than £15 per tonne. Set-aside and the increase in oilseed rape production have led to a rise in the price of straw.

Spring cereals with their lower yields will have a higher break even price.

Margins per hectare (£)

	Spring barley normal land	Spring barley on set-aside	Set-aside alone
Output			
Grain 4.4 t @ £105	467		
4.4 t @ £85		378	
Straw 2.7 t @ £20	49	49	
Area payment (1995/96)	232	304	304
	———	———	———
	748	731	304
Variable costs	148	148	0
	———	———	———
Gross margin	600	583	
Variable element of fixed		74	
costs (fuel, overtime, repairs)	74	74	12
	———	———	———
Margin	526	509	292

An arbitrary price for set-aside barley of £85 per tonne is used above. However, the break-even price for this 4.4 tonne per hectare spring barley crop is £36 per tonne. This is slightly higher than for a 6.9 tonnes per hectare wheat crop, but not as high as might have been expected. The lower variable costs and fixed area payments for all cereals make up for some of the difference in yield. The message is that a fairly uniform contract price of, say, £50 per tonne could attract farmers in a range of different areas and farm types.

Capital cost per litre. This cost is very sensitive to scale. Larger facilities could leave costs per litre 75% lower than that calculated in this example. For example, French figures show total costs (not including raw material) per litre of only 3.7 pence per litre for a 5000 hl/day plant.

Grant or soft loan assistance may be available for a new facility. There are a surprisingly wide range of sources including Government Regional Selective Assistance (grants of up to 40% in "Development Areas"), Enterprise Company soft loans or share capital, specific EC funded assistance in areas affected by coal and steel industry restructuring and Enterprise Zone assistance. In agriculture EC FEOGA grants (25% with 5% UK top up) were available in the past for projects aimed at improving the marketing of agricultural produce. This scheme has ended, but may be reinstated in a revised form soon. Grant funding of 40% of the capital cost of £20.9 m in our 30 million litre ethanol plant example would greatly reduce the finance burden of the enterprise, reduce the ethanol production cost by 3.7 pence per litre and reduce the overall risk for the investor(s).

Note that in this study the capital cost has been spread over a life of 15 years for the investment. Businesses may demand a faster payback for an investment like this which is regarded as risky. Reducing the timescale to, say, 5 years would very greatly increase the cost per litre.

By-product Income. By product sales have a major impact on the net ethanol price. An increase in the price of the DDGS of £10 per tonne would reduce the cost of ethanol by 1.0 pence per litre. The price at which DDGS can actually be sold depends on the scale of distilling in the UK. It is unlikely to trade above current prices of distillers' dark grains.

The recent CAP reforms aim to cut the market price of cereal by around 30%. As a result all other competing feeds will fall in price to remain competitive. Although DDGS is an attractive feed and may trade at a small premium to cereals, it must inevitably follow the same demand price trend. A 30% cut in the DDGS price used in this example would increase the ethanol production cost by almost 3.0 pence per litre.

6.6   Implications of GATT

The agricultural provisions of the General Agreement on Tariffs and Trade are the major reason for the reform of the CAP. The main features of GATT are that over a 6 year period the amount of export subsidies and the volume of subsidised exports of each product must fall by 36% and 21% respectively, that import levies on average and for individual products must be cut by 36% and 15% respectively, import tariffs must become fixed rather than variable, the EC must allow minimum access for foreign produce at a level of 5% of total EC needs and total internal agricultural support must fall by 20%.

The net effect of this is that surplus production must be greatly reduced (hence set-aside) and EC production must be able to compete with imports (hence price cuts). Interestingly arable area payments are not regarded as "internal agricultural support". The EC can continue to pay these to attract farmers to take set-aside.

There are several implications for ethanol production from cereals.

1. Set-aside is the main tool for cutting production in the EC. The payment of large area payments in return for set-aside is not under threat as area aid is not included in the measure of "internal agricultural support". The growing of cheap grains on set-aside is therefore likely to be a relatively long term opportunity, at least for the 6 year GATT introductory period.

2. With world grain prices as low as £40 per tonne it may be cheaper to import cereals for bioethanol production rather than use UK cereals grown on set-aside. However the GATT deal does not eliminate import levies. A good level of protection will remain, though at times of very low world prices imports may be competitive as the levy will now be a fixed amount rather than variable as in the existing system to bring all imports up to a minimum import price.

3. There is some concern that the CAP returns for cereals will not lead to the reduction in surpluses required to meet the cut in subsidised exports required by GATT. The implication is that either set-aside must be increased or cereal prices must fall more sharply than envisaged to increase consumption in the EC or allow competitive unsubsidised exports. Either scenario has the potential to create cheaper raw materials for bioethanol production.

4. One proposal from the EC's role in the GATT negotiations is that set-aside must not be increased above present levels. This effectively reduces the EC's room for manoeuvre in controlling surpluses.

5. A major stumbling block in the negotiations has been the increasing production of oilseed rape in Europe. USA soya farmers are losing EC markets as oilseed rape meal (the by-product of oil extraction) displaces soya as the protein supplier in feed rations. The growing of oilseed rape on set-aside for industrial uses (pharmaceutical, chemical and bio-diesel) could have greatly increased the production of meal. As a result under the "Blair House agreement" the EC has agreed to limit meal production from industrial oilseed rape to 1 million tonnes. It is felt that this "quota" could be quickly swallowed up by those EC countries supporting developments of RME (rape methyl ester) for biodiesel. Also the UK Government is not currently supporting such developments and will not give excise duty exemptions to RME. As a result the growing of cereals for ethanol or other industrial uses may be more attractive in the UK. There is no externally imposed limit on the growing of industrial cereals on set-aside and on the production of feed by-products such as DDGS.

6.7   Conclusions

Production of fuel ethanol from wheat purchased at £115/tonne is not directly competitive with synthetic ethanol fossil fuels or MTBE. However, the biggest single cost in ethanol production from wheat is the cost of wheat and growing wheat on set-aside offers potential to reduce this cost substantially and subsequently reduce the cost of bioethanol to as low as 21 p/litre. At this production cost bioethanol is still uncompetitive with MTBE, but could compete with the current market price of synthetic ethanol, and if duty concessions were given it could be priced competitively with fossil fuels.

CHAPTER 7 HOW PREVIOUS FUEL ETHANOL PROGRAMMES HAVE WORKED

7.1 Previous ethanol schemes

The two biggest fuel ethanol programmes to date have been in Brazil and the USA. In Brazil the fuel ethanol programme is sometimes referred to as the National Alcohol Programme (NAP) or Proalcohol and has utilised ethanol in blends with petrol and as a petrol substitute. The USA programme is known as the gasohol programme. Gasohol is the term used in the USA for alcohol/petrol blends. When the gasohol programme was introduced, gasohol was defined as a blend of petrol with at least 10% by volume of fuel alcohol. In 1992, different classes of gasohol were defined. The original 10% alcohol/petrol blend is referred to as 10% gasohol, the term 7.7 % gasohol includes alcohol/petrol blends where the alcohol content is at least 7.7% but less than 10% and 5.7 % gasohol includes alcohol/petrol blends where the alcohol content is at least 5.7% but less than 7.7%.

7.2 Brazil

7.2.1 Feedstocks used

Sugar cane is the major feedstock for the Brazilian fuel ethanol programme. The advantages of using sugar cane as a feedstock were that production technology for the crop was well developed, climatic conditions were suitable for growing sugarcane in nearly all the populated regions of the country, and the technology for producing ethanol from sugar cane was already developed through the alcoholic drinks industry. The success of the programme was also aided by the fact that manufacturing capability existed for both industrial and agricultural equipment. More than 90% of materials used were of domestic origin (Goldemberg *et al.*, 1985).

7.2.2 Extent of fuel ethanol use

The Brazilian alcohol programme was launched in November 1975, with the aim of reducing oil imports, and consequently alleviating balance of payment difficulties (de Oliveira, 1991), by blending ethanol with petrol in amounts that would neither disturb engine efficiency nor require any adaptation to engines (Goldemberg *et al.*, 1985).

Initial production capacity was 625 million litres in 1975, and a target of 2 500 million litres was set for 1979, which was easily achieved. Surpluses from the sugar industry could be diverted to alcohol production, by annexing distilleries to sugar plants. After 1979, due to further increases in oil prices, the programme was extended to encourage the use of ethanol as a complete petrol substitute and a production target of 10.7 billion litres of ethanol was fixed for 1985. While the requirements of the initial programme were met by sugar producers who diversified into alcohol production, the expansion of the programme resulted in the establishment of independent distilleries to cope with the increased demand for ethanol.

At the onset of the programme, there was little confidence in alcohol engines due to technical problems. However, these problems were overcome and by 1988, approximately 3.6 to 4 million vehicles were running purely on hydrated ethanol (30-33% of all Brazilian vehicles).

7.2.3 Government support

At the time of the oil crisis Brazil was importing 80% of its oil requirement and oil imports were becoming a major constraint on Brazilian economic development. The alcohol programme was launched at this time to offer a renewable substitute for

petrol. The Brazilian ethanol programme invested roughly $3.7 billion to install 450 distilleries (de Oliveira, 1991).

A range of methods were used by the Brazilian government to encourage the production of ethanol and promote its acceptance in the market place. A government act required the mixture of dehydrated alcohol with petrol at levels that did not require any engine modification and an advertising campaign promoted ethanol as the national fuel (Goldemberg *et al.*, 1985). All-petrol cars were phased out in the mid 1980's during a complete ban on car imports which ended in 1990. High import taxes have kept the figure low (Homewood, 1993).

7.2.4 By-products

The major by-products of ethanol production from sugar cane, in an independent distillery are bagasse and vinasse. Other by-products are CO_2, fusel oil and yeast. An autonomous distillery will produce: 70 - 90 litres of ethanol, 250-350 kg of bagasse and 910-980 litres of vinasse from 1000 kg of sugar cane. Recent progress in the use of vinasse, bagasse and dried yeast has made the production of ethanol less polluting and more profitable.

Bagasse is the dry pulp left over from crushing sugar cane and can be used as an animal feed, as a fuel for the generation of steam and electricity and as a raw material for the cellulose and paper industries, and is probably the most important by-product of bioethanol production (Laluce, 1991). A number of distilleries are producing electrical energy from bagasse to meet their own energy requirements and some of them are selling surplus power to electricity companies.

Vinasse is the liquid waste from the distillation of sugar cane juice. It makes a good fertiliser source of nitrogen, phosphate and potassium, and is used on most Brazilian farms. Some units have been constructed to use vinasse for the production of biogas. The fertilising properties of the biodigested vinasse are quite similar to the original untreated vinasse so the treated vinasse can still be used as a fertiliser in addition to being used as a feedstock for fuel biogas production.

Where a distillery is annexed to a sugar mill, the products are sugar ethanol, cake, bagasse and vinasse (Laluce, 1991). Cake is used mainly as fertiliser and occasionally as an additive for animal feed.

7.2.5 Energy ratios

Published energy ratios for the production of bioethanol from sugarcane are positive, and range from 1:2.07 Mouris (1984) - 1:4.53 (da Silva *et al.*, 1978). These energy ratios are a marked improvement on the energy ratios calculated in this study for ethanol production from wheat. The ability of Brazilian distilleries to meet all their energy requirements by generating electricity from the by-product bagasse probably accounts for the difference in energy ratio between bioethanol production from wheat and sugarcane.

7.2.6 Cost of petrol versus ethanol

In 1985, Goldemberg *et al.*, stated that the cost of producing fuel ethanol was $0.202 per litre, the price paid by the government was $0.23 per litre and the retail price at the pump was $0.285 per litre. In comparison the cost set for petrol was $0.25 per litre and the retail price at the pump was $0.336 per litre. However, the set price of petrol was high because it subsidised other oil derivatives such as naptha, liquid propane gas

and fuel oil. Without including these subsidies the cost of petrol was only $0.15 per litre.

More recently Goldemberg (1993) stated that the cost of ethanol in Brazil is $0.21 per litre, the cost of petrol is $0.18 per litre, and Homewood (1993) quotes a world cost of petrol of $0.145 per litre and gives ethanol production costs of $0.189 - $0.252 per litre, but it is not clear how these costs relate to retail prices in Brazil.

7.2.7 Present and future policy

From the import substitution point of view the alcohol programme has been successful. Between 1975 and 1986 around $8.5 billion was saved on oil imports and another $1.4 billion was saved in 1987. In addition to this, the alcohol programme has created 700 000 jobs, stimulated the development of subsidiary industries for the production of pesticides, fertilisers and equipment (Laluce, 1991), and making ethanol from sugar cane has become 40% cheaper since 1979. Sugar producers say that there is further potential for reduction in costs (Homewood, 1993). Nevertheless, the programme remains highly controversial, particularly as far as costs are concerned, because costs of alcohol production are above market prices and therefore subsidies are needed to sustain production (de Oliveira, 1991).

Until quite recently, oil prices were expected to increase further, thereby improving alcohol's competitiveness in the future. However, since 1986 oil prices have fallen and are expected to remain low over the next 10 years. Also Brazilian oil exploration has been successful. Domestic oil production is forecast to match liquid fuel demand by 1995, so the need to replace imported oil with ethanol is no longer there. It has therefore become necessary to reassess the ethanol programme. In 1987 the National

Energy Commission undertook a reassessment of this programme but it concluded that no fundamental change was needed. In fact it proposed a further increase in alcohol production to substitute for oil products (de Oliveira, 1991). However, the director of the government's national fuel department recently forecasted that ethanol will become simply an additive to petrol and that by the year 2000 production of cars which run purely on ethanol will have stopped (Homewood, 1993). Laluce (1991) also concludes that ethanol has a better future as a petrol additive than as a substitute fuel. Shortages of ethanol in 1990 damaged the scheme's credibility and since then ethanol cars made up between only 30 and 40 % of new cars built (less than half the previous number); the rest are for alcohol/petrol blends (Homewood, 1993).

It has been suggested that the Brazilian scheme might have a better future if productivity could be improved, for example by using wasteland on the farms in Sao Paulo. However, there will have to be investments in the ethanol programme made by the producers. New strains of cane and better management could push productivity up by 10% (Homewood, 1993).

7.3 USA

7.3.1 Feedstocks used

The USA gasohol programme has been primarily based on the use of maize as a feedstock. The availability of the feedstock is reflected in the distribution of ethanol use. Much work has been carried out in the USA on the production of ethanol from lignocellulosic materials, eg wood, but commercial production still uses corn as the main feedstock, with perhaps small amounts of wheat.

7.3.2 Extent of ethanol use

The USA is the world's second largest producer of bioethanol, after Brazil, but use of gasohol varies greatly from state to state. The Midwest region has the highest consumption, accounting for over half the annual ethanol consumption (405 million gallons of ethanol in 1990). In comparison, 278 million gallons were consumed in the South, 75 million gallons in the West and less than 13 million gallons in the Northeast (Anon, 1991). USA department of transport figures show that gasohol is used in 33 states, with the percentage of gasohol use ranging from 49.4% of "highway use" petrol in Nebraska to 0.04 % in Utah. The variations in regional ethanol consumption are due to several factors such as variations in state tax credits for gasohol, the distance from ethanol producers and limitations of the distribution infrastructure, such as pipelines and storage facilities (Anon, 1991).

In the Northeast there is relatively little grain production and few tax credits are available. Growth in ethanol use in the South is mainly due to marketing by regional producers and blenders. The Midwest has more large ethanol producers than other regions of the country due to the availability of corn feedstock. Local production and consumption result in reduced transit expenses from the producer to blender to retailer, and greater consumption of gasohol in the Midwest region. In the West, distribution is difficult and freight costs generally prohibit the cost competitiveness of ethanol (Anon, 1991).

7.3.3 Government support

At the beginning of the USA gasohol programme support was given in the form of loan guarantees for the construction of ethanol production plants (Chambers *et al.*, 1979).

The gasohol programme in the USA can be divided into federal programmes and state programmes. Federal gasohol programmes were originally concerned with reducing USA dependence on imported oil and substituting renewable resources for fossil fuels whereas state gasohol programmes have focused on the use of agricultural products grown or distilled in the state. In the USA, the tax on fuel in any state is the sum of federal fuel tax, which is the same throughout the USA and state fuel tax, which is set by the state and may vary across the country. There have been federal tax incentives for gasohol since 1979 but the number of states offering state fuel tax incentives has shrunk in recent years due to the revenue loss incurred. At current oil prices, gasohol is not price competitive without such incentives (McElhaney, Pers Comm, 1993).

Table 7.1 shows that while ethanol and gasohol are taxed at a lower rate than petrol, bioethanol is taxed at a higher rate than ethanol produced from natural gas and methanol, and gasohol containing methanol is taxed at a lower rate than gasohol containing ethanol. This reflects the competition that bioethanol faces from other alternative fuels.

State tax rates on motor fuels range from 8 to 26.8 cents per gallon and tax reductions for gasohol are available in 11 states and range from 8 cents per gallon in Alaska, to 1 cent in Connecticut and Iowa. In Illinois, only 70 % of the price is subject to sales tax. In Louisiana, gasohol is exempt if the alcohol is produced in the state (McElhaney, Pers Comm, 1993).

Table 7.1 Federal excise tax rates on motor fuels

Fuel type	tax rate (%)
gasoline	14.1
diesel fuel	20.1
special fuels (propane)	14
neat alcohol(85% Alcohol)	
ethanol from natural gas	7.1
methanol from natural gas	7.1
ethanol not from natural gas	8.65
methanol not from natural gas	8.05

gasohol

10% gasohol	
ethanol	8.7
methanol	8.1
7.7% gasohol	
ethanol	9.94
methanol	9.48
5.7% gasohol	
ethanol	11.02
methanol	10.68

7.3.4 By-products

The by-products of ethanol production from corn are similar to those produced when wheat is used as a substrate. The major by-product is distillers' dried grains, a high protein cattle feed (Scheller, 1981). Some of the larger ethanol production facilities are attached to corn wet milling plants which break down the corn into various products namely corn oil, gluten meal, gluten feed and starch. The starch which is obtained in slurry form may be processed into corn flower, or it may be saccharified by acids or microbial enzymes and used to produce high fructose corn syrup for use in soft drink production (Murtagh, 1986).

7.3.5 Energy ratios

Scheller (1981) states that the use of gasohol will result in a net reduction of fossil fuel consumption, however, the data give a poor energy ratio of 1: 1.11. Pimental (1991) states that bioethanol production has an energy ratio of less than one taking by-products into consideration.

7.3.6 Present and future policy

Like the Brazilian bioethanol programme, the USA gasohol scheme has many opponents. Evaluations of the programme by the USA Department of Agriculture (USDA) have concluded that it is not viable. In 1990, a USDA review concluded that even with a 25% increase in world oil prices and exceptionally low cereal prices, a subsidy equivalent to 60% of the price of petrol would be needed, and higher subsidies than this were paid during the 1980s (Anon, 1991).

The initial aims of the gasohol programme were to reduce oil imports. However, recently there has been renewed interest in ethanol blends because of their increased

oxygen content and potential to reduce carbon monoxide emissions. This interest resulted in a redefinition of gasohol and changes to the incentive structure at the beginning of 1993 (McElhaney, pers com. 1993). It is important to note that gasohol does not now just refer to petrol blended with bioethanol, but includes petrol blended with synthetic ethanol and methanol. It has been stated that the ability of ethanol blends to reduce CO levels is greater than any alternative oxygenated fuel because their oxygen content is almost twice that of other oxygenated fuels and recent analysis indicates that ethanol blended fuels can reduce the formation of urban ozone (Shepard, 1990).

The USA clean air amendments of 1990, which were due to phase in during November 1992 require decreased aromatic content and higher oxygenation of the fuels sold in the winter months in the cities that do not meet US Environmental Protection Agency (EPA) carbon monoxide standards. Less polluted cities and regions will be encouraged to run on fuel that contains high oxygen additives (Englewood, 1991). It has been suggested that the requirements of the clean air act amendment could result in an increase in demand for ethanol (Englewood, 1991).

Investing in oxygenate capacity was predicted to be highly profitable because of the clean air act but demand has failed to live up to expectations, despite the fact that USA oxygenate capacity was very limited at the time the clean air act amendments were passed. The demand for ethanol will depend on how it compares in cost, performance, availability and convenience to the other octane boosters. Although ethanol has the highest oxygen content of the possible additives, it also has some disadvantages. It is water soluble and requires special tanks and pipes to isolate it from any source of water.

7.4 Conclusions.

Both the Brazilian and USA bioethanol programmes were set up to reduce oil imports. The reduction in oil price has put the future of the Brazilian programme for ethanol as a petrol substitute in doubt, but it seems likely that ethanol will continue to be used in petrol blends. It is important to note that although a very high proportion of cars run on ethanol in Brazil, car ownership per head of population is much lower than in the UK. In the USA there do not appear to be any plans to stop government support for gasohol, but the aims of the programme may be changing to one of pollution reduction at the federal level, and this may result in bioethanol having to compete with other, cheaper sources of oxygenates such as ethanol produced from natural gas and MTBE.

CHAPTER 8 CONCLUSIONS

8.1 Production

Although the majority, if not all of the industrial ethanol produced in the UK is synthetic, the technology for bioethanol production from wheat is well developed. Wheat is already used as a substrate for industrial ethanol production in some countries and the process for industrial ethanol production from wheat is very similar to grain alcohol production for the UK alcoholic drinks industry. It is interesting to note that the existence of the sugar and alcoholic drinks industries is considered to have been an advantage in the initial stages of the Brazilian fuel programme. The fact that potable ethanol is already produced from wheat in the UK would be an advantage for industrial ethanol production. For example, some work has already been carried out to determine the properties of wheat required for ethanol production.

8.2 Economics

The cost of producing bioethanol was calculated to be 38.1 p/litre assuming a cost of £115 per tonne for wheat. When a distribution/profit margin plus the fuel tax is added, it can be seen that (at this cost) bioethanol cannot compete with fossil fuels or synthetic ethanol. However, growing wheat on set aside could be financially attractive to farmers at a surprisingly low price per tonne. Contracts for industrial cereals have been offered and taken up by some farmers at only £45/tonne. A drop in the price of wheat to this level would result in a net cost of 21p per litre of bioethanol. It is not exactly clear how this relates to the production cost of synthetic ethanol, but it is considerably less than the market price of ethanol (39p/litre) which is itself currently low. It has been suggested that the current low market price may be related to the increased volumes of bioethanol on the market from French and Dutch producers.

This could be an important factor in the viability of a UK bioethanol industry. If the recent increased production has resulted in lower prices, this suggests that there is already a surplus of ethanol on the market and production in the UK might maintain depressed prices. The cost of the feedstock could be reduced by producing ethanol as a co-product with starch, as only the lowest value starch is used for ethanol production. This approach may improve the energy balance of bioethanol produced from wheat.

8.3 Markets for bioethanol

Ethanol is not a new product nor is fermentation a new method of manufacturing. Therefore ethanol has an established range of applications and ethanol consumers already have the choice of synthetic ethanol or bioethanol. Industrial bioethanol produced in the UK would have to be priced so that it could compete with synthetic ethanol in existing markets, or niche markets would have to be established in which the method of manufacture was seen to be important and synthetic ethanol could therefore not compete.

Fuel. A potential market in which synthetic ethanol could not compete is as a renewable fuel or renewable fuel additive. If bioethanol was to be used as a fuel substitute, like rape methyl ester (RME: a rape oil based diesel substitute), the best approach would probably be to target the fuel at inner cities, for vehicles such as buses or taxis. Although a very high percentage of cars in Brazil run on ethanol it is important to remember that the car ownership per head of population in Brazil is a fraction of that in the UK. Therefore, the volume produced in the UK is unlikely to be sufficient to allow nationwide availability at service stations. Targeting the fuel at inner cities would make better use of the fuel's environmental benefits and would also

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have the advantage of reducing distribution and marketing costs. If ethanol was used in this way, it would effectively be competing in the diesel market. Bulk buyers of diesel pay as little as 37 p/litre. Like RME, ethanol could not compete if the full customs and excise fuel tax were levied. Some allowance for the fuel's environmental benefit would need to be acknowledged by government. At present the Scrivener directive which proposes a 90% tax relief for biofuels is being considered at European level. If the UK government agreed to this then fuel bioethanol, produced at a cost of 21p per litre could be competitive. However, the UK government has not been keen to support any reduction in duty for RME, a biofuel for which the environmental argument is stronger since it has a more positive energy balance than bioethanol. The energy balance study presented in Chapter 5 shows that under typical conditions where straw is not utilised, the amount of energy used to produce bioethanol is almost equal to that gained from its use. If a renewable fuel is defined as an energy source which is produced without depleting a finite resource, then under these conditions, bioethanol cannot be classed as a renewable fuel, and has no obvious advantage over synthetic ethanol. These disadvantages combined with the requirement for specialised vehicles for use of ethanol (although buses running on methanol, an alcohol fuel with more handling problems than ethanol are on trial in Germany) would seem to make the use of bioethanol as a fuel in the UK unlikely. This will continue to be the case until the price of oil increases considerably and the energy balance is improved. An important finding of this study is that the energy used in growing the wheat crop is a very small proportion of the energy input for bioethanol production. Efforts to improve the energy balance must therefore be concentrated on the industrial processing side. Modifying agricultural inputs will have no notable effect on the energy ratio while the industrial processing inputs are at their current level.

Oxygenate. The use of bioethanol as a fuel oxygenate may be seen as a more viable area of development than use as a fuel substitute, for the following reasons:

1. No engine modification is required for its use

2. Bioethanol's poor energy balance is less important when it is used as a fuel additive rather than a fuel, because the ethanol is not simply added to extend the fuel but to act as an oxygenate which reduces emissions and increases the octane number. However, if the energy balance argument is followed through, it could be concluded that bioethanol would have no obvious advantage over use of synthetic ethanol as an oxygenate, unless it could be marketed at a lower price. In addition, bioethanol would also have to compete with other established oxygenates such as MTBE, which have a lower production cost. It is interesting to note that while the USA fuel alcohol programme originally used only bioethanol, it has been expanded to include synthetic ethanol and methanol, with all petrol alcohol blends being taxed at a lower rate than petrol.

Another factor to be considered is that although the use of ethanol as a fuel additive does not have the problems of special engine requirements associated with use as a fuel substitute, its use as an additive on a large scale would require oil company backing. Oil companies might prefer to use bioethanol as a feedstock for ETBE because ETBE petrol blends are easier to handle than ethanol petrol blends.

Cosmetics and toiletries. Although some sources state that cosmetics manufacturers prefer synthetic ethanol to bioethanol because it has less odour, it has also been reported that there is strong competition between fermentation and synthetic ethanol in the cosmetic and toiletries sectors. One major cosmetics and toiletries manufacturer has stated that they would prefer to use bioethanol to synthetic ethanol if it were

available at a competitive price because they favour "natural" products. It is possible that other manufacturers who market products with a natural image may take this view, but the potential size of this market is not clear.

Solvent. In September 1993 it was reported that although there was a current reduction in synthetic ethanol production throughout Europe, there were expectations for a 1 - 3% average annual rise in demand to the year 2000, caused by the use of ethanol as a solvent to replace more toxic volatile organic compounds. However both synthetic and bioethanol are suitable for this market, and bioethanol would not seem to have a clear advantage, although it could be argued that a bioethanol industry would benefit from any general increase in demand for ethanol.

Markets: conclusion

It is concluded that use of bioethanol as an oxygenate could become a feasible option before use as a fuel. Bioethanol faces competition from other oxygenates but as there is increasing interest not only in renewable energy sources but in renewable sources of a range of industrial feedstocks, an improvement in the energy balance might give bioethanol an advantage over other oxygenates. If the price of oil increases in the future then the price of competing oxygenates may also increase.

The cosmetics and toiletries markets may be the best option for development in the short term but the potential size of this market is unclear. The industrial ethanol market has been estimated to be approximately 400 000 tonne/year in western Europe, and the cosmetics and toiletries sector is the biggest user of ethanol. A UK bioethanol industry would have to secure 10% of this market in order to match the current area of high erucic acid rapeseed (16 000 ha) grown for industrial use. Therefore, if wheat

is to be developed as a major industrial crop, this must be linked to the establishment of new markets for ethanol such as a fuel additive or substitute. Alternatively the co-production of ethanol with starch may offer scope for greater utilisation of wheat.

Bioethanol from wheat does not have an overall cost advantage over other sources of ethanol and/or other fuels, though cheaper raw material from set aside may help keep it competitive. With this background bioethanol depends on securing markets or price premiums as a result of its environmental benefits for its viability. The most successful areas of development are therefore likely to be those which allow the natural image of bioethanol to be used as a marketing tool.

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