Feasibility of Producing Diesel Fuels From Biomass in New Zealand

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June 2003

Summary

The Energy Efficiency and Conservation Authority (EECA) has identified biofuels as one option for meeting the Government policy direction of a progressive transition to renewable sources of energy. The emphasis in this report is on the production of biofuels from renewable organic resources available, or potentially available, in New Zealand and which can substitute for conventional transport diesel fuel in vehicles.

The fuels considered are

- Biodiesel produced from tallow or vegetable oils
- Fischer – Tropsch liquids from lignocellulosic materials
- Pyrolysis liquids from lignocellulosic materials
- Ethanol from lignocellulosic material.

In this report lignocellulosic material generally refers to wood although agricultural wastes such as corn residues and high yielding crops such as miscanthus, switchgrass, and hemp are also included.

Each fuel is discussed in terms of production technology, raw materials, and economic factors. Life cycle emissions and energy balances for the various options are presented and the report concludes with a comparison of the four options.

Biodiesel, produced from tallow, is considered to offer the best option for the early introduction of diesel biofuels in New Zealand. It can be produced at a cost close to petroleum diesel and it can be used in unmodified diesel engines. Plant capacities as low as 35 000 t/a have been noted which, coupled with the interchangibility of diesel and biodiesel, indicates regional facilities could be considered. Sufficient tallow is available to substitute for 6 – 7% of current diesel use. Biodiesel can also be made from vegetable oils, probably in the same plant, but current prices for the bulk oils do not allow for economic production. Niche operations giving cheaper vegetable oil may be possible.

Fischer – Tropsch plants are large scale, high capital operations. Feed stock requirements of the order of 2 000 oven dry tonnes/day of wood have been considered. Such plants are not economic with the liquid fuel product being at least twice the cost of conventional diesel.

Pyrolysis processes do not produce a diesel product suitable for vehicle use but a liquid oil referred to as Bio-oil. Pyrolysis oils are not yet economic but there are a number of potential advantages attached to the process. Pyrolysis units are relatively small, 200t/d oven dry feed, and have flexibility in feedstocks accepted. Wood waste, forest trimmings, organic domestic waste, or purpose grown high yielding crops can be processed. The bio-oil produced can be used in place of diesel in stationary applications such as boilers or turbines thereby releasing the diesel replaced for transport use. No assessment as to how much diesel can be replaced by bio-oil in such applications has been found. Such information is crucial to determining whether pyrolysis has any part in meeting New Zealand's fuel requirements.

Ethanol produced from biomass is not economic but technical advances are being made that may change this in the near future. Wood and agricultural wastes such as corn stover will be important feed materials in the next generation plants rather than sugar and starches that are currently used. Plant sizes of 2 000 t/d dry feed are considered optimum in the USA being a compromise between economies of scale and increasing costs for raw material collection and transport. Ethanol is not a diesel fuel per se although up to 15% azeotropic ethanol can be emulsified with diesel to produce a fuel that is claimed to be usable in unmodified diesel engines. Pure ethanol can be blended with diesel but a package of additives to boost the cetane number of the blend and to address problems of low vapour pressure in the blend is required.

All four fuels show substantially lower life cycle emissions than diesel for greenhouse gases with biodiesel giving the greatest benefit in this regard.

The original Terms of Reference from EECA are attached as an Appendix to the report.

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1. Introduction

The Energy Efficiency and Conservation Authority (EECA) has identified biofuels, which refers to liquid fuels produced from a biomass resource, as one option for meeting the Government policy direction of a progressive transition to renewable sources of energy. In particular biofuels are seen as potential replacements for diesel in the transport sector.

Technologies available for biofuel production include

- Pyrolysis, a process that involves heating biomass in restricted contact with air. Vapours emitted from the reactor are collected and cooled to yield a liquid, referred to as bio-oil. A char product is also obtained.
- Fischer - Tropsch synthesis, a process that involves the gasification of the biomass and subsequent reaction of the gas components to yield a liquid fuel also referred to as bio-oil in the context of this report.
- Esterification of vegetable oils and animal fats (tallow) with an alcohol (usually methanol) to form alkyl esters (usually methyl esters) of long chain fatty acids. In the context of this report the long chain alkyl esters are referred to as biodiesel.
- Fermentation of sugars, obtained from sugarcane and similar crops or derived by acid or enzymatic hydrolysis of lignocellulose, to produce ethanol.

None of these technologies is new. Indeed a crude form of pyrolysis was used centuries ago for the production of wood char and in more recent times coal gas was produced by, essentially, a pyrolysis process. Beverages containing ethanol have long been made by fermentation of sugars. Fisher-Tropsch synthesis for oil production, developed circa 1920, was used in Germany during the Second World War and has been used in South Africa from about the late 1950's when trade sanctions restricted crude oil availability. In both cases coal was the feedstock.

In the 1970's and early 1980's the Liquid Fuels Trust Board (LFTB) evaluated the above technologies for liquid fuels production from biomass sources. An overview of these programmes was published by the Liquid Fuels Management Group, successors to the Liquid Fuels Trust Board (1 – 4).

All four approaches to biofuel production have continued to attract worldwide research attention and substantial improvements to the technologies have been made. Biodiesel is now available commercially, especially in Europe, where it is made almost exclusively from rapeseed oil, and to a lesser extent in the USA where it is made from soybean oil (5). A recent report provides a review of biodiesel and discusses the potential for its manufacture and use, in New Zealand, from tallow (6). Ethanol produced from biomass has been used in Brazil as a vehicle fuel since the mid

1970's. The technology for ethanol production from biomass has improved substantially since then such that ethanol production from lignocellulosic materials such as corn stover, the remnants left in the field after harvesting the corn, is close to being economic. Ethanol/diesel blends are apparently near commercialisation in the USA. Pyrolysis and Fischer - Tropsch technologies have also been developed substantially in recent years.

In parallel to developments in the basic technologies new feedstocks have been identified and proposed. Mustard seed oil, for example, has been proposed for biodiesel (7). Hemp can give seed oil for biodiesel production and a lignocellulosic residue for pyrolysis (8).

An overview of the current status for each of the above technologies for production of biofuels in New Zealand is presented. Raw material requirements are evaluated and for each option the current or potential availability of raw materials is considered. Lifetime analyses for carbon dioxide and other emissions are presented for each technology together with energy balances. The report concludes with a comparison of the four options.

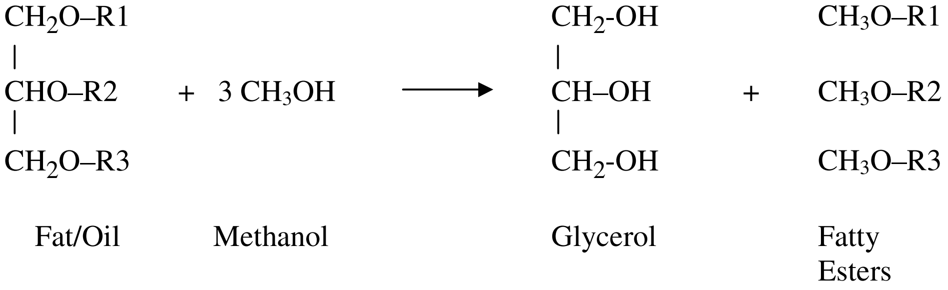
2. Biofuels Technologies

2.1 Biodiesel

Biodiesel refers to alkyl esters of long chain fatty acids. It is produced in substantial quantity from rapeseed oil in Europe and, to a lesser extent, from soybean oil in the USA. Although biodiesel has a slightly lower energy content than diesel it can be used either blended with diesel, generally up to 20% w/w although higher contents are possible, or neat as a direct replacement for diesel. Engine modifications are usually not required. Table 1 gives an indication of production and use in Europe.

2.1.1 Production

Biodiesel is produced by reaction of fats and oils with an alcohol, usually methanol when the methyl esters are produced. Glycerol is produced as a by-product. The process is depicted by the following reaction.



$$\begin{array}{lllllll}
CH_2O\text{–}R1 & & & & CH_2\text{-}OH & & CH_3O\text{–}R1 \\
| & & & & | & & \\
CHO\text{–}R2 & + & 3\ CH_3OH & \longrightarrow & CH\text{–}OH & + & CH_3O\text{–}R2 \\
| & & & & | & & \\
CH_2O\text{–}R3 & & & & CH_2\text{-}OH & & CH_3O\text{–}R3 \\
\text{Fat/Oil} & & \text{Methanol} & & \text{Glycerol} & & \text{Fatty Esters}
\end{array}$$

Figure 1 shows a schematic of the tallow methyl esters production process. The basic process shown can be used with soybean, canola, or other vegetable oil feed.

The feed oil or fat may be treated to remove free fatty acids and/or gums before reaction with an excess of methanol to produce methyl esters (biodiesel) and glycerine. Excess methanol is recovered from the methyl esters for recycle. High quality glycerol is recovered for sale in a distillation stage.

Process engineering companies have developed improved reactor designs and glycerol recovery systems in recent years and now offer proprietary technology for biodiesel plants. Lurgi Gmbh, for example, has recently constructed a green fields plant to produce 100 000t/a of biodiesel, using proprietary technology, at Marl, Germany (9).

Approximately 0.9 tonnes of biodiesel is obtained from a tonne of vegetable oil or tallow (Figure 1).

2.1.2 Raw Materials

2.1.2.1 Oils from Crops

Biodiesel is currently produced from a limited range of feed oils. Rapeseed and soybean oils are used predominantly for commercial production of biodiesel in Europe and USA respectively. Some sunflower and safflower oil is used for biodiesel production but in relatively small quantities. Many other oils have been suggested as suitable for biodiesel including, inter alia, palm oil and mustard seed oil (7). In the latter instance an additional benefit is that the meal remaining after oil extraction has potential as a pesticide/fungicide.

Table 2 lists a range of plants from which oil can be extracted. Indicative oil yields are included but actual yields may vary widely depending on the plant variety and climate. Not all of these oils may be suited to biodiesel production particularly those high in polyunsaturated acids such as, for example, linseed and hemp oils that contain significant amounts of linolenic acid which has three double bonds in the fatty acid chain. High levels of unsaturation, which are indicated by high Iodine Values, are associated with oxidative instability and a tendency to form gums and resins. In general terms and given that soybean oil is used as feed for biodiesel a maximum Iodine Value of 130, coupled with low polyunsaturated levels, may be considered satisfactory.

A variety of plant oils have been reviewed for biodiesel production in New Zealand (10). Reported yields for New Zealand production are included in Table 2. Generally these are in approximate agreement with other yields given in Table 2 with the exception of linseed oil for which significantly higher yields have been given for New Zealand. Of the common oils rapeseed oil would appear to be favoured in terms of oil yield at 1000kg/ha. Sims used a feasible yield of 2.3 t/ha of rapeseed and an oil recovery of 364 l/t of seed in New Zealand giving oil yield at circa 760 kg/ha (10).

2.1.2.2. Tallow

Tallow, animal fat that is a product from the meat industry in New Zealand, has been investigated previously as a potential feed for methyl ester production (4). Tallow has a higher content of saturated fats than most crop oils and the methyl esters are more saturated than, for example, rape and soybean esters. The saturated nature of the esters limits the amount that can be blended with diesel to about 7%w/w before cold flow properties of the blend become unacceptable.

In a recent New Zealand study of tallow methyl esters, production costs for tallow methyl esters were calculated as being similar to the diesel fuel price (6). Using the available tallow, currently exported from New Zealand, for tallow methyl ester production would provide for a 6% national diesel/ester blend.

2.1.2.3 Algal Oils

A further possible source of oil for biodiesel production may be found in oil producing algae cultured in ponds. Potential oil production at 60 000 – 160 000 l/ha/y, some thirty times the yield obtainable from land based crops, was considered feasible (11). Substantial work by the National Renewable Energy Laboratory, USA, in the 1980-1990's led to development of micro algae strains having 60% oil content. In an extended trial using 15 cm deep ponds, with a total surface area of 1000m^2, and with carbon dioxide injection to sustain algal growth, a maximum algae yield at 50 g/m^2/day was obtained. A lower average yield of about 10 g/m^2/day, approximately equivalent to 15 000 l/ha/y of oil, was obtained due to temperature fluctuations and other uncontrollable factors. Carbon dioxide uptake was quoted at 90% (12).

Experiments on producing microalgal oil have been done recently at the Christchurch wastewater treatment ponds (13). These experiments demonstrated that algae could be harvested from the ponds and processed to give an oil that could be converted to biodiesel. Algae were collected at the rate of 1 g/m^3 of water. Carbon dioxide injection into the water was not used. There is insufficient information to calculate this yield in terms of g/m^2/y for comparison with data from the research quoted above.

If similar yields of algae could be achieved at Christchurch to those obtained in the NREL tests (10 g/m^2/day) then, depending on the efficiency of oil recovery from the algae, up to 8 000 t/y of oil could be obtained from a pond area of 440 ha, the area of the waste water treatment ponds. While not sufficient to support a stand-alone biodiesel plant the potential amount of oil obtained could be a significant addition to the tallow resource.

Table 3 gives some indicative analyses for oils from different algae but these can vary substantially depending on growth conditions (12). Higher oil production with a different composition is obtained when the algae are stressed for nutrients than when adequate nutrient levels for maximum growth are maintained. In a number of cases substantial concentrations of polyunsaturated fatty acids (up to six double bonds) were found making the oil unsuitable for biodiesel production. A research programme is needed to further develop algal oil but it would not be a short-term project.

2.1.3 Economic Considerations

Substantial quantities of biodiesel are now used as transport fuels, particularly in Europe and to a lesser extent in America. In all cases the biodiesel fuel costs up to twice that of diesel. Subsidies either through direct tax reductions applied to the fuel or indirectly through farming subsidies are required to enable it to be competitive with the pump price of diesel.

Production costs for methyl esters from tallow in New Zealand have been estimated for the base year of 2002 (6). These were

- $499 /tonne biodiesel for a 70 000 t/a plant, 8000 hours/y plant size
- $482 /tonne biodiesel for a 116 000 t/a plant, 8000 hours/y plant size

The prevailing costs for tallow (spot price), methanol (Asia Pacific region price), and glycerol at, respectively, $550 /tonne, $310 /tonne, and $3330 /tonne were used. The exchange rate at that time of $NZ = $US0.45 was used to convert from $US values for methanol and glycerol.

With rapeseed oil at $US 434 /t (Rotterdam spot price, 2002) methyl ester costs at $931 /tonne for a 70 000 t/a plant in New Zealand were calculated.

The prevailing diesel cost at that time (2002) was about $435 /t (crude oil at $US 24.32 /bbl)

The current exchange rate is about $NZ = $US0.55. The current (May 2003) prices for methanol is about $US 255 (14). Current prices for tallow and glycerol are not available. Using the current methanol price and the previously used prices for tallow and glycerol, converted to $NZ with the current exchange rate, a current production cost for tallow methyl esters of $570 /tonne is obtained. The current, April 2003, Rotterdam prices for soybean oil is $US510 /t (15) which still gives a calculated biodiesel production cost approximately twice the cost of tallow esters.

Sims (10) provided indicative land areas, both suitable and available, for crop production in the Manawatu, Canterbury, and Southland/Otago. Suitable areas were given as 270 000, 523 000, and 730 000 hectares respectively with available areas of 14 000, 30 300, and 30 600 hectares. Diesel use in New Zealand is about 2.4 million tonnes/year and a 10% substitution requires about 250 000 t/y of biodiesel. Assuming the oil yield for rapeseed at 800 kg/ha (Table 2) and 0.9 tonnes of biodiesel from a tonne of vegetable oil estimated land area for rapeseed to provide sufficient biodiesel for 10% substitution is 350 000 hectares, well in excess of the available land area. The required land for rapeseed oil production for 10% diesel substitution can also be compared with data from the Ministry of Agriculture and Fisheries showing arable and crop land in use in New Zealand at 211 933 hectares of which 128 423 hectares was in Canterbury (16).

Given that the breakeven price for biodiesel requires a vegetable oil price of about $450 /tonne, about half the world spot price, the prospect for diverting currently used land to rapeseed production, for biodiesel, appears remote.

Production costs of algal oil from the aborted NREL programme were estimated at $US1.40 - $US4.40 / litre (12). These costs are not economically viable although it is conceivable that lower costs could be achieved with substantial research into algae species and production methods.

2.2 Biomass Gasification and Liquefaction

The Fischer - Tropsch process for liquid fuels production was developed in the 1920's by the German chemists F. Fischer and H. Tropsch (17). The process was used in Germany before and during World War II to produce fuels from coal. It has been used at the Sasol plants in South Africa since the 1950's to produce transportation fuels and chemicals from coal, initially because of trade sanctions imposed at that time. In the 1970's the NZERDC and LFTB commissioned several studies to evaluate the technology for a New Zealand plant producing (mainly) diesel from lignite and wood. In more recent times liquid hydrocarbons production from natural gas, using Fischer - Tropsch synthesis, has enabled development of remote gas fields. Some 13 000 bbl/day are produced at a remote Malaysian gas field. Oukaci (17) describes these developments and gives further detail of the historical development of the Fischer - Tropsch synthesis. The Fischer-Tropsch Archive offers a substantial database of reports related to the process (18). Liquid fuels production from biomass now provides the focus for further developments.

2.2.1 Fischer –Tropsch Synthesis

The basis of the process is gasification, with restricted oxygen availability, of the feed material to form synthesis gas (a mixture of carbon monoxide and hydrogen) followed by catalytic conversion of the gas to liquid hydrocarbons. The basic chemical reactions are depicted by the following equations

Gasification with steam and/or oxygen: $C + H_2O \longrightarrow CO + H_2$

Fischer - Tropsch reaction: $(n/2 + m)\ H_2 + m\ CO \longrightarrow C_mH_n + m\ H_2O$

These equations are indicative only with considerable variation in the product being obtained dependent on the specific process conditions and catalysts employed. Natural gas, coal, and biomass can all be used as feed material for synthesis gas manufacture and thus hydrocarbon production. Some post-treatment, usually hydrotreatment, of the Fischer - Tropsch product may be required to produce acceptable diesel fuels.

Figure 2 shows a schematic of the process.

Small gasifiers are commonly fixed bed units fed with relatively large pieces of feed material. For large scale operations fluid bed gasifiers prevail with feed material shredded or ground. Atmospheric or pressurised operation with steam, air, or oxygen (or a combination of these) injection can be used. The synthesis gas produced may be processed through a catalytic 'shift reactor' to adjust the carbon monoxide/ hydrogen ratio to that required for Fischer - Tropsch synthesis. Dinkelbach (19) provides further details on the types and attributes of fixed and fluid beds for gasification.

Hydrocarbon synthesis, from synthesis gas, is a catalytic process commonly with an iron-based catalyst although cobalt and other metal catalysts have been used. Synthesis can be achieved in a fluid bed reactor but modern plants use a slurry reactor in which the catalyst is dispersed in, commonly, a heavy hydrocarbon fraction. Synthesis gas is bubbled through the reactor to form hydrocarbons that pass from the reactor to a condenser from which the product is recovered.

A variety of process configurations are possible ranging from recycle of synthesis gas through the synthesis reactor, to obtain maximum output of liquid fuels, or a once through operation when the off-gas from the synthesis reactor is combusted for electric power generation. Substantial electric power can be produced for sale with this option.

Operating commercial plants are based on coal or natural gas. Rentech (20) and Syntrolem (21) are two companies, inter alia, specializing in gasification/Fischer–Tropsch technology

No commercial biomass gasification/liquefaction plants have been built although detailed conceptual studies have been reported (22-24). Outputs from such a plant for electricity, naphtha, and diesel (including kerosene) / GJ of feed have been given as 0.197, 0.067, and 0.199 GJ respectively for once through operation and 0.037, 0.125, and 0.369 GJ with full recycle of synthesis gas for maximum liquids production (25). The corresponding efficiencies, the ratio of output to input energy based on higher heating value of the feed, are given as 43.7% for once through and 49.4% for full recycle.

2.2.2 Raw Materials

As noted the only commercial Fischer-Tropsch plants use natural gas or coal. Synthesis gas production from natural gas and coal is a well-established technology. It is produced on a large scale in New Zealand as the first stage in methanol production. Coal based synthesis gas, used in the Sasol plants, is also similarly well established technology.

A number of relatively large gasification plants operating on wood or biomass residues as feed have been built generally to provide a fuel gas for power or direct uses such as kiln firing. Considerable development work is continuing (26). Details of the IEA gasification studies have been given (27). A range of materials have been used and considered as feed for gasification plants. Overend (26) notes that the 60 MWth Lahti Kymijärvi project in Finland, using Foster Wheeler's atmospheric CFB (circulating fluid bed) gasifier, has now completed 3 years of reliable operation on residues of fuels, paper and textiles, wood, and peat providing a hot, but low-calorific-value, gas (around 2 MJ/Nm^3). Residues are used at moisture contents as high as 50%. He also notes the use of demolition wood in a Lurgi CFB gasifier. Bagasse, wood wastes, and domestic wastes have also been proposed as potential gasifier feeds (28). Pulverised wood, dried chicken litter, and dried sewage sludge provided a composite biomass fed material in the TNO study (23).

Wood, from coppice plantations, and wood wastes are the most commonly considered biomass feed for producing a gaseous fuel either for direct use or liquefaction to give transport fuels. Gasification of purpose grown coppice willow was an integral step in the UK ARBRE project for power generation from biomass (29). Dinkelbech (19) considered thermochemical conversion processes, including gasification for producing fuels and energy from willow. A Bechtel study (22) used maple chips as the feed to generate synthesis gas followed by liquefaction using Fischer - Tropsch synthesis. Poplar wood chips have been used as a gasifier feed.

Some 26 Mm^3 /y of wood are harvested in New Zealand at the present time and this is expected to increase to about 31 Mm^3 by 2013 (30). Processing the wood generates 6 Mm^3 (44.2 PJ) of wood wastes of which 2.4 Mm^3 are used by the industry and leaving 3.6 Mm^3 (26.5 PJ) available for other uses. Additionally 4 Mm^3 of forest residue are available of which 0.6 Mm^3 (4.4 PJ) is at the landings (relatively easily accessible) and the remainder, termed cutover, is scattered on the forest floor (not easily accessible). Short rotation wood yields about 15 oven-dry t/ha/y (300 GJ/ha/y) but there is no significant amount available in New Zealand at the present time (30).

Estimated costs, in New Zealand, for various wood resources are \$5.30 – 7.80 /GJ for plantation fuel wood, \$2.70 – 4.00 /GJ for forest residues, and \$0.25 / GJ for processing wastes (30). Transport to a processing plant is included in these costs.

Assuming annual diesel consumption in New Zealand at 2.4 Mt/y and that petroleum diesel is equivalent to Fischer - Tropsch diesel, 240 00 t/y of Fischer - Tropsch diesel is required to provide 10 % substitution of the diesel usage. From the process yields given previously, for maximum liquid production and assuming diesel at 40 GJ/t, approximately 26 PJ of wood will be required. 81 000 tonnes of gasoline and 0.92 PJ of power will be co-produced with the diesel.

Sufficient waste wood is available to meet this demand but it is spread throughout the country. No estimated cost for collection and transport of this wood waste to a central location has been found. To supply the required wood volume from short rotation forests will require 86 000 hectares planted. Other crops giving high yield of lignocelluloses can be used to supplement wood supply. Hemp, with yields up to 15 t/ha/y, is one possibility.

2.2.3 Economic Considerations.

Published cost information on Fischer - Tropsch liquids production from biomass is limited possibly because of difficulties in assigning a price to one product in a multiproduct process. This is further exacerbated when adjustment of process conditions can change the relative outputs of the various products. Ideally cost estimates for specific process configuration and a specific product mix are required.

Shen et al (31) gave costs (2002 base) for Fischer - Tropsch liquids production from remote natural gas as $US 19 /bbl compared to crude oil at $US 26 /bbl. The natural gas cost used was $US 0.5 /MMBtu (approx $US 0.5 /GJ). He noted also that high capital costs were one of the hurdles for commercial Fischer-Tropsch fuels.

Bechtel (22), in their Aspen Model of F-T liquids from biomass gave a capital cost of $US 142 million for a plant processing 3550 t/d (2 000 oven dry t/d) of maple chips. Output for this plant was 49 t/d gasoline, 105 t/d diesel, and 86MW of power.

Faaij et al. (32) indicated investment costs of between $US 280-450 million, depending on system configuration. They gave, for the short term, production costs of F - T liquids at $US 16/GJ ($US 98 /bbl) whereas in the longer term, with large-scale production, higher CO conversion and improved selectivity in the F - T process, the production costs of F - T liquids could drop to $US 9/GJ ($US 55 /bbl). Biomass was costed at $US2 /GJ. The prevailing price of diesel was $US 4 /GJ.

Marano and Ciferno (33) gave a required selling price for F - T liquids from biomass at approximately $US13 - 16 /GJ ($US80 - 97 /bbl) depending on the source of the biomass.

Diesel in New Zealand costs about $10 /GJ. Costs shown above for F- T liquids are at least twice this level and even the predicted price obtained with foreseeable technology improvements is approximately twice the cost of New Zealand diesel. Clearly the cost of F - T liquids is not competitive with petroleum diesel at the present time and will not be for the foreseeable future.

2.3 Pyrolysis

Pyrolysis involves heating carbonaceous materials in the absence of oxygen. It is an ancient technology used ages ago to produce charcoal, from wood, for heating and for smelting metals from various ores. Charcoal for barbecues and similar uses has been produced from wood on a small scale in New Zealand in recent times. Coal gas is produced by pyrolysis of coal with coke as a co-product.

Modern pyrolysis technology has been developed, and continues to be developed, principally for maximum liquid production at the expense of charcoal or coke. The pyrolysis product is known as Bio-oil.

2.3.1. Pyrolysis Technology

In contrast to ‘traditional’ pyrolysis operations, employing relatively large pieces of feed material and reaction times of several hours, modern fast pyrolysis uses a ground feed material with reaction times measured in seconds. A wide variety of feed materials can be used including coal, wood, biomass such as bagasse, municipal waste, scrap plastic, and tyres. Typically the feed is ground to less than 1 mm size using, for example, hammer mills. Steam explosion techniques have been proposed to break the feed into a powder.

The pyrolysis reactor is essentially a fluid bed reactor containing hot sand or similar inert material into which partially dried and ground biomass is fed. Organic material is thermally decomposed to yield complex organic vapours and solid char that pass from the reactor in the fluidizing gas stream. Char is separated in a cyclone and the organic vapours are then rapidly quenched to give liquid Bio-oil. The cooled gas is returned to the reactor to maintain the fluid bed The char is used for process heat mainly to maintain the temperature in the fluid bed at about 450 – 500^{o}C

A schematic of the process is shown in Figure 3.

Various fluid bed reactors have been proposed for fast pyrolysis including bubbling, vacuum, ablative, and rotating cone. Bridgwater (34) describes these variations in some detail in a publication from PyNe, the Pyrolysis Network, a global network of active researchers and developers of fast pyrolysis of biomass. Bridgwater (35) also has provided a status report on pyrolysis.

Commercial pyrolysis units are available from Ensyn Group Inc (36) and Dynamotive Energy Systems Corporation. (37). Ensyn have commercial plants rated at 40 t/d (oven dry) wood in Wisconsin, USA. Dynamotive have recently announced the intended construction of a 100 t/d pyrolysis unit, capable of producing up to 60,000 litres of Bio-oil per day, that will be part of an integrated 2.5MW pyrolysis energy project in Canada (38). A comparison of the two competing technologies is included in a report by the University of New Hampshire on bio-oil production from wood in that state (39).

Typically bio-oil yields of 70 – 80% w/w on the dry feed are obtained with the higher yields being associated with lower lignin content in the feed. The balance is split between char and fuel gases.

Bio-oil contains between 15 – 30% water, it is acidic with a pH at 2.5, and generally contains about 0.5% solid char. Elemental analysis gives approximately 56%, 6%, and 37% for carbon, hydrogen and oxygen respectively. The heating value is 16 – 19 MJ/kg, less than half that of petroleum diesel (34).

Bio-oil cannot be used in motive diesel engines without substantial upgrading. Hydrotreatment processes to give more conventional hydrocarbon products have been investigated and shown to yield a product similar to fuel oil that can substitute for fuel oil or diesel in many static applications including boilers, furnaces, engines, and turbines for electricity generation (40). The main thrust of pyrolysis developments appears to be aimed at small-scale onsite production of a liquid fuel that is easily transported from the production site to users.

2.3.2 Raw Material Considerations

Pyrolysis processes can accept a wide range of feed materials. Most commonly wood is the feed material but paper, agricultural wastes, and high yielding crops such as hemp, have been considered. Much of the discussion in Sect 2.2.2, Raw Materials (for Fischer - Tropsch processes), is relevant to pryrolysis processes. Dynamotive Corp. has reported on bagasse as a feed material for pyrolysis (41). High yielding, up to 15 t/ha (dry), perennial grasses such as miscanthus (42) and switchgrass (43) have been considered as pyrolysis feeds. Pyrolysis of polymers has also been studied in some detail when monomers of the plastic have been produced with the bio-oil (44).

2.3.3 Economic Considerations

Bridgwater (34) has developed an equation relating pyrolysis plant size, biomass cost, and bio-oil cost. For a 5 t/h feed (oven dry wood) unit product costs are $US13.50/GJ, $US9.50 /GJ, and $US5.00 /GJ for feed costs at $US115 /t, $US57.5 /t, and $US0 /t respectively. Corresponding product costs for a 20 t/h feed unit are $US14.03, $US9.43, and $US4.37 /GJ. These costs apply to 1998 and an exchange rate of $US1.15 = 1 Euro.

A study in New Hampshire gave product costs at $US16.4 /GJ for 60 t/d oven dry wood and $US12 /GJ for 240 t/d dry wood (39). The feed cost in these studies was set at about $12 / oven-dry tonne.

Grinding the feed material to less than 2 mm mesh size is a significant process cost, approximately $US25/ tonne for short rotation poplar chips (45). Alternative methods could, such as steam explosion techniques, may offer potential savings.

The costs of producing bio-oil shown above are nor consistent. If the data from Bridgwater is used bio-oil costs approaching the New Zealand diesel cost, $10 /GJ, could be obtained with low cost feed.

2.4 Ethanol from Biomass

Ethanol production by fermentation processes has been used for centuries in the production of alcoholic beverages. The raw material was sugars or carbohydrates easily converted to sugars.

Alcohols have long been considered as transport fuels, mainly as a petrol replacement, with a major impetus in development around the oil crisis in the early 1970's. The NZERDC and the LFTB both funded comprehensive studies into ethanol production, including from wood resources (1,2). A small pilot plant for ethanol production from wood operated at the Forest Research Institute in Rotorua as part of the technology development.

In the same period Brazil adopted ethanol as a transport fuel to replace petrol on a large scale. Ethanol produced from starchy root crops and, mainly, sugar cane was used neat in vehicles with adapted engines and also as a 20% blend with petrol. Brazil used about 14 billion litres of ethanol for transport fuels in 2002 (46).

Significant studies into ethanol production and use continued after the 70's particularly in the USA where the National Renewable Energy Laboratory funded studies over a period from 1975 to the present day. In 2000 the Office of Fuels Development, Energy Efficiency, and Renewable Energy decided set the focus on ethanol production research, development and deployment as the most promising option for a future strategy (47).

2.4.1 Production

The process for ethanol production involves fermentation of sugar solutions to obtain a dilute solution of ethanol. Carbon dioxide is produced as a by-product.

Sugar solutions can be produced directly from sugar beets or cane by leaching processes. The majority of ethanol produced in America is derived from cornstarch. The kernels are milled to open up the grain then subjected to enzymatic hydrolysis to form fermentable sugars. Cellulosic biomass, including wood, corn stover, and hemp stalks, require more severe pretreatments, commonly using acid, to generate fermentable sugars. Enzymatic hydrolysis processes, with or without acid, are the most recent technical development for obtaining sugars from lignocelluloses.

Pure ethanol is recovered from the fermentation broth by distillation.

Figure 4 presents a schematic of the process.

Current (2002) ethanol production in the USA, mostly from cornstarch, is about 10.8 GL/y from 67 producing plants and is estimated to be 17 GL/y in 2005 (48). Blends of gasoline with 5% ethanol are available commercially in the USA.

Ethanol cannot be used as a diesel fuel without extensive modifications to the engine or to the ethanol. Anhydrous ethanol can be readily blended with diesel to form a composite fuel. Azeotropic ethanol (95% ethanol, 5% water) can be blended with diesel and an emulsifier to form a stable fuel. Cetane enhancers can be added to overcome the low cetane number of ethanol. Both of these blended fuels have been used in extensive tests but are not yet available commercially (49).

2.4.2 Raw Materials

The current feed material of choice for ethanol production in America is cornstarch. Cheese whey, beverage industry wastes, and potato waste are also used to a much lesser extent (48). Ethanol is produced from whey in New Zealand. Table 4 gives some data for ethanol yields, calculated from crop yield and fermentable content, for a variety of crops (50). The data in this table is generally derived from American studies and may not represent typical crop yields obtainable in New Zealand. Some crops shown may not be suited at all to New Zealand and are included for information only. Kurdos and Mulcock (51), in reports prepared for the LFTB in the 1970s, gave fodder beet as the preferred feed for ethanol production in New Zealand but noted that jerusalem artichoke, which has the highest ethanol yield in Table 3 at 11 000 l/ha, was worth further consideration.

Wood, which has been considered in past years, continues to attract attention as a potential feed for ethanol production. The National Renewable Energy Laboratory, Colorado, produced a design study, including economic analysis, for ethanol production from lignocellulose material, specifically hardwood chips (52). A second NERL report following the same format is more specific for corn stover feed (53). An Oregon study on ethanol production from cellulosic materials considers a variety of feedstocks including wood, agricultural wastes, and municipal solid waste (54). This report has a commentary on then current (2000) proposals for ethanol production from cellulosic materials in the USA. Nine specific projects were noted. Iogen, a Canadian company, have a demonstration plant for ethanol production utilizing advanced enzyme hydrolysis technology to produce fermentable sugars from lignocelluloses. An association with Shell Oil, through Shell Global Solutions, to further develop the Iogen technology was announced last year (55). Genencor International, based in Palo Alto, California, is working with the NREL to develop enzymes for lignocellulose hydrolysis.

Given the range of materials considered as a feed stock for ethanol production the discussion in Section 2.2.2, Raw materials for Fischer – Tropsch processes, has direct relevance for ethanol production.

To replace 10% of New Zealand diesel, some 240 000 t/y (9.6 PJ/y), with ethanol will require approximately 370 000 t/y of ethanol based on the relative energy contents. Corn stover yield was given at 5 t/ha with ethanol yield at 0.27 t/t of stover, equivalent to 1.35 tonnes of ethanol per hectare (53). The land area required for 370 000 tonnes of ethanol is thus 274 000 hectares. In 1999 approximately 20 000 hectares were used for maize/sweetcorn production in New Zealand of which 2 000 hectares were in the Canterbury region (16). Hemp, with a biomass yield of about 15 t/ha/y, would require approximately 95 000 hectares assuming a similar ethanol yield to that obtained from corn stover.

Similar calculations for wood feed indicate 34 PJ of wood are required to supply sufficient ethanol for 10% diesel replacement. This amount of wood is roughly equal to the New Zealand waste wood estimates (30). Alternatively short rotation wood, yielding about 300 GJ/ha/y, requires about 100 000 hectares planted to satisfy feed requirements for 10% diesel replacement by ethanol.

2.4.3. Economic Considerations

Cost estimates included in report from the NREL, Colorado (53), indicate a minimum ethanol cost of $US0.283 /l ($US1.07 / gallon) for a plant producing 207 000 t/y ethanol from 2000 t/d dry corn stover feed. Capital cost was $US 197.4 million for the base year 2000. Ethanol yield was 340 l/t of dry stover equivalent to 0.27 t/t of stover. The corn stover cost was set at $US33 /t.

In a companion report (52), for a plant producing 156 000 t/y ethanol from dry hardwood (poplar) chips a minimum alcohol cost of $US0.38 /l ($US1.44 /gallon) was estimated. Capital cost was $US 233 million for the base year 2000. Ethanol yield was 257 l/t of dry wood. The wood feed cost was set at $US27.55 /t.

Both the above plants were sized for 2 000t/d of dry feed. This size represents a compromise between economies of scale which can be obtained as the processing plant gets larger and diseconomies of scale associated with the collection and transport of feed material from larger land areas needed for supply.

Continuing improvements in technology were anticipated to give ethanol prices less than $US 0.264 /l ($US1/gallon) for ethanol by 2005. This is about twice the cost of New Zealand diesel on an energy basis.

3. Life Cycle Emissions and Energy balances

Life cycle emissions for a particular species refer to all emissions of that species occurring through all phases of production and use of a fuel. Emissions associated with all inputs in the cycle, for example emissions associated with electricity generation used in motors, is included. For crops, emissions associated with energy input into soil preparation, fertilizer production and harvesting are measured.

For biomass allowance is made for carbon dioxide sequestered from the atmosphere by photosynthesis. Since the sequestered carbon dioxide is released on combustion the net greenhouse effect, in terms of carbon dioxide, is zero. Combustion refers not only to fuel use in the vehicle but can also include combustion of biomass for generation of process energy to produce the fuel.

Materials considered as waste in terms of life cycle calculations have no greenhouse gas emissions assigned for their production and preparation. In this context tallow is considered a waste since the primary product, meat, bears the cost of all carbon dioxide inputs. A useful report giving an overview of biodiesel and petroleum diesel lifecycles is available (56).

3.1 Greenhouse gas emissions

Greenhouse gas emission is a measure of the total greenhouse gas emissions expressed in terms of carbon dioxide equivalent. In addition to carbon dioxide other greenhouse gas emissions, such as methane, are weighted according to their ‘greenhouse’ effect relative to carbon dioxide and included in the reported value. Carbon dioxide has a weighting of 1. In this report the units are g CO_2 equivalent /MJ.

Life cycle greenhouse gas emissions for a range of biomass-derived fuels are shown in Table 5. Petroleum diesel is included for reference. The values in Table 5 have been recalculated from the original data to a common base of 1 MJ of fuel into the engine. The original data were given in terms of emissions per unit distance but differed in the vehicles, and thus fuel economy, used in the various tests. The results are indicative only due to assumptions made in recalculations, particularly in converting from fuel economy to the base of 1 MJ.

Negative values for greenhouse gas are assigned to the sequestered carbon dioxide. The high negative values for F-T liquids and ethanol reflect the high raw material input per MJ of output. In these cases process energy requirements were met from the feed, a feature that is reflected in high emissions for conversion and distribution of the fuels produced.

For all fuels from biomass total greenhouse gas emissions are lower than for the base diesels. Biodiesel from tallow, considered a waste product of the meat industry, has the lowest emissions followed by Fischer - Tropsch liquids. Other fuels show higher values that generally reflect the amounts of fossil fuels, such as electric power or, for canola biodiesel the added alcohol, used in their production.

3.2 Other Gaseous Emissions.

Life cycle analyses can also be used to assess other emissions, both gaseous and particulates, for a fuel.

Table 6 presents results for a number of emissions for the fuels considered above for greenhouse gas emissions, excepting for F-T liquids that are derived from natural gas in these data compared to coppice wood previously. Biodiesel from rapeseed is included. The source data were given on a /MJ basis so no recalculations have been required. Separate values are given for pre-combustion, which includes inputs into the feed, conversion, and distribution, and for combustion in the engine.

Most striking are the high pre-combustion emissions for NMHC (non methanic hydrocarbons), carbon monoxide, and particulates for ethanol production where biomass provides the process energy. Biodiesel NOX emissions post combustion are higher than for diesel but conversely NHMC and carbon monoxide are lower than the base diesel.

3.3 Energy Balances

Energy balances for the production of a number of fuels from biomass are shown in Table 7. These are calculated to the common base of GJ output/GJ of input. Petroleum diesel is included for comparison.

Fossil energy inputs are given for each fuel. From this a fossil energy ratio, defined as the ratio of product energy to the fossil fuel energy input is calculated (56). For F-T liquids and ethanol from corn stover the process energy is derived from biomass and fossil energy inputs are small. The higher value for tallow biodiesel, 6.15, derives from the treatment of tallow as waste and thus having no energy input in its preparation. Biodiesel from soybean oil does not have this advantage thus the fossil energy is lower at 3.33. In both biodiesel fuels a major energy input is the methanol used in the conversion process. Using biomass-derived ethanol can reduce this. Ethanol from corn has a fossil fuel ratio of 1.33 indicating a modest excess of output energy compared to the input energy.

The life cycle energy efficiency (56), defined as the ratio of product energy to feed energy, is also shown in Table 7. Again the almost total use of biomass energy for process energy in ethanol (corn stover) and F-T liquids production, at the expense of conversion to product energy, results in low energy efficiencies. Conversely biodiesel have high energy efficiencies since process energy needs are not met from the feed. An energy efficiency for ethanol from corn is not given since the feed energy only includes the process energy and not the energy content of the corn itself. The purpose for including corn ethanol data is to show the positive fossil energy ratio.

4. Comparisons of Process Options

4.1 Resource Considerations

Of the four options considered only biodiesel, from tallow, has a significant resource base available in the near term. Approximately 115 000 t/a of tallow, currently exported from New Zealand, could be used to make sufficient biodiesel to replace about 6 – 7 % of current diesel usage. To increase production of biodiesel requires further supplies of tallow or more likely production of vegetable oils. Rape seed appears the most likely choice but with an oil yield of about 0.8 t/ha/y, equivalent to about 0.7 tonnes diesel/ha/y, the land required is 350 000 hectares to obtain 10% diesel substitution. This is the minimum since it includes no consideration of crop rotation. Algae have, potentially, much higher yields of oil, up to 15 t/ha/y. Considerable research still remains to be done on this option to confirm yields, acceptability of oil quality, and production costs. At best this must be considered a long-term option.

Waste wood is available in sufficient quantity to replace 10% of current diesel demand, either with F-T liquids or ethanol, or to give sufficient pyrolysis liquid to allow displacement of diesel (equal to 10% of national diesel usage) from static applications. It is not known whether there is sufficient flexibility in diesel usage to accept this last option. The wood waste is, to a large extent, dispersed through the country and, for forest cutovers particularly, not readily accessible. Some scheme for collection and transport is required before its use as a feed for fuel production can be considered.

Coppicing is not established in New Zealand but the high yield appears attractive for fuel production With a yield of about 15/t/ha/y approximately 100 000 hectares has to be established for coppicing to provide for the equivalent of 10% of current diesel supply.

Other high yielding crops, about 15 oven dry t/ha, are miscanthus and switch grass. These are being studied for fuel production in the UK and USA respectively. No information as to the yields obtainable in New Zealand from these two crops is available. Hemp, also with a yield at about 15 oven dry t/ha, has been suggested as a suitable feed for fuel production in New Zealand.

4.2 Product Considerations

Of the biomass fuels considered, F-T liquids derived from wood contain a diesel fraction that, with possibly some minor upgrading, is most similar to current petroleum diesel. It seems probable that F-T liquids would be accepted into the refinery as a crude oil and incorporated into main diesel stream with minimum disturbance. A substantial gasoline fraction is also co-produced.

Biodiesel can be used as a substitute fuel for diesel or used to make blends usually containing up to 20% biodiesel. The level used is dependent on the biodiesel properties. With tallow esters a maximum level of circa 7 % is likely before cold flow properties of the blend are becoming unacceptable. With rapeseed and soybean biodiesel higher levels of biodiesel can be blended. Biodiesel blends can be used in unmodified diesel engines and thus are essentially interchangeable with commercial diesel. As such regional production and distribution of the fuel is possible since vehicles will accept either fuel with very little effect on vehicle operation. Neat biodiesel can also be used in unmodified diesel engines although some minor adjustments may be necessary for best performance. The reduced emissions obtainable with biodiesel indicate the better use would be in heavily trafficked areas.

Pyrolysis liquids cannot be used as a diesel fuel per se without substantial upgrading. Although methods for upgrading pyrolysis liquids have been suggested none appear to have been used commercially. More commonly the fuel is considered for firing boilers or for use in other fixed installations. As such pyrolysis liquids offer the option of substituting for diesel in non-transport applications, effectively leading to reduced diesel consumption nationally. No data has been found that allows any estimate of the extent to which this may be possible in New Zealand.

As with pyrolysis liquids ethanol is not a diesel fuel per se although anhydrous ethanol may be used, with or without substantial additives included, in modified diesel engines. Azeotropic ethanol, containing 5% water, can be mixed with diesel and a suitable emulsifier to give diesahol that is claimed to be suitable for use in a diesel engine. There remain a number of technical difficulties with the blend, notably that it has a low vapour pressure, but research continues into establishing it as a viable diesel alternative (49, 59).

4.3 Process Considerations

The four different processes considered have varying attributes.

The process for biodiesel production is relatively straightforward. Plant sizes up to 100 000 t/y are now common but the impending construction of a plant sized at 35 000 t/y was noted not withstanding the economies of scale that are, presumably, achieved with large plants. Capital costs for a 100 000 t/d plant were estimated at around $45 million in 2002 (6).

A plant built at Timaru to produce methyl tallow esters was considered in an LFTB study in the mid 1980s (60). A production rate in excess of 40 000 t/a was considered. Tallow was to be drawn from the South Island which in 1982 had tallow production around 55 000 t/y. There is no reason why a local plant of this nature could not be built, based on tallow but able to accept vegetable oils if they were produced.

Designs for F-T plants used in this report have been based on wood inputs of 2 000 oven dry t/d with diesel and petrol outputs at 135 000 and 45 000 t/a respectively. Capital costs was estimated to be $US 280 – 450 million. These large plants must be built close to feed material locations to minimize feed material input costs. Ideally for a plant of this nature dedicated short-term rotation crops seem preferable to somewhat less certain forest wastes.

A similar situation applies with ethanol from crops or wood waste. The minimum plant size was estimated by NERL to be 2 000 t/d wood feed. This is in part a compromise between increasing costs of feed as the collection area gets larger and reduced processing costs as the plant size increases. Ethanol output from a wood based plant was 156 000 t/y with estimated capital costs at $US 233 million for the base year 2000.

Pyrolysis is more adapted to small-scale operation with plant sizes up to 100 - 200t/d wood feed and capable of producing up to 60,000 – 120 000 litres of Bio-oil per day. Capital costs for a 120 t/d oven dry wood feed have been quoted at $US8.8 million. These can be viewed as relatively cheap modular plants designed to be self-contained units for processing wood in remote locations, and generating a liquid fuel that can be readily transported. Furthermore the pyrolysis process is quite adaptable to a variety of feed materials from including wood, agricultural and domestic wastes, and polymers.

4.4 Final Considerations

Biodiesel produced from tallow is the only diesel substitute currently available at a price comparable to that of petroleum diesel. Plant sizes over a wide range are possible but smaller sizes may suffer from reduced economies of scale. While tallow is the cheapest, and only, indigenous feed stock at present vegetable oil can be used for biodiesel production. There may be an opportunity for ‘niche’ vegetable oil production if, for example, some return can be obtained and the crop is beneficial in a rotation scheme. In the longer term algal oil production, to supplement the available tallow, may be possible. The costs of vegetable oils are currently significantly higher than tallow. Biodiesel is used extensively in Europe and the USA without the need for vehicle modification. It can be used to advantage in vehicles operating on neat biodiesel in highly trafficked areas because of generally lower emissions obtained, excepting for NOX that may show either small increases or decreases depending on the situation. Urban fleet operators may be prime candidates to use biodiesel.

Pyrolysis has an attraction in that it is relatively small scale and can produce a liquid fuel from a range of feed materials including domestic wastes and polymers. The bio-oil produced would require extensive upgrading for acceptance as a transport diesel fuel. It can displace diesel in fixed applications and the extent to which this is possible needs to be clarified before any firm decisions can be reached as to the viability of installing pyrolysis units.

F-T liquids and ethanol are produced in substantial, high capital cost operations with minimum feed requirements about 2 000 oven dry t/d. Given the high feed requirement such plants appear more suited to areas that can meet this need, probably the forest areas of the Central North Island. The cost of producing ethanol is not yet economic but technological improvements and cost reductions continue to be made. F-T liquids production from biomass is not economic at the present time.

5. Conclusions

5.1. Biodiesel made from tallow offers the best opportunity as a diesel replacement in New Zealand at the present time.

5.2. The production cost of tallow biodiesel appears to have increased in the past year and is now above the prevailing diesel price. This calculation is influenced most by the present exchange rate for the NZ/US dollar. Specific prices for the material inputs are required to obtain an accurate production cost.

5.3. The interchangeability of biodiesel and petroleum diesel allows regional facilities for production and distribution of biodiesel to be considered.

5.4. Available tallow allows for approximately 7% of the national diesel to be replaced by biodiesel.

5.5. Lifecycle and tailpipe emissions, both gaseous and particulates, are generally less for biodiesel than petroleum diesel. The exception is for NOX emissions that may increase.

5.6. At production levels of 200 oven dry t/d biomass feed the cost of bio-oil from biomass pyrolysis approaches the cost of diesel providing low cost biomass feed is available.

5.7. Bio-oil from pyrolysis is not a diesel fuel. To contribute to the transport diesel supply opportunities for diesel substitution by bio-oil need to be identified. These may occur in fixed installations such as boilers, drying kilns, and similar installations.

5.8. Pyrolysis units have an advantage of that small scale units are available and can be used in remote locations. The product oil is easily transported.

5.9. Fischer-Tropsch processes for liquid production from biomass are uneconomic and appear likely to remain so for the foreseeable future.

5.10. Ethanol from biomass is not yet economic but technology improvements may change this in the near future.

5.11. Ethanol can be used as a diesel fuel but engine modifications and fuel additives are required to allow its use in diesel engines.

5.12. A diesel/azeotropic ethanol mixture, with a suitable emulsifier, gives a fuel that is claimed to be suitable for use in unmodified diesel engines. Technical problems, particularly related to vapour pressure, have to be resolved before this fuel can be widely used.

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7. Acknowledgements.

Support for this study from Eric Park, Sustainable Christchurch Leader, Christchurch City Council and the Energy Efficiency and Conservation Authority is acknowledged.

Jim Watts, Blair Anderson, Ian Bywater, Chris Bathurst, and Susan Krumdieck, all from Christchurch, Jeremy Yeoman from EECA, Wellington, and Professor Ralph Sims, Massey University, Palmerston North, provided preliminary discussion on the study and/or comments on the draft report. These contributions are gratefully acknowledged.

Table 1. Biodiesel Use in European Countries

Data is in kilotonnes

Country	1998	1999	2000	2001	2002	Comments
Austria[1]	16		30			Used as 100% biodiesel in adapted vehicles
France[1]	319	344	330			30% in captive fleets 5% in general diesel
Germany[2]	100	130	340	450	550	Used as 100% biodiesel in adapted vehicles
Italy[1]	96	96	75			5% in general diesel
Spain[1]			50			
Sweden[1]			50			Used as 100% biodiesel in adapted vehicles

Source: Reference (6)

Table 2. Vegetable Oil Yields

Biodiesel yield = oil yield x 0.8 approx.

.

Crop	IndicativeYield kg oil/ha[1]	New Zealand Yields, kg/ha[2]	M.Pt °C	Iodine Value	Methyl Ester Pour Point °C
Mutton Tallow			42	40	10
Corn (Maize)	145		-5	120	
Oats	183				
Lupine	195				
Kenaf	230				
Calendula	256				
Hemp	305			165[3]	
Soybean	375	500	-16	130	-1
Linseed (Flax)	402	1000	-24	178	
Euphorbia	440				
Pumpkin Seed	449				
Coriander	450				
Mustard Seed	481				
Camelina	490				
Sesame	585			110[3]	
Safflower	655	500		100[3]	-6
Tung Oil Tree	790		-2.5	168	
Sunflowers	800	1000	-17	125	-4
Peanuts	890		3	93	
Rapeseed	1000	800	-10	98	-9
Olives	1019		-6	81	
Castor Beans	1188		-18	85	
Jojoba	1528			85[3]	
Jatropha	1590				
Avocado	2217			85[3]	
Coconut	2260		25	10	
Oil Palm	5000		35	50[3]	

Note: These are generally conservative estimates but crop yields can vary widely
Source 1: www.journeytoforever.org/biodiesel_yield.htm
Source 2: Reference (10)
Source 3: www.betterbubbles.net/oilprops.htm

Table3. Major fatty acids of various micro algae.

Fatty acids in bold are present at levels of 15% or higher

Algae Strain	Nitrogen-sufficient cells	Nitrogen-deficient cells
Ankistrodesmus	16:0, 16:4, **18:**1, **18:3**	16:0, **18:**1, 18:3
Botryococcus braunii	**16:**0, **18:**1, 18:2, **18:3**	16:0, **18:**1, **18:**3, 20:5
Dunaliella bardawil	not determined	12:0, 14:0/14:1, **16:**0, **18:**1, 18:2, 18:3
Dunaliella salina	14:0/14:1, **16:**0, 16:3, 16:4, 18:2, **18:3**	**16:**0, 16:3, 18:1, 18:2, **18:3**
Isochrysis sp.	14:0/14:1, 16:0, 16:1, **18:**1, 18:3, **18:**4, 22:6	**14:0/14:**1, **18:**1, 18:2, 18:3, 18:4, 22:6
Nannochloris sp.	14:0/14:1, 16:0, 16:1, 16:2, 16:3, 20:5	not determined
Nitzschia sp.	14:0/14:1, 16:0, 16:1, 16:2, 16:3, 20:6	not determined

Source: Reference (12)

Table 4. Average Yield of 99.5 % ethanol from various crops

Probable yield calculated from the crop yield and average fermentable content

Material	Litres/tonne	Litres/hectare
Apples	55	1296
Barley	300	776
Buckwheat	316	316
Corn	318	2002
Grain Sorghum	301	1170
Grapes	59	837
Jerusalem artichokes	78	11230 [1]
Molasses, blackstrap	280	417
Oats	240	533
Potatoes	87	2798
Rice, rough	301	1638
Rye	298	505
Sorghum cane	280	4680
Sugar Beets	84	3855
Sugarcane	59	5193
Sweet Potatoes	129	1778
Wheat (all varieties)	322	739
Yams	103	870

Source: Reference (50)

Notes:

1) Estimate for three harvests of heads per year

Table 5 Life Cycle Greenhouse Gas Emissions

Fuel	**Raw Material**	**Sequestered CO_2**	**Feed into Process**	**Conversion and Distribution**	**Combustion**	**Total**
Diesel[1]	Crude Oil	0	13	6	67	86
Diesel[2]	Crude Oil	0	6	6	70	82
Diesel[3]	Crude Oil	0	4	14	59	77
Biodiesel[1]	Tallow	-72	0	7	72	7
Biodiesel[2]	Canola Oil	-64	14	7	92	49
F-T Liquids[3]	Coppice Wood	-162	7	113	59	17
Ethanol[2]	Wheat	-138	3	89	81	35
Ethanol[2]	Wood	-135	3	95	81	44
Diesahol[1]	Wood	-5	1	17	75	88

Values are g/MJ

Source 1; Reference (49)
Source 2; Reference (57)
Source 3; Reference (33)

Table 6. Life Cycle Emissions other than Greenhouse Gases

Fuel	Raw Material	NMHC		NOx		CO		Particulates	
		Pre-combustion	Combustion	Pre-combustion	Combustion	Pre-combustion	Combustion	Pre-combustion	Combustion
Diesel	Crude Oil	56	84	100	944	23	230	5.4	35
Biodiese1	Tallow		4		1156		136		27
Biodiesel	Canola Oil	141	4	140	1156	35	136	2.5	27
Biodiesel	Rapeseed Oil	142	4	158	1156	35	136	3.1	27
F-T Liquids	Natural Gas	44	49	153	843	35	190	2.1	23
95% Ethanol	Wheat	66	67	282	795	746	287	23	26
95% Ethanol	Wheat / Wheat straw for Fuel	850	67	232	795	3250	287	42	26
95% Ethanol	Wood	524	67	53	795	1800	287	25	26
Diesahol	Wood	53	80	103	863	75	260	5.0	27

All values are mg/MJ
NMHC is Non Methanic hydrocarbons
Source; Reference (49)

Table 7. Energy Balances for selected fuels production

	Diesel[1]	**Biodiesel**[1]	**Biodiesel**[2]	**F-T**[3]	**F-T**[3]	**Ethanol**[4]	**Ethanol**[5]
Feed Material	Crude Oil	Soybean	Tallow	Wood – Once through	Wood- Max Liquid	Corn Stover	Corn
Inputs							
Feed Energy	1	1	1	1	1	1	1
Outputs							
Diesel	0.833						
Biodiesel		0.806	0.917				
Ethanol						0.486	1.087
Electric Power				0.197	0.037	0.045	
Naphtha				0.067	0.125		
Diesel Cut				0.198	0.369		
Co-product							0.186
Efficiency	0.833	0.806	0.917	0.437	0.494	0.531	1.124
Fossil Energy inputs	1	0.250	0.149	0.025	0.037		0.814
Fossil Energy Ratio	0.833	3.33	6.15				1.33

All values are GJ
F-T is Fischer-Tropsch
Source 1; = Reference (56)
Source 2; = Reference (49)
Source 3; = Reference (25)
Source 4; = Reference (53)
Source 5; = Reference (58)

Figure 1. Schematic of Tallow Methyl Esters Production Process

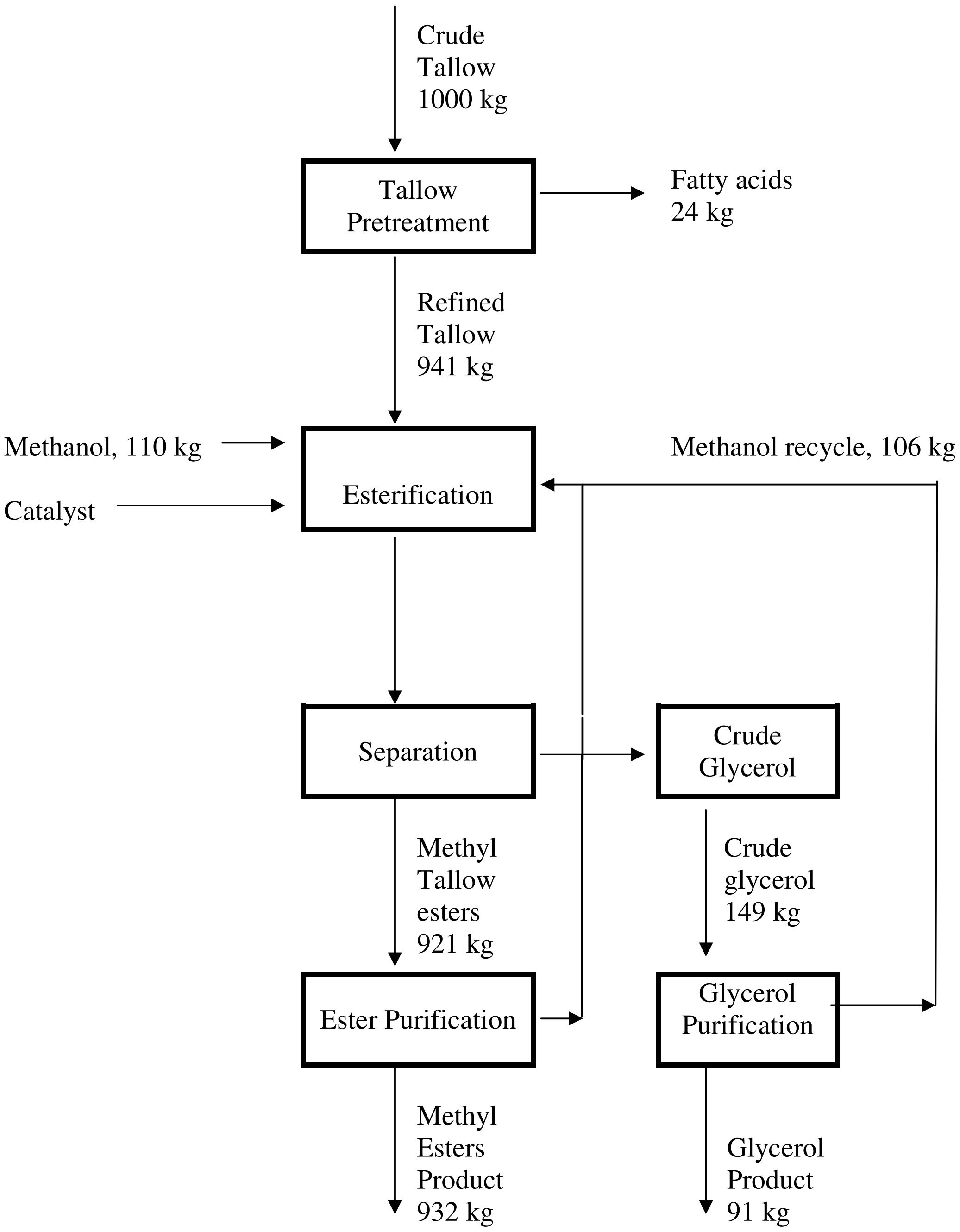


Figure 2. Schematic of Fischer - Tropsch Process for Diesel Production from Biomass

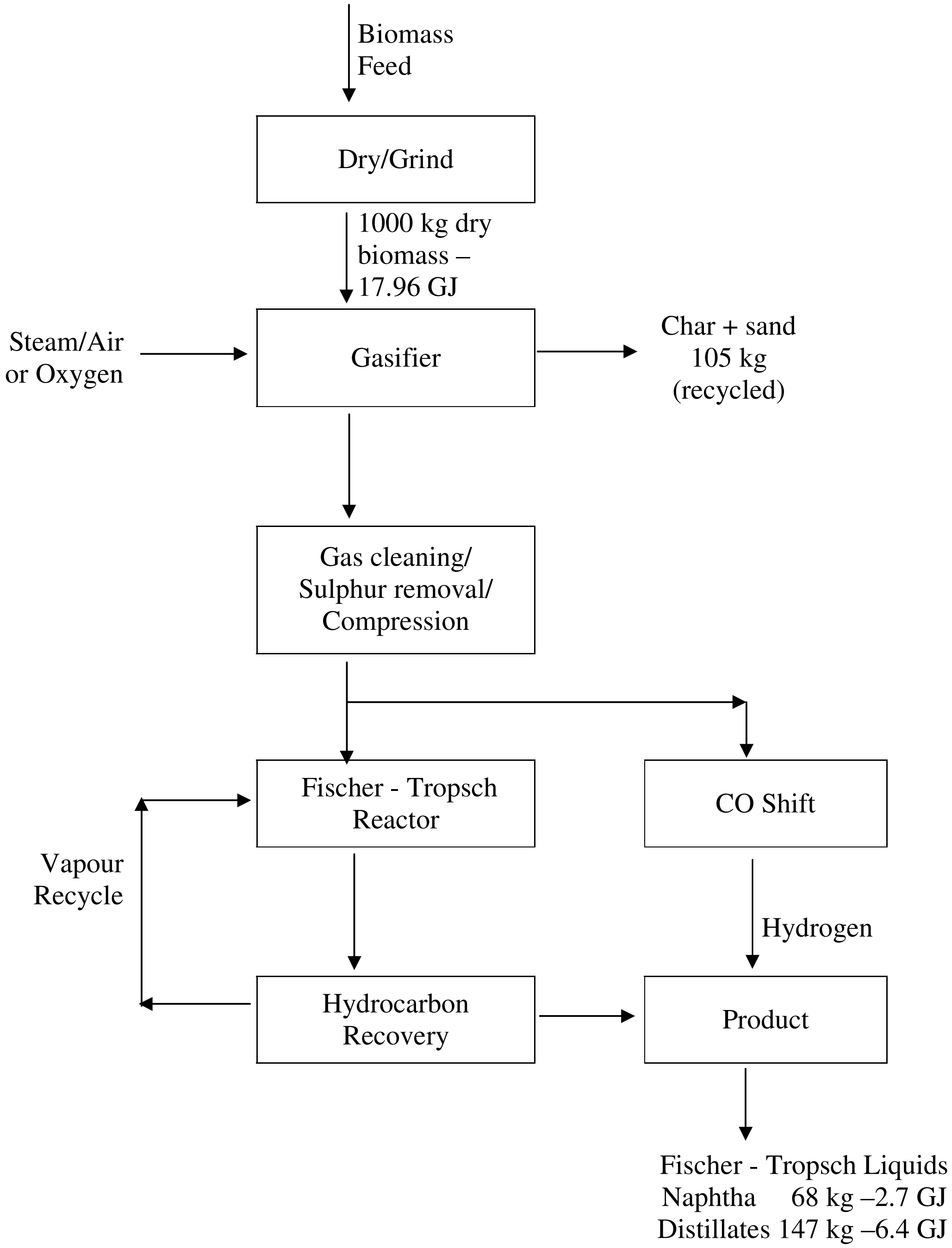


Figure 3. Schematic of Pyrolysis Process for Bio-Oil Production from Biomass

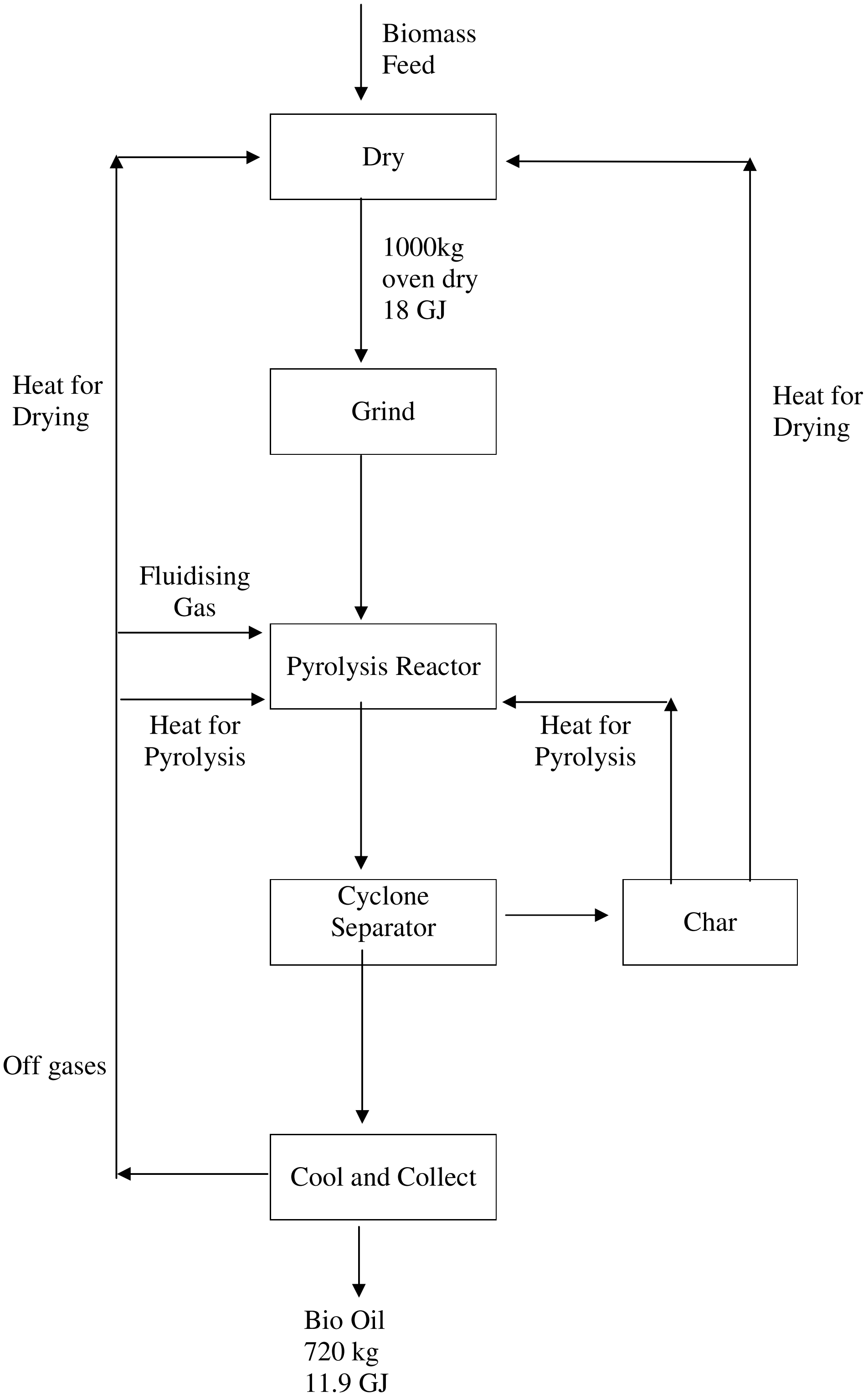
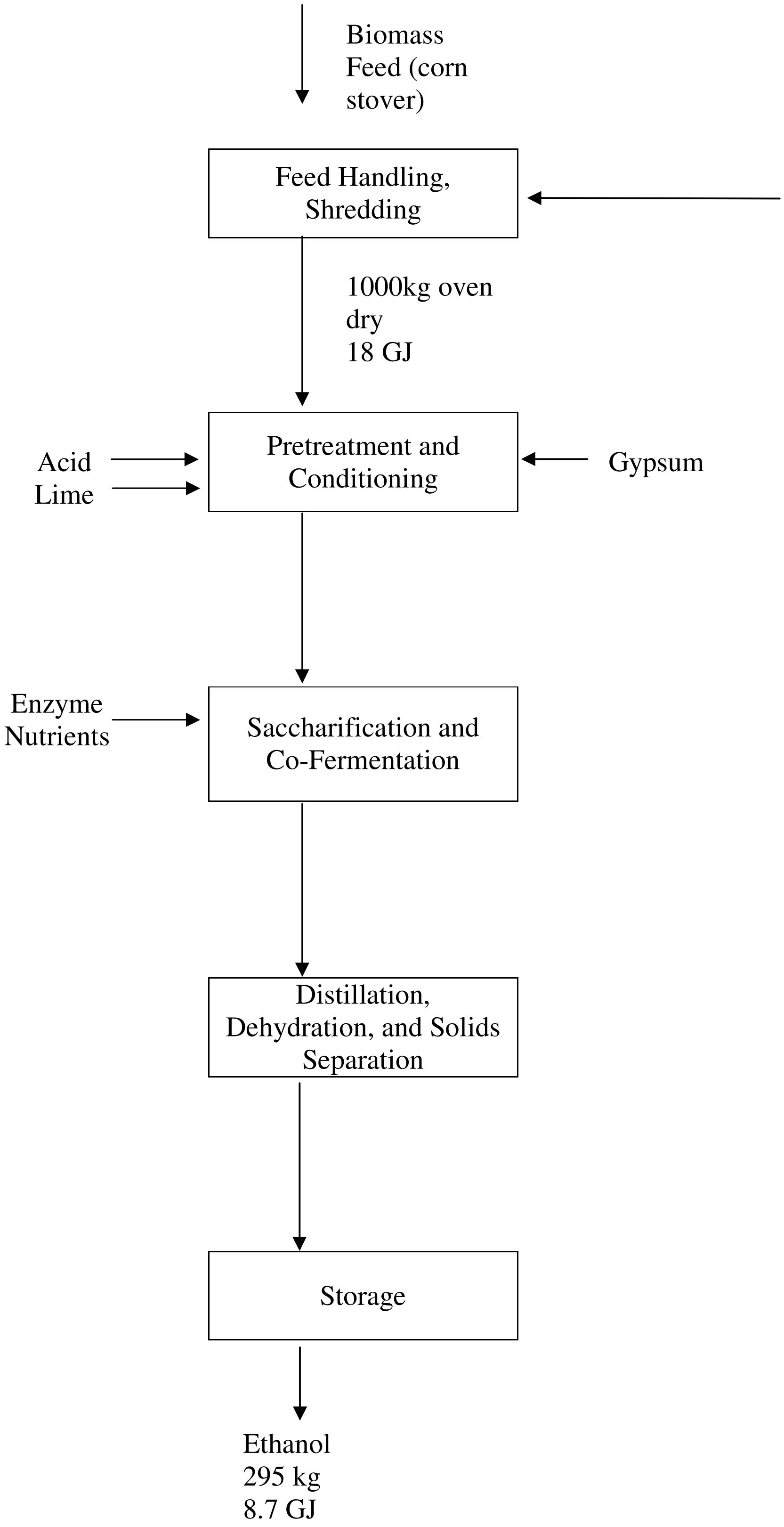


Figure 4. Schematic of Ethanol from Biomass Process



Appendix

Terms of Reference

Project: Bio-diesel from crops - A feasibility study

Background

The Government sets out two key policy directions in the National Energy Efficiency and Conservation Strategy, namely a continuing improvement in our energy efficiency and a progressive transition to renewable sources of energy. To help achieve this transition the New Zealand Renewable Energy Target sets a target of an additional 30PJ of consumer energy from renewable sources by 2012, with an indicative target of 2PJ of renewable energy for the transport sector. One potential renewable transport fuel, which may help meet this goal, is bio-diesel.

The recent report produced by Barry Judd for EECA, "Biodiesel from Tallow", provides an overview of the logistics of bio-diesel production and distribution in New Zealand, and discusses specifically the potential for producing bio-diesel from Tallow and waste cooking oils. The proposed study is expected to complement this overview, by providing a rational assessment of the economic feasibility of producing bio-diesel from crops in New Zealand. The primary focus should be on the production capacity and costs for automotive-quality bio-diesel (i.e. able to be used in existing engines without modification), which can be produced in the near future.

Purpose

The purpose of this project is to assess the feasibility of producing bio-diesel from crops in New Zealand, including realistic estimates of production capacity and costs. The project will:

> Estimate the capacity for bio-diesel production from crops in New Zealand, including an update of the situation for oilseeds (based on latest crops and yields), as well as a literature review and critical analysis of other crops and technologies (e.g. short-rotation woody crops, pyrolisis and steam explosion techniques)
>
> Estimate the costs of producing bio-diesel from crops in New Zealand (including growing, harvesting and processing crops, production of bio-diesel, any necessary additional infrastructure, facilities etc.)

Briefly consider opportunities for combining bio-diesel production with other beneficial processes (e.g. effluent disposal, improving crop cycles etc), if this is likely to influence the economic feasibility

Briefly discuss environmental, health and social costs or benefits (e.g. CO_2 emissions reductions, local air quality impacts, fuel security and regional economic development benefits)

Issues to be canvassed include:

1. Supply issues: The quantity of bio-diesel that can be readily produced in New Zealand

2. Economic issues: The cost of producing bio-diesel from crops in New Zealand

3. Technical and implementation issues: Technological feasibility of bio-diesel production, and likely barriers

4. Energy and CO_2 balance issues: Amount of energy consumed in producing bio-diesel from crops relative to energy contained in bio-diesel, and estimated net reduction in Kyoto-relevant CO_2 per PJ of consumer bio-diesel

5. Relevant environmental, health and social issues: Costs and benefits for the environment, human health and society

Deliverables

1. A progress report covering each of the issues above and highlighting where further investigation will be required, by 28th March 2003.

2. A draft report by 14th April 2003, and if required a briefing for interested officials or agencies. (Date later changed to 30th April by EECA)

3. A final report, taking into account comments on the draft and issues discussed at the briefing, by 28th April 2003 (changed to 31st May by EECA)

The report will:

- ☐ Assess the feasibility of producing bio-diesel from crops in New Zealand
- ☐ Discuss each of the above issues
- ☐ Highlight any major barriers to producing bio-diesel from crops in New Zealand
- ☐ Identify areas which require further investigation