5. Canola

5.1 Background

Canola is a member of the *Brassica* Family, which includes broccoli, cabbage, cauliflower, mustard, radish, and turnip. It is a variant of the crop rapeseed. Grown for its seed, the seed is crushed for the oil contained within. After the oil is extracted, the by-product is a protein-rich meal used by the intensive livestock industry.

In the 1990s canola production increased dramatically due to new disease resistant varieties (Black Leg Resistance) and strong oilseed prices compared to wheat and wool. Australia has a production land base able to increase canola, though low oilseed prices could restrict expansion.

Canola is a very small seed, which means sowing depth must be controlled to minimise patchy germination. The current sowing practice is to cover the seed lightly with soil, which ensures more protection from drying out after germination.

Canola is generally sown in autumn (late April/early May), develops over winter, flowers in the spring and is harvested early summer (late November/early December) with a growing period of around 180-200 days

Climatic effects such as sudden heat waves can reduce yields and hot dry conditions can limit oil content. Summer weather ensures low moisture (less than 6%) at harvest. Carry-in stocks of canola are minimal because of a lack of on-farm storage.

Canola is a good rotational crop, acting as a break crop for cereal root diseases. However for disease-related reasons, a rotation period of 3-5 years is required for canola crops. Moreover, if on-going research on combating fungal root disease in wheat by seed inoculation proves successful, the land area available for growing canola will come under pressure when canola prices fall.

5.1.1 Canola alternatives

CSIRO has a research program on the use of linola as a substitute for canola (A. Green, CSIRO Plant Industries, pers. comm.) and a joint venture with United Grain Growers of Canada for the development and commercialisation of the crop. Linola is a form of linseed that was developed using conventional plant breeding to make the oil more suitable for edible uses, particularly for cooking oil. Linseed normally has a very high level of linolenic acid, which makes it oxidatively unstable and prevents its use in cooking, particularly commercial cooking (but gives it the drying properties associated with its traditional industrial usage). CSIRO reduced linolenic from 50% down to 3% and consequently raised linoleic up to 65-70%. This makes “linola” oil equivalent in composition and function to high-linoleic sunflower or safflower oils. Green (pers. comm.) would expect linola oil to perform the same as those oils in biodiesel applications.

5.2 Full Fuel-Cycle Analysis

5.2.1 Tailpipe

We are unable to find any tailpipe emissions data for heavy vehicles using pure canola oil. It is over a decade since research was undertaken on the use of pure vegetable oils, such as canola, as heavy-vehicle fuels. Though it is possible to modify diesel engines to run on pure vegetable oils (as discussed in the section on viability and functionality) the consensus of the industry is that biodiesel is a superior fuel. This view was expressed by a number of stakeholders verbally and in writing.

5.2.2 Upstream

Details of canola seed production and processing are given in the chapter that deals with biodiesel.

The upstream emissions for canola oil will be the same as those for canola biodiesel (canola ethyl-ester) except that no transesterification phase is required.

5.2.3 Results

At present pure canola oil is not a viable automotive fuel (see Section 5.3). Thus no results are presented.

5.3 Viability and Functionality

According to material supplied by P. Calais of Murdoch University, though the power output and tailpipe emissions using plant or animal oils are in most cases comparable with the power output and the emissions when running on petroleum diesel fuel, the main problem encountered has been the higher viscosity of the oils causing difficult starting in cold conditions, the gumming up of injectors, the coking-up of valves and exhaust, and the often high melting or solidification point of many vegetable and animal fats and oils. (Pullan et al, 1981)

The viscosity of plant and animal fats and oils varies from hard solids to light oils at room temperature. In most cases, these ‘oils’ are actually a solution of various fatty acids, often with the various components having widely varying melting points. This may give the oil a temperature range over which solidification occurs, with the oil gradually thickening from a thin liquid, through to a thick liquid, then a semi-solid and finally to a solid.

High melting points or solidification ranges can cause problems in fuel systems such as partial or complete blockage as the oil thickens and finally solidifies when the ambient temperature falls (Pullan et al., 1981). Though this also occurs with petroleum-based diesel, particularly as the temperature falls below about ~ 10° C for ‘summer’ formulations and ~ -5° C for ‘winter’ diesels, it is relatively easy to control during the refining process and is generally not a major problem.

Most vegetable oils and some animal oils have ‘drying’ or ‘semi-drying’ properties and it is this which makes many oils such as linseed, tung and fish suitable as the base of paints and other coatings. But it is also this property that further restricts their use as fuels.

Drying results from the double bonds in the oil molecules which can be easily broken by atmospheric oxygen converting the fatty acid into a peroxide. Cross-linking at this site can then occur and the oil irreversibly polymerises into a plastic-like solid (Cole et al., 1977).

In the high temperatures commonly found in internal combustion engines, the process is accelerated and the engine can quickly become gummed-up with the polymerised oil. With some oils, engine failure can occur in as little as 20 hours (Duke, 1983).

The traditional measure of the degree of bonds available for this process is given by the ‘Iodine Value’ (IV) and can be determined by adding iodine to the fat or oil. The amount of iodine in grams absorbed per 100 ml of oil is then the IV. The higher the IV, the more unsaturated (the greater the number of double bonds available) is the oil and the higher the potential to ‘gum up’ when used as a fuel in an engine.

Though some oils have a low IV and are suitable without any further processing other than extraction and filtering, the majority of vegetable and animal oils have an IV which does not permit their use as a neat fuel.

Generally speaking, an IV of less than about 25 is required if the neat oil is to be used in unmodified diesel engines and this severely limited the types of oil that can be used as fuel. Table 1 lists various oils and some of their properties.

The IV can be easily reduced by hydrogenation of the oil (reacting the oil with hydrogen), the hydrogen breaking the double bond and converting the fat or oil into a more saturated oil and reducing the tendency of the oil to polymerise. However this process also tends to increase the melting point of the oil and converts the oil into margarine.

As can be seen from Table 5.1, only coconut oil has an IV low enough to be used without any special precautions in a unmodified diesel engine. However with a melting point of 25°C, the use of coconut oil in cooler areas would obviously lead to problems.

Table 5.1

Melting point and Iodine Values of oils

Oil	Approx. melting point °C	Iodine Value
Castor oil	-18	85
Coconut oil	25	10
Cotton seed oil	-1	105
Linseed oil	-24	178
Olive oil	-6	81
Palm oil	35	54
Palm kernel oil	24	37
Peanut oil	3	93
Rapeseed oil	-10	98
Soybean oil	-16	130
Sunflower oil	-17	125
Tung oil	-2.5	168
Beef tallow		50
Mutton tallow	42	40
Sardine oil		185

Source: CRC Handbook of Chemistry and Physics, 64th and 76th Ed. pp D-221

All of these problems can be at least partially alleviated by dissolving the oil or hydrogenated oil in petroleum diesel. Linseed oil for example, could be mixed with petroleum diesel at a ratio of up to 1:8 to give an equivalent IV in the mid-twenties. Likewise coconut oil can be thinned with diesel or kerosene to render it less viscous in cooler climates. Obviously the solubility of the oil in petroleum also needs to be taken into account. Another method is to emulsify the oil or fat with ethanol.

Most vegetable oils are a mixture of different esters such as oleic acid (main constituent of olive oil), ricinoleic acid (main constituent of castor oil), linoleic acid and linolenic acid (main constituents of linseed oil), palmitic acid (main constituent of palm kernel oil) and so on. In an analogous way to that in which crude oil is refined to make a useable automotive fuel, canola oil needs to be transesterified to make an automotive fuel that is useable in unmodified diesel engines. When the oil is processed in a transesterfication process, the various fatty acids react with the alcohol to form a mixture of lighter esters and glycerol. The name of the specific fuel is called after the plant (or animal) source plus the alcohol. Made from rapeseed oil and methanol, the biodiesel is called Rape Methyl Ester (RME), from canola oil and ethanol, Canola Ethyl Ester (CEE), and from used McDonald's cooking oil and ethanol or methanol, McDiesel.

Nevertheless, there is a niche market, mainly in Germany and Austria, in the conversion of diesel vehicles to run on vegetable oil. One example is that of http://www.elsbett.com/gd/tuniinfe.htm in Germany.

5.4 Health Issues

The health issues associated with the use of canola oil in a diesel engine are not known.

5.5 Environmental Impact and Benefits

The environmental issues associated with the use of canola oil in a diesel engine are not known.

6. Hydrated Ethanol

6.1 Background

Development and use of alcohol fuels in transport have for the most part been driven by the desire in many countries to find renewable substitutes for imported petroleum-based fuels. Alcohol fuels have also been used as additives to conventional fuels to improve fuel characteristics. More recently they have been the focus of attention as a possible means of reducing greenhouse gas emissions, and noxious urban emissions from transport.

Ethanol will easily blend with gasoline but blending with diesel requires an emulsifier or additive to form a stable fuel. Alcohols can be used in diesel engines by either modifying the fuel or by extensive engine adaptations.

Ethanol can be produced in two forms – hydrated and anhydrous. Hydrated ethanol has a purity of 95% suitable for blending with an ignition improver, or as a 15% emulsion in diesel that is known as Diesohol, which is discussed in the next chapter. A second stage refining process is required to produce anhydrous ethanol (100% purity) for use in ethanol blends in petrol, as discussed in Chapter 13. Most industrial ethanol is denatured (to prevent oral consumption) by the addition of small amounts of an unpleasant or poisonous substance.

This chapter will examine hydrated ethanol produced from wheat, sugar cane, molasses and wood, and will discuss one source of ethanol from a non-renewable resource. Hydrated ethanol production is a one-stage refining process, unlike the two-stage anhydrous ethanol. However, from the viewpoint of the LCA, the upstream emissions for ethanol production will be different for every process.

6.1.1 Characteristics of alcohol fuels

Ethanol (C_2H_5OH) is an alcohol, an oxygenated organic carbon compound. It is the intoxicating component of alcoholic beverages, is used as a solvent (methylated spirits), and is widely used in the chemical and pharmaceutical industries. By contrast, diesel is a mixture of a range of hydrocarbon compounds, none of which contains oxygen. In blended fuels, the addition to diesel of the oxygen contained in the alcohol changes a number of important fuel characteristics. These include changes in combustion properties, energy content and vaporisation potential.

The energy content of ethanol ranges from 21 to 23 MJ/L. This compares to 38.6 MJ/L for diesel. The energy content of ethanol depends on whether it is hydrated or anhydrous. Expressed in mass terms the energy content ranges from 24 MJ/kg to 26.7 MJ/kg (http://www.afdc.doe.gov/altfuels.html). Boustead & Hancock (1979) quotes 29.7 MJ/kg. The former values probably represent the lower heating value (LHV) whereas the higher value is probably the higher heating value (HHV).

6.1.2 Production and distribution

Ethanol production

Ethanol can be manufactured numerous sources. For example, a recent thesis examined the life-cycle emissions of ethanol from wine (Ericson and Odehn, 1999). This report examined ethanol from:

- biomass via the fermentation of sugar derived from grain starches or sugar crops;
- biomass via the utilisation of the non-sugar lignocellulosic fractions of crops;
- petroleum and natural gas via an ethylene (C_2H_4) intermediate step (reduction or steam cracking of ethane [C_2H_6] or propane [C_3H_8] fractions).

Ethanol from sugar and starch fractions

At present there are only two commercial sources of ethanol in Australia. It is manufactured from biomass via the fermentation of sugar that is derived either from wheat starch or from molasses. The Australian Greenhouse Office has recently funded a research project to examine the manufacture of ethanol from sugar cane residue (bagasse).

Ethanol from molasses

Ethanol has traditionally been produced in Australia from molasses (C molasses), a low value by-product of the sugarcane industry. CSR Distilleries supplies around half of the Australian ethanol market with an annual plant capacity of 55 million litres (www.csr.com.au/about/Facts_Distilling.htm).

Production of ethanol from molasses constitutes part of the sugar refining process. The overall process consists of the following main steps :

1. **Crushing**: Sugar cane “as farmed” is chopped at the sugar mill to facilitate handling and processing.
2. **Sugar extraction**: This is effected in a countercurrent flow of warm water. The solids after extraction (bagasse) containing less than 0.5% sugar are squeeze-dried to remove maximum of sugar solution (liquor). Dry bagasse is used as fuel to power sugar mill operation.
3. **Raw sugar production**: Sugar-containing liquor is concentrated in evaporators. Crystalline sugar is separated in centrifuges. This process is repeated several times yielding raw sugar. It may be further refined if necessary.
4. **Fermentation of molasses**: Liquid residue from sugar production (molasses) containing approximately 50% sugar and 50% mineral matter is mixed with yeast and fermented yielding 6 to 7% ethanol. Solid residue after fermentation (dunder) contains mostly yeast and minerals and is used as fertiliser. Yeast is sometimes separated and used by the food industry.
5. **Distillation**: The fermented mash, now called "beer," contains about 10% alcohol, as well as all the non-fermentable solids from the wheat and the yeast cells. The mash is pumped to the continuous flow, multi-column distillation system where the alcohol is removed from the solids and the water. The alcohol leaves the top of the final column at about 96% strength, and the residue mash, called stillage, is transferred from the base of the column to the co-product processing area.
6. **Denaturing**: Ethanol that will be used for fuel is denatured at the time of transport with a small amount (0-5%) of some product, such as gasoline, to make it unfit for human consumption.

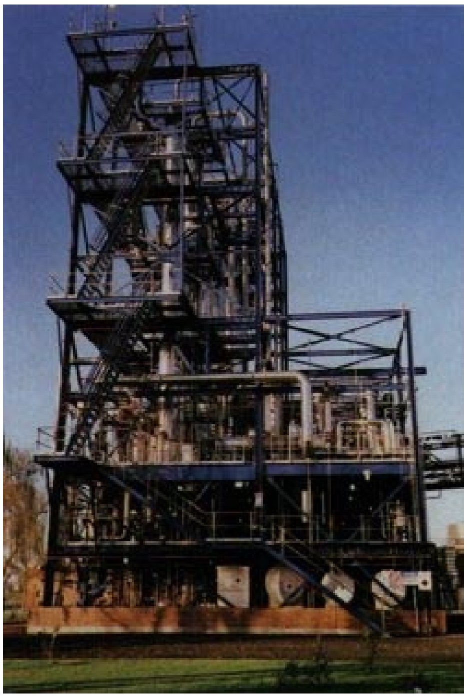

Figure 6.1
The ethanol plant at Manildra’s Bomaderry plant near Nowra.
(http://www.manildra.com.au/prospectus/prospectus6.html)

In the case of CSR’s azeotropic ethanol-from-molasses plant at Sarina in Queensland, the processing energy input is supplied from combustion of the sugar cane bagasse. Surplus bagasse is also used by CSR for electrical power cogeneration.

Ethanol from wheat starch

Ethanol is also produced from wheat at Manildra’s gluten and starch plant at Nowra (Figure 6.1). The major products of the mill are gluten and starch. The ethanol produced from the waste starch stream with further supplementations of starch is essentially a by-product of the gluten manufacturing process.

There are basically seven steps in the ethanol production process from wheat starch:

1. **Milling**: The wheat (or corn, barley, etc.) first passes through hammer mills, which grind it into flour. The flour is then transported by rail to Manildra’s industrial plant near Nowra.
2. **Liquefaction**: The meal is then mixed with water and alpha-amylase, and passes through cookers where the starch is liquefied. Heat is applied at this stage to enable liquefaction. Cookers with a high temperature stage (120-150ºC) and a lower temperature holding-period (90ºC) are used. These high temperatures reduce bacteria levels in the mash.
3. **Saccharification**: The mash from the cookers is then cooled and the secondary enzyme (gluco-amylase) added to convert the liquefied starch to fermentable sugars (dextrose), a process called saccharification.
4. **Fermentation**: Yeast is then added to the mash to ferment the sugars to ethanol and carbon dioxide. This carbon dioxide, being completely renewable in origin, is not included in the calculations. Using a continuous process, the fermenting mash flows, or cascades, through several fermenters until the mash is fully fermented and then leaves the final tank. In a batch fermentation process, the mash stays in one fermenter for about 48 hours before the distillation process is started.
5. **Distillation**: The fermented mash, now called "beer", contains about 10% alcohol, as well as all the non-fermentable solids from the wheat and the yeast cells. The mash is then pumped to the continuous flow, multi-column distillation system where the alcohol is removed from the solids and the water. The alcohol leaves the top of the final column at about 96% strength, and the residue mash, called stillage, is transferred from the base of the column to the co-product processing area.
6. **Denaturing**: Ethanol for fuel is then denatured with a small amount (0-5%) of some product, such as gasoline, to make it unfit for human consumption.
7. **Co-Products**: The main co-products created in the production of ethanol are carbon dioxide, stockfeed from recovered solids in stillage (distillers grain), and bio-fertiliser from liquid effluent. Carbon dioxide is given off in great quantities during fermentation and many ethanol plants collect that carbon dioxide, clean it of any residual alcohol, compress it and sell it for use to carbonate beverages or in the flash freezing of meat. This carbon dioxide, also being completely renewable in origin, is not included in the calculations. Distillers grains, wet and dried, are high in protein and other nutrients and are a highly valued livestock feed ingredient. Some ethanol plants also create a "syrup" containing some of the solids that can be a separate product sold in addition to the distiller's grain, or combined with it. Manildra uses this process to produce fructose, sugars, glucose syrup, and other products.

APACE Research (R. Reeves, pers. comm.) point out that modern, integrated ethanol-from starch plants, such as that of Manildra, have a processing energy input of approximately 4.5 MJ/L of azeotropic ethanol, and 5.9 MJ/L of anhydrous ethanol. Based on a lower heating value of 19.43 MJ/L for azeotropic ethanol and 21.15 MJ/L for anhydrous ethanol, and assuming natural gas to steam conversion efficiency of 70%, Reeves estimates the processing energy input to be 0.33 of the lower heating value for ethanol for azeotropic ethanol, and 0.40 for anhydrous ethanol. Details are given in Appendix 6.

The starch feedstock used by Manildra for ethanol production is waste starch from Manildra’s gluten production, or is derived from reject grain. This means that there is no energy input (or greenhouse gas emissions) associated with this waste product.

Energy and emission data for ethanol production are available from a number of sources including an NREL study (Kadam et al., 1999) and from Swedish data published on the BioAlcohol Fuels Website (Bioalcohol Fuel Foundation, 2000) These data sources look at different processes (from acid to enzyme) and different feedstocks including woodwaste and straw. Data on ethanol has been taken from documents and personal communications with APACE Research (R.Reeves, pers. comm.).

No individual process data is available for the Manildra process so it has been modelled as a black-box with waste product and coal-based heat into the plant, with ethanol as the main output. The ethanol was assumed to be azeotropic so the energy use per litre of ethanol production was 9 MJ.

There are no solid residues available for combustion from Manildra’s ethanol-from-starch plant. All liquid effluent streams, principally the underflow from the stripping distillation column, are irrigated onto surrounding land for intensive pasture production. Thus the liquid effluent has displaced use of conventional fertilisers and significantly increased the soil carbon content on Manildra’s adjacent environmental farm. Given that the source of carbon is from renewable sources, no credit for fixing fossil carbon is given from a greenhouse perspective. For the same reason carbon dioxide emissions from fermentation are not included as greenhouse impacts as they are from short-term sustainable carbon cycles.

Without clear estimates of the nutrient replacement achieved through land application of effluents, and evidence of this lowering fertiliser use, it is not possible to provide credits for avoided fertiliser use. The effect of these credits is thought to be small in any case.

Because of the low value of the grain feedstocks, they are treated as waste products and not as by-products of the starch process, and thus have no environmental burdens associated with them. If the value of these feedstocks increase, or higher grade grain is used in the Manildra plant, then (as discussed below) an alternative allocation needs to include environmental burdens of the feedstock.

Ethanol from sugar cane residue (bagasse)

The production of ethanol from sugar cane residue is more akin to the production of ethanol from wheat residue than the production of ethanol from molasses. The steps are the same as detailed in the previous section. The main difference is geographic. At present, ethanol produced from sugar cane residue is an activity that takes place in Queensland rather than in the northern New South Wales sugar industry.

Ethanol from wood

Lignocellulose is the structural component of plant biomass and can be derived from trees, grasses, and from cereal and paper wastes. Lignocellulose is also a large component of municipal waste. Both the cellulose and hemicellulose portions of the material (which in the case of plants may comprise 65 to 80 per cent of the non-sugar and starch components) can be converted into ethanol. The proportion of cellulose and hemicellulose from various lignocellulose sources is dependent upon the specific biomass crop. The process is shown in Figure 6.2.

The mass production of ethanol from lignocellulose is still largely in the research and development stage. Production facilities operate mostly at laboratory or pilot scale. The two major research efforts aimed at extracting ethanol from lignocellulose involve technologies using either acid or enzymatic hydrolysis, with the enzymes used being derived from micro-organisms. After hydrolysis the sugars produced are fermented and the ethanol in solution is distilled out, as for ethanol produced from starch and sugar crops.

For the foreseeable future, ethanol produced from non-lignocellulosic biomass sources is likely to be the only feasible option for economical large-scale ethanol production, such that the costs become competitive with that of diesel. Production from sugar and grain crops will dominate ethanol production until the lignocellulose process is proved technically and economically more viable.

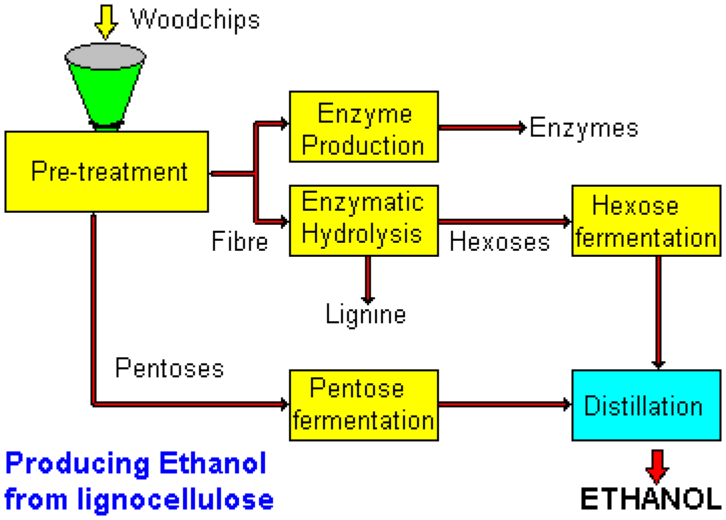

Figure 6.2
Production of ethanol from lignocellulose
Picture is from http://www.swedetrack.com/eflwa22a.htm

Synthetic ethanol from other feedstocks

The most common source of synthetic ethanol is hydration of ethylene. Ethylene itself is a commodity produced on a large scale by oil refineries and broadly used by chemical industries as a feedstock for the manufacture of various chemicals. The majority of ethylene is produced by thermal cracking of hydrocarbons.

The process for hydration of ethylene to ethanol is long established. It involves a two step process using sulfuric acid. In the first step ethylene is reacted with sulfuric acid to form diethyl sulfate:

$$C_2H_4 + H_2SO_4 = C_2H_5OSO_3H$$

$$C_2H_4 + C_2H_5OSO_3H = C_2H_5OSO_2OC_2H_5$$

In the second step diethyl sulfate is hydrolysed with water to ethanol and sulfuric acid:

$$C_2H_5OSO_2OC_2H_5 + 2H_2O = 2C_2H_5OH + H_2SO_4$$

In early 1970’s the above process was simplified and direct hydration of ethylene carried out by passing ethylene and water vapour mixture over phosphoric acid supported on a solid surface:

$$C_2H_4 + H_2O = C_2H_5OH$$

This process today accounts for production of the vast majority of synthetic ethanol.

An alternative route to synthetic ethanol involves the Fischer-Tropsch process whereby the syngas (mixture of hydrogen and carbon monoxide) is reacted at pressure over a metal catalyst to yield a mixture of products including alcohols. An appropriate reaction leading to ethanol is as follows:

$$4H_2 + 2CO = H_2O + C_2H_5OH$$

The feedstock for the process (syngas) can be produced from coal via gasification or from natural gas via steam reforming. The problem with the Fischer-Tropsch process for ethanol production is its inherent low selectivity. While catalysts yielding mostly oxygenated products have been developed, it still means that ethanol will be produced along with a number of other alcohols and hydrocarbons. For this reason the Fischer-Tropsch process is used for conversion of natural gas and coal into a range of liquid fuels and waxes rather than specific chemicals.

Other potential routes to synthetic ethanol involve conversion of acetylene to acetaldehyde and subsequent hydrogenation, hydrolysis of esters, or homologation of methanol. None of these is of commercial significance.

6.2 Full Fuel-Cycle Emissions

6.2.1 Tailpipe emissions

The ability of ethanol to contribute to a reduction in greenhouse gas emissions on a FFC basis is very much influenced by the nature of the feedstock and by the source of power used for the production process. CO_2 emissions from the combustion process alone are fairly similar for alcohol fuels and gasoline on an energy equivalent basis, assuming complete combustion.[1]

Table 6.1 reproduces the US value for emissions from diesel and ethanol buses given in Beer et al. (2000). These data are based on 6 data points in the case of 93% ethanol (E93) and 47 data points in the case of 95% ethanol (E95). All of these buses used the same DDC 6V92TA engine. Motta et al. (1996) analysed a subset of these data and note no relationship between the emissions and the vehicle odometer readings.

Table 6.1
Average, maximum, and minimum values of the tailpipe emissions (g/km) recorded for diesel and ethanol buses undergoing an urban (CBD) cycle on a dynamometer

Fuel		CO	NMHC	THC	NOx	PM	CO_2	C_2H_5OH	HCHO	CH_3CHO
Diesel	**Average**	**7.72**	**1.30**		**21.26**	**0.79**	**1736.97**			
	Max	28.94	1.75		36.75	1.77	2313.75			
	Min	2.50	0.81		11.50	0.06	1436.88			
E93	**Average**	**9.84**			**5.16**	**0.36**	**2119.17**	**1.27**		
	Max	13.88			6.63	0.46	2256.25	2.86		
	Min	1.56			4.13	0.15	1986.88	0.03		
E95	**Average**	**20.62**	**7.02**	**7.59**	**11.37**	**0.31**	**2154.10**	**4.60**	**0.20**	**1.06**
	Max	38.31	21.04	22.24	20.94	0.61	3611.88	21.17	0.40	2.42
	Min	0.69	0.69	3.51	5.00	0.04	1481.88	0.11	0.01	0.03

C_2H_5OH – ethanol emissions
HCHO – formaldehyde emissions
CH_3CHO – acetaldehyde emissions

On a gram CO_2 emitted per kilometre travelled, the ethanol buses emitted more than the diesel buses, indicating that the fuel economy of the ethanol buses was below theoretical expectations.

The above results refer mainly to older technology buses. As noted below, Ventura bus lines in Melbourne started running an ethanol powered bus on 1 December 2000. The publicity material claims that this is a 100% ethanol-powered bus, but we note that an ignition improver is also being used. CADETT (1998) provides information on these (third generation) ethanol-powered engines and points out that the fuel used is actually 95% ethanol along with an ignition improver (Beraid) and denaturants. The ignition-improving agent Beraid is the non-ionic polymer polyethylene glycol

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[1] Emissions of CO_2 from ethanol are 64.4 grams per MJ, and from diesel 69.7 grams per MJ. Emissions of CO_2 from the combustion of one litre of fuel are 1.5 kilograms for ethanol, and 2.7 kilograms for diesel.

according to Ahlvik and Brandberg (2000). Beraid is necessary in Scania's ethanol engines because the fuel ignites at a much higher temperature than diesel or petrol. The non-ionic polymer works by lowering the ignition temperature of the ethanol to the required level. According to http://www.ethanolmt.org/janfeb01.html#7, the ignition improver used by Ventura is made from animal fat. According to the Swedish KFB web-site, ether can also be used as an ignition improver. The composition of the Swedish fuel is given in Table 6.2.

Table 6.2
Composition of ethanol used in Swedish ethanol buses

Fuel composition		
Ethanol	% by wt	90.2
Ignition improver	% by wt	7.0
MTBE	% by wt	2.3
Isobutanol	% by wt	0.5
Corrosion inhibitor	ppm	90
Colour (red)		

Table 6.3 compares the exhaust emissions from the Swedish ethanol buses with the emissions from diesel buses using the best available technology, namely catalysts, particle traps and ultra-low sulfur diesel.

Table 6.3
Exhaust emissions (g/kWh) from 3rd generation Swedish ethanol buses

Emissions (g/kWh)	Euro2 Standard	Best available diesel	Ethanol Bus Skaraborg
Particles	0.15	0.05	0.04
Oxides of Nitrogen	7.0	6.3	3.93
Carbon Monoxide	4.0	0.1	0.13
Hydrocarbons	1.1	0.1	0.09

6.2.2 Upstream emissions

Full fuel cycle estimates of ethanol (Blinge, 1998; IEA 1999c) indicate that the source of the ethanol is crucial in determining whether ethanol is greenhouse-friendly in relation to diesel.

The Canadian Renewable Fuels Association claims that if corn farmers use state-of-the-art, energy efficient and sustainable farming techniques, and ethanol plants integrate state-of-the-art production processes, the amount of energy contained in the ethanol and its co-products can be more than twice the energy used to grow the corn and convert it into ethanol. See the web site at http://www.greenfuels.org/ethaques.html

Their claim is based on the fact that ethanol contains about 23.6 (high heating value)[2] MJ per litre. The energy content, however, may not be as important as the energy replaced. Due to the higher combustion efficiency of ethanol and its octane credit at the refinery, for example, ethanol can replace 28.1 MJ of gasoline (Levelton Engineering Ltd. and (S&T)[2] Consulting Inc.).

Using the displacement value for calculating the energy content of co-products, there is a further 3.9 MJ/L of energy in ethanol represented by the co-products. The total energy represented by a litre of ethanol is therefore 32 MJ. It takes about 5 MJ of energy to grow the corn required for one litre of

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[2] Also known as Gross Calorific Value

ethanol. This is about 15.5% of the energy in the ethanol and the co-product. It takes a further 14 MJ (43.9% of the energy in the ethanol) to process the corn to ethanol using current technology and practices. It is expected that fully optimised plants will be able to lower this to 11 MJ (35.0%) in the near future.

Because the major consumer of energy in the ethanol chain is the ethanol processing plant, emissions from the use of ethanol could be improved significantly if there were scope for reducing fossil energy consumption on the plant. Taschner (1991) and Colley et al. (1991) have drawn attention to the effect of using co-products of ethanol production (such as cereal straw) as an energy source, rather than leaving it to release greenhouse gases through decomposition. When ethanol is derived from wastes produced during processing sugar and starch crops for other purposes, a significant greenhouse benefit might be realised, if fossil fuel use could be attributed to the primary product (for example gluten or starch).

If ethanol is to provide a major reduction in transport greenhouse gas emissions it will need to be demonstrated that it is both technically and economically feasible on a large scale from lignocellulose processes.

6.2.3 Upstream emissions from C molasses

Sugar cane production assumptions

Ethanol production from the sugar industry is taken to be from the molasses by-product of raw and refined sugar production. Much of the data for sugar cane production has been taken from an unpublished honours thesis by Marguerite Renouf from University of Queensland Environmental Management Centre. Where practical original data sources cited in the thesis have been reproduced.

Sugar cane is produced on the east coast of Australia between Maclean in Northern NSW up to Mossman in North Queensland (Zeitner 2000). Total cane production in 1999/2000 is estimated at around 40.6 million tonnes from a farming area of 419 000 ha giving a yield on 96.8 tonnes per ha (Zeitner 2000). From this harvest 5.6 million tonnes of sugar will be produced, giving a sugar yield from cane of 13.8% (Zeitner 2000). The value of the sugar produced was $257 per tonne. (Zeitner 2000).

Table 6.4
Assumptions for inputs to sugarcane crops

Activity	Power consumption[1] (kWh/ha/yr)	Nitrogen[2] kg N/ha/yr	Phosphorous[3] kg phosphorous (P) /ha/yr	Lime[4] kg lime/ha/yr
Pre-plant field preparation	200.0			
Plant cane	150.0	170	24.2	3.75
Ratoon cane (minimum tillage)	80.0	160	24.2	3.75
Ratoon cane (trash blanketed, zero tillage)	46.7	160	24.2	3.75

Sources:
1 Personal communication with Peter McGuire, BSES extension officer.
2 Moody et al. (1996)
3 Bloesch et al. (1997)
4 Schroeder et al. (2000)

Cane growing

Energy use in land cultivation varies depending on the operation. Sugar cane is initially grown from short section of cane (plant cane). For the next four year the cane is cut and allowed to regrow (ratoon cane) before replanting with new cane stems. Energy and fertiliser inputs to cane farming are listed in

Table 6.4. Relevant outputs from cane growing are in the form of nitrous oxides from soil disturbance and from fertiliser application which are detailed Table 6.5.

Table 6.5
Outputs from cane growing

	applied kg per year	Emission factor % of N applied	Nitrogen emitted kg N/ha/year	Conversion factor (N – N_20)	N_2O per Ha	% activity in 5 year rotation	Total per annum
soil disturbance			0.29	1.57	0.46		0.46
plant cane nitrogen	170	1.25%	2.125	1.57	3.34	20%	0.66725
ratoon cane nitrogen	160	1.25%	2	1.57	3.14	80%	2.512
Total N_20 per Ha							3.63

Harvesting of cane

Inputs to cane harvesting are listed in Table 6.6 and consist of energy input to harvesting and loading machinery. Outputs from harvesting are the cane itself, at 96.8 tonnes per ha per year, and combustion emissions from burnt cane harvesting which is assumed to occur in 40% of farms. The National Greenhouse Gas Inventory estimates that the residue left behind after cane harvesting is 25% of the cane weight. The calculation for sugar cane material available for combustion is listed in Table 6.7 with emissions from this combustion being listed in Table 6.8.

Table 6.6
Machinery use for harvesting sugarcane

Activity	Power consumption (kWh/ha/yr)
Harvester	30
Loader	104
Total	134

Table 6.7
Data on combustion of sugar cane residues in Australia

Year	Production	Residue to Crop Ratio	Fraction of Residue Remaining at Time of Burning	Dry Matter Content	Burning Efficiency	Fraction Burnt	Mass of Residue
1998	39378	0.25	1.0	0.20	0.96	0.40	762.8

Source (NGGIC (2000): APPENDIX TABLE 4—1998 Field Burning of Agricultural Residues 4F-4 (sheet 1)): Crop production of sugar cane)

Table 6.8
Emission factors for field burning of Sugar Cane Trash

		CH_4	N_2O	NOx	CO	NMVOC
Total Mass of fuel burnt	ktonnes	763	763	763	763	763
Total emission	Tonnes	1420	90	5260	55530	3250
Emission factors	kg/tonne	1.86	0.12	6.89	72.78	4.26

Source (NGGIC (2000): APPENDIX TABLE 4—1998 Field Burning of Agricultural Residues 4F-4 (sheet 2): Emissions from on-site agricultural waste burning from sugar cane)

Sugar milling

Sugar milling involves crushing cane with large rollers to extract the sugar juice. This material is then clarified to remove any impurities and concentrated into a syrup by boiling off excess water, seeded with raw sugar crystals in a vacuum pan and boiled until sugar crystals have formed and grown. The crystals are separated from the syrup using a centrifuge before more crystals are grown in the syrup.

Molasses (final molasses) is the syrup remaining after the sugar has "passed through the centrifuge for the last time in a mill or refinery." (Sugar Research Institute 2001) The sugar it contains cannot be removed economically and typically includes sucrose (34.1%), reducing sugars (16.5%), ash (11.3%), water (21.8%) and various sugar, gums and acids (16.3%) (Sugar Research Institute 2001). Australian production of molasses in 1999 was 1,119,000 tonnes of which 650,000 tonnes was exported. (Australian Molasses Trading Pty Ltd 2001). This give a molasses yield of around 0.21 tonnes per tonne of sugar produced.

Australian molasses is used mainly in the fermentation (ethyl alcohol, yeast, lysine and monosodium glutamate) and stockfeed industries. (Australian Molasses Trading Pty Ltd 2001). Molasses commercial value is dependent on sugar content, with trading prices in 2000 being around A$100-120 per tonne for 48% sugar content black strap molasses.

The cane material from which the juice was extracted is called bagasse and it has value as a fuel, and has been used to fuel sugar processing for many years. With the advent of greenhouse issues the energy from bagasse is also being harnessed for electricity generation for general grid use.

For bagasse combustion the assumptions shown in Table 6.9 have been made based on work by Dixon et al. (1998).

Table 6.9
Assumptions on bagasse used for energy generation

Parameter	Value
Moisture (wet basis)	50%
Ash (dry basis)	5%
Fibre content	13.8%
HHV (DAF)	19.65 MJ/kg
Gross calorific value (HHV) (as-fired)	9.34 MJ/kg
Net calorific value (LHV)	8.14 MJ/kg
Bagasse yield per tonne of cane	287kg

Source: From Dixon et al. (1998) with net heating value estimated from gross calorific value based on 50% moisture at 2.4 MJ/kg for latent heat of vaporisation for water

Energy use for sugar milling is assumed to be provided by bagasse combustion and is dealt with in more detail in the section on allocation issues for molasses.

Ethanol production.

Inputs to ethanol manufacture have been developed from data provided by NREL (Kadam et al., 1999) and from site specific data provided from personal communications with Energy Strategies Limited on energy use in Sarina and Bomaderry distilleries. The inputs are listed in Table 6.10. The outputs, apart from the azeotropic ethanol, are CO2, which is not accounted as it is from renewable source, and bio-dunder material left after the fermentation process, which can be used as a fertiliser.

Table 6.10
Inputs to fermentation process

Fermentation source for ethanol	Input material	Mass of input material	Energy source	Energy use (primary energy)[2, 3]	Diesel to denature ethanol[1]	Calcined Lime (Aus)[1]	Ammonia[1]	Additional energy to convert to Anhydrous (Brunoro, pers. comm.)
Molasses	Molasses (Aus)	4.32 kg	Bagasse/ coal[3]	13.1 MJ	6 g	2 g	-	0.24 MJ
Wheat	Wheat	2.17 kg	Natural Gas	9 MJ	6 g	2 g	-	0.24 MJ
Wheat from starch waste	Starch	1.12 kg	Coal	9 MJ	6 g	2 g	-	0.24 MJ
Wheat (energy from wheat straw)	Wheat	2.17 kg	Wheat straw	9 MJ	6 g	2 g	-	0.24 MJ
Wood	wood waste	3.68 kg	Wood waste	9 MJ	6 g	2 g	4 g	0.24 MJ

1 Kadam (1999). 2 The value 9 MJ is based on Bomaderry and in agreement with Kadam (1999).
3 For molasses from the Sarina distillery the value is 13.1 MJ. Note that, on an annual basis, 50% of this energy is from bagasse (David Brunoro, Policy Analyst, Energy Strategies Ltd., pers. comm., July 2001).

Allocation issues for molasses

Molasses is an internationally traded commodity, with the key criteria for molasses quality being the total sugar content. In value terms, molasses is worth approximately one seventh the value of sugar on a weight for weight basis, being approximately $50 per tonne for molasses compared with $350 per tonne for refined sugar (Australian Molasses Trading Pty Ltd, 2001).

Following guidance in the international standards on LCA (International Standards Organisation, 1997), allocation of emissions between sugar and molasses is avoided by expanding the system boundary of the study. Under this approach the environmental value, or impact of molasses is not based on prices, but on the environmental impact of replacing the current uses of molasses from which molasses for ethanol production will be taken. This requires detailed knowledge of the market for these material to determine which products would fill any gap left by a shift of molasses into fuels rather than its current uses. Current uses for molasses, according to Australian Molasses Trading Pty Ltd are predominantly exported feedstock and other fermentation processes. As a fermenting agent molasses is likely to be replaced by other fermentable materials and waste products such as wheat starch and low-grade wheat products. Wheat starch is also a minor by-product whose production cannot increase to meet demand and must thus be taken away from other uses. The supply chain of food and crop wastes will eventually be supplemented with dedicated crops for animal feed, and it is the amount and nature of these dedicated crops, (which have the ability to increase production to meet demand rather than shift from one use to another) that represent the impact of increased molasses use in fuels. Figure 6.3 shows the allocation for the range of products produced in the sugar production cycle. Soybeans are used as a proxy for final animal feed product required to fill the gaps in food and agricultural waste products produced by the use of molasses.

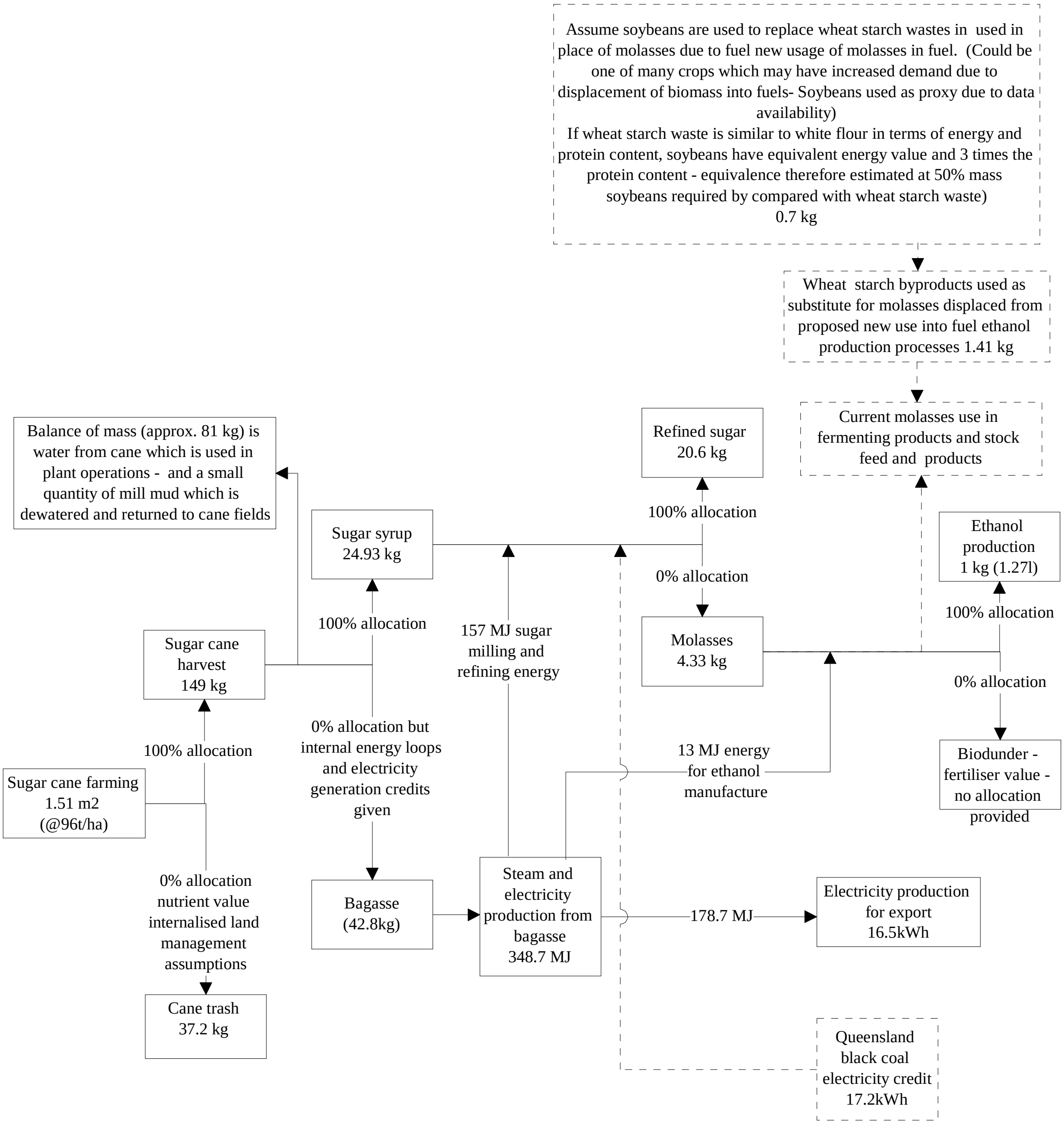

Figure 6.3
Expanded system boundary allocation for molasses use in ethanol for fuels.

An alternate allocation procedure is to use and economic allocation between sugar and molasses in which molasses as a co-product of sugar is allocated an appropriate proportion of the emissions from sugar production. Details of this allocation are shown in Figure 6.3 along with mass flows for different aspects of sugar production.

The other two by-products produced in sugar cane production are sugar cane trash and bagasse. Cane was traditionally burnt prior to harvesting to remove this material. However the trend now is increasingly towards green harvesting, in which the cane trash is removed and left in the field to hold the soil together and provide some nutrients for the next crop. Burnt cane harvesting is used on about 40% of cane lands in Queensland (Queensland Sugar Corporation, 1997), and this has been accounted for in the upstream modelling of sugar production.

Bagasse is the fibrous material remaining after the sugar syrup has been extracted from the sugar cane. This material is generally used for energy production, but can also be used for paper pulp. In this study energy generation is based on data detailed in Table 6.9. Following data from Dixon et al.

(1998) 45% of the energy generation is assumed to be required for sugar mill operations. A further 5.7 MJ is assumed to be used for ethanol production energy requirements. Figure 6.4 shows that this leaves a total of 186 MJ which is available for electricity production for export. After accounting for electricity production losses (assumed at 66%) a total of 17.2 kWh of electricity is exported, with a credit being given for Queensland coal based electricity of the same amount.

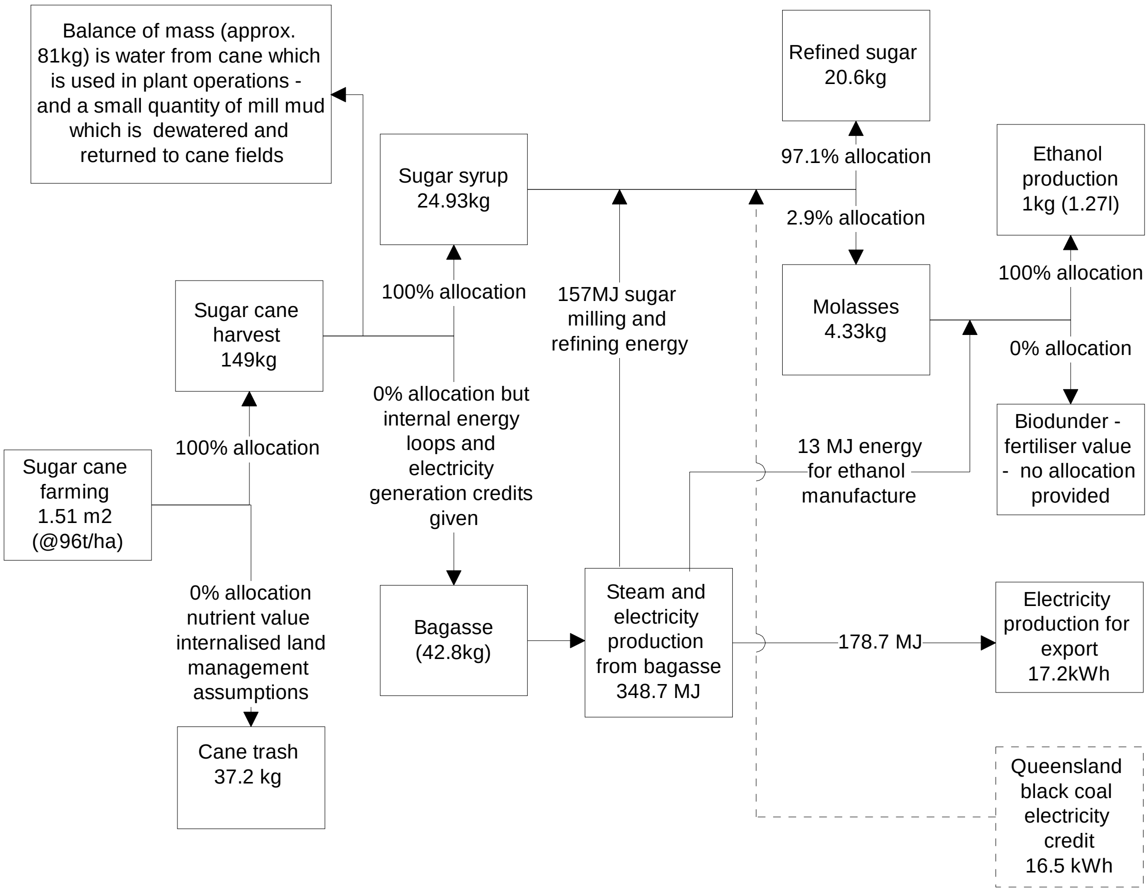

Figure 6.4
Alternative allocation using economic value of co-production for allocation between molasses and sugar.

The results given in the subsequent sections provide quantitative estimates of the exbodied emissions from ethanol under seven scenarios. Two comprise the use of molasses (with expanded system boundaries to determine the energy allocations) and with an economic allocation for the molasses. Three scenarios relate to the use of wheat – one assuming that wheat starch from waste wheat is used, one assuming that premium wheat is used, and one assuming that premium wheat is used for the manufacture of ethanol, with the wheat waste being used to provide power to the plant. There is also a scenario that considers ethanol production from lignocellulose (woodwaste), and a scenario that considers a fossil-fuel based source for ethanol, via ethylene.

6.3 Results

6.3.1 Emissions on a mass per unit energy basis

Table 6.11
Exbodied emissions per MJ for diesel and ethanol

Full Lifecycle	Units	LS diesel	Ethanol azeotropic (molasses - Sarina exp.system boundary)	Ethanol azeotropic (molasses - Sarina-Economic Allocation)	Ethanol anhydrous (wheat starch waste - Bomaderry)	Ethanol azeotropic (wheat)	Ethanol azeotropic (wheat) fired with wheat straw	Ethanol azeotropic (woodwaste)	Ethanol azeotropic (ethylene)
Greenhouse	kg CO_2	0.0858	0.0398	0.0689	0.0349	0.0633	0.0314	0.0076	0.0987
NMHC total	g HC	0.140	0.079	0.078	0.071	0.133	0.917	0.591	0.405
NMHC urban	g HC	0.111	0.076	0.076	0.069	0.076	0.860	0.590	0.361
NOx total	g NOx	1.044	0.917	0.916	0.890	1.077	1.027	0.848	0.991
NOx urban	g NOx	0.987	0.888	0.912	0.887	0.919	0.869	0.846	0.966
CO total	g CO	0.253	0.830	0.980	0.298	1.033	3.537	2.087	0.327
CO urban	g CO	0.242	0.824	0.979	0.297	0.301	2.797	2.087	0.316
PM10 total	mg PM10	40.7	26.9	26.4	46.1	49.4	68.2	51.2	29.1
PM10 urban	mg PM10	39.3	26.4	26.3	46.1	46.8	65.6	51.1	28.8
Energy Embodied	MJ LHV	1.18	0.40	0.46	0.41	0.65	0.76	2.58	2.06

Table 6.12
Precombustion emissions per MJ for diesel and ethanol

Precombustion	Units	LS diesel	Ethanol azeotropic (molasses - Sarina exp.system boundary)	Ethanol azeotropic (molasses - Sarina-Economic Allocation)	Ethanol anhydrous (wheat starch waste - Bomaderry)	Ethanol azeotropic (wheat)	Ethanol azeotropic (wheat) fired with wheat straw	Ethanol azeotropic (woodwaste)	Ethanol azeotropic (ethylene)
Greenhouse	kg CO_2	0.0191	0.0398	0.0689	0.0349	0.0633	0.0314	0.0076	0.0585
NMHC total	g HC	0.057	0.0122	0.0108	0.0036	0.0658	0.85	0.524	0.338
NMHC urban	g HC	0.027	0.009	0.009	0.002	0.009	0.793	0.523	0.294
NOx total	g NOx	0.100	0.122	0.121	0.095	0.282	0.232	0.053	0.196
NOx urban	g NOx	0.043	0.093	0.117	0.092	0.124	0.074	0.051	0.171
CO total	g CO	0.023	0.543	0.693	0.011	0.746	3.250	1.800	0.040
CO urban	g CO	0.012	0.537	0.692	0.010	0.014	2.510	1.800	0.029
PM10 total	mg PM10	5.42	0.869	0.279	20	23.3	42.1	25.1	3.03
PM10 urban	mg PM10	4	0.294	0.176	20	20.7	39.5	25	2.69
Energy Embodied	MJ LHV	1.18	0.40	0.46	0.41	0.65	0.76	2.58	2.06

Table 6.13
Combustion emissions per MJ for diesel and ethanol

Combustion	Units	LS diesel	Ethanol
Greenhouse	kg CO_2	0.067	0.000 (0.040 for ethylene derived ethanol)
NMHC total	g HC	0.084	0.067
NMHC urban	g HC	0.084	0.067
NOx total	g NOx	0.944	0.795
NOx urban	g NOx	0.944	0.795
CO total	g CO	0.230	0.287
CO urban	g CO	0.230	0.287
PM10 total	mg PM10	35.26	26.08
PM10 urban	mg PM10	35.26	26.08
Energy Embodied	MJ LHV	0	0

Table 6.14
Summary of emissions per MJ for diesel and ethanol

		LS diesel	Ethanol azeotropic (molasses - Sarina exp.system boundary)	Ethanol azeotropic (molasses - Sarina- Economic Allocation)	Ethanol anhydrous (wheat starch waste - Bomaderry)	Ethanol azeotropic (wheat)	Ethanol azeotropic (wheat) fired with wheat straw	Ethanol azeotropic (woodwaste)	Ethanol azeotropic (ethylene)
Greenhouse	Pre combustion	0.0191	0.0398	0.0689	0.0349	0.0633	0.0314	0.0076	0.0585
Greenhouse	Combustion	0.0667	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0402
NMHC total	Pre combustion	0.0565	0.0122	0.0108	0.0036	0.0658	0.8500	0.5240	0.3380
NMHC total	Combustion	0.0835	0.0670	0.0670	0.0670	0.0670	0.0670	0.0670	0.0670
NMHC urban	Pre combustion	0.0271	0.0086	0.0094	0.0023	0.0089	0.7930	0.5230	0.2940
NMHC urban	Combustion	0.0835	0.0670	0.0670	0.0670	0.0670	0.0670	0.0670	0.0670
NOx total	Pre combustion	0.1000	0.1220	0.1210	0.0947	0.2820	0.2320	0.0531	0.1960
NOx total	Combustion	0.944	0.795	0.795	0.795	0.795	0.795	0.795	0.795
NOx urban	Pre combustion	0.043	0.093	0.117	0.092	0.124	0.074	0.051	0.171
NOx urban	Combustion	0.944	0.795	0.795	0.795	0.795	0.795	0.795	0.795
CO total	Pre combustion	0.0225	0.5430	0.6930	0.0105	0.7460	3.2500	1.8000	0.0395
CO total	Combustion	0.2301	0.2874	0.2874	0.2874	0.2874	0.2874	0.2874	0.2874
CO urban	Pre combustion	0.0123	0.5370	0.6920	0.0100	0.0136	2.5100	1.8000	0.0290
CO urban	Combustion	0.2301	0.2874	0.2874	0.2874	0.2874	0.2874	0.2874	0.2874
PM10 total	Pre combustion	5.42	0.87	0.28	20.00	23.30	42.10	25.10	3.03
PM10 total	Combustion	35.26	26.08	26.08	26.08	26.08	26.08	26.08	26.08
PM10 urban	Pre combustion	4.00	0.29	0.18	20.00	20.70	39.50	25.00	2.69
PM10 urban	Combustion	35.26	26.08	26.08	26.08	26.08	26.08	26.08	26.08
Energy Embodied	Pre combustion	1.18	0.40	0.46	0.41	0.65	0.76	2.58	2.06

6.3.2 Vehicle emissions - trucks (g/km)

This section gives the calculated values for the emissions from trucks, on a per-kilometre basis.

Table 6.15
Exbodied emissions per km for diesel and ethanol

Full lifecycle	Units (per MJ)	LS diesel	Ethanol azeotropic (molasses - Sarina exp.system boundary)	Ethanol azeotropic (molasses - Sarina- Economic Allocation)	Ethanol anhydrous (wheat starch waste - Bomaderry)	Ethanol azeotropic (wheat)	Ethanol azeotropic (wheat) fired with wheat straw	Ethanol azeotropic (woodwaste)	Ethanol azeotropic (ethylene)
Greenhouse	kg CO_2	0.9250	0.4340	0.7530	0.3820	0.6910	0.3440	0.0826	1.4693
NMHC total	g HC	1.509	0.866	0.851	0.772	1.453	10.023	6.463	6.673
NMHC urban	g HC	1.192	0.827	0.835	0.757	0.830	9.393	6.453	5.893
NOx total	g NOx	11.250	10.020	10.010	9.730	11.770	11.220	9.270	12.130
NOx urban	g NOx	10.638	9.700	9.960	9.700	10.040	9.495	9.246	11.690
CO total	g CO	2.723	9.071	10.721	3.256	11.301	38.641	22.841	3.835
CO urban	g CO	2.612	9.011	10.701	3.250	3.289	30.641	22.841	3.651
PM10 total	mg PM10	438.4	294.5	288.0	504.0	540.0	745.0	559.0	338.2
PM10 urban	mg PM10	423.1	288.2	286.9	503.0	511.0	716.0	558.0	332.3
Energy Embodied	MJ LHV	12.7	4.41	5.04	4.53	7.09	8.26	28.20	36.20

Table 6.16
Precombustion emissions per km for diesel and ethanol

Precombustion	Units	LS diesel	Ethanol azeotropic (molasses - Sarina exp.system boundary)	Ethanol azeotropic (molasses - Sarina- Economic Allocation)	Ethanol anhydrous (wheat starch waste - Bomaderry)	Ethanol azeotropic (wheat)	Ethanol azeotropic (wheat) fired with wheat straw	Ethanol azeotropic (woodwaste)	Ethanol azeotropic (ethylene)
Greenhouse	kg CO_2	0.2060	0.4340	0.7530	0.3820	0.6910	0.3440	0.0826	1.0300
NMHC total	g HC	0.609	0.133	0.118	0.0393	0.72	9.29	5.73	5.94
NMHC urban	g HC	0.292	0.094	0.102	0.025	0.098	8.660	5.720	5.160
NOx total	g NOx	1.080	1.330	1.320	1.040	3.080	2.530	0.580	3.440
NOx urban	g NOx	0.468	1.010	1.270	1.010	1.350	0.805	0.556	3.000
CO total	g CO	0.243	5.930	7.580	0.115	8.160	35.500	19.700	0.694
CO urban	g CO	0.132	5.870	7.560	0.109	0.148	27.500	19.700	0.510
PM10 total	mg PM10	58.4	9.5	3.05	219	255	460	274	53.2
PM10 urban	mg PM10	43.1	3.21	1.92	218	226	431	273	47.3
Energy Embodied	MJ LHV	12.7	4.41	5.04	4.53	7.09	8.26	28.2	36.2

Table 6.17
Tailpipe emissions per km for diesel and ethanol

Combustion	Units	LS diesel	Ethanol
Greenhouse	kg CO_2	0.719	0.000 (0.439 for ethylene derived ethanol)
NMHC total	g HC	0.900	0.733
NMHC urban	g HC	0.900	0.733
NOx total	g NOx	10.170	8.691
NOx urban	g NOx	10.170	8.691
CO total	g CO	2.480	3.141
CO urban	g CO	2.480	3.141
PM10 total	mg PM10	380.00	285.00
PM10 urban	mg PM10	380.00	285.00
Energy Embodied	MJ LHV	0	0

Table 6.18
Summary of emissions per km for diesel and ethanol

		LS diesel	Ethanol azeotropic (molasses - Sarina exp.system boundary)	Ethanol azeotropic (molasses - Sarina-Economic Allocation)	Ethanol anhydrous (wheat starch waste - Bomaderry)	Ethanol azeotropic (wheat)	Ethanol azeotropic (wheat) fired with wheat straw	Ethanol azeotropic (woodwaste)	Ethanol azeotropic (ethylene)
Greenhouse	Precombustion	0.2060	0.4340	0.7530	0.3820	0.6910	0.3440	0.0826	1.0300
Greenhouse	Combustion	0.7190	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.4393
NMHC total	Precombustion	0.6090	0.1330	0.1180	0.0393	0.7200	9.2900	5.7300	5.9400
NMHC total	Combustion	0.9000	0.7325	0.7325	0.7325	0.7325	0.7325	0.7325	0.7325
NMHC urban	Precombustion	0.2920	0.0941	0.1020	0.0246	0.0977	8.6600	5.7200	5.1600
NMHC urban	Combustion	0.9000	0.7325	0.7325	0.7325	0.7325	0.7325	0.7325	0.7325
NOx total	Precombustion	1.0800	1.3300	1.3200	1.0400	3.0800	2.5300	0.5800	3.4400
NOx total	Combustion	10.170	8.690	8.690	8.690	8.690	8.690	8.690	8.690
NOx urban	Precombustion	0.468	1.010	1.270	1.010	1.350	0.805	0.556	3.000
NOx urban	Combustion	10.170	8.690	8.690	8.690	8.690	8.690	8.690	8.690
CO total	Precombustion	0.2430	5.9300	7.5800	0.1150	8.1600	35.5000	19.7000	0.6940
CO total	Combustion	2.4800	3.1409	3.1409	3.1409	3.1409	3.1409	3.1409	3.1409
CO urban	Precombustion	0.1320	5.8700	7.5600	0.1090	0.1480	27.5000	19.7000	0.5100
CO urban	Combustion	2.4800	3.1409	3.1409	3.1409	3.1409	3.1409	3.1409	3.1409
PM10 total	Precombustion	58.40	9.50	3.05	219.00	255.00	460.00	274.00	53.20
PM10 total	Combustion	380.00	284.99	284.99	284.99	284.99	284.99	284.99	284.99
PM10 urban	Precombustion	43.10	3.21	1.92	218.00	226.00	431.00	273.00	47.30
PM10 urban	Combustion	380.00	284.99	284.99	284.99	284.99	284.99	284.99	284.99
Energy Embodied	Precombustion	12.70	4.41	5.04	4.53	7.09	8.26	28.20	36.20

6.3.3 Uncertainties

We use the uncertainty estimates given by Beer et al. (2000) on the basis of the tailpipe emissions to estimate the uncertainties associated with the above results to be as given in Table 6.19.

Table 6.19
Estimated one standard deviation uncertainties (in percent) for hydrated ethanol emissions

	g/MJ	g/t-km	g/p-km
CO_2	15	15	13
NMHC	45	17	73
NOx	21	8	35
CO	40	36	46
PM10	46	45	46

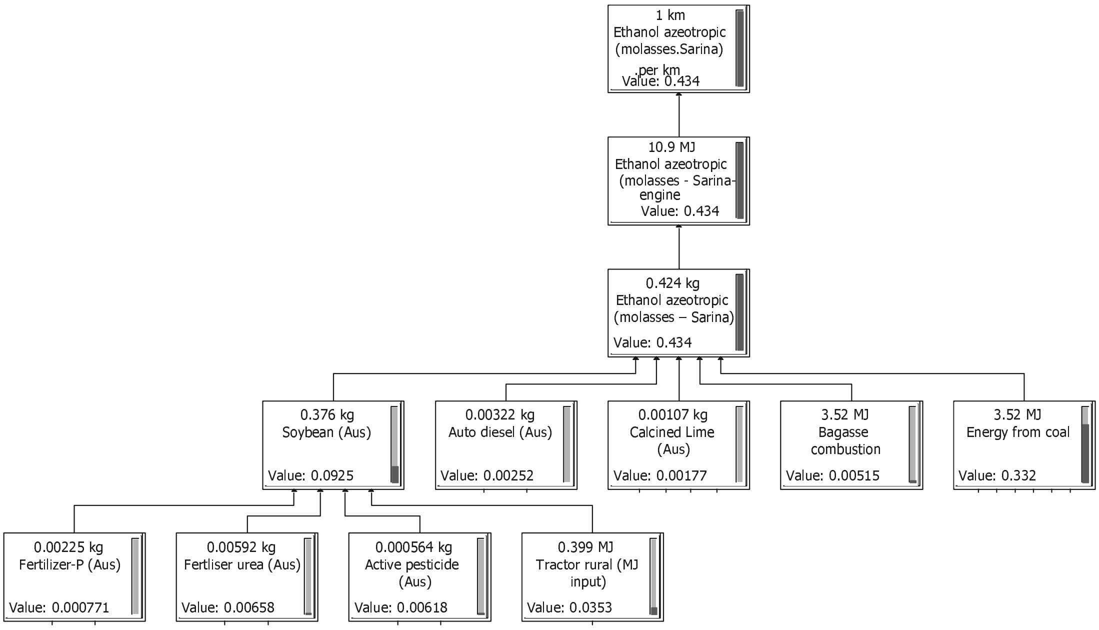

Figure 6.5
Exbodied greenhouse gases emissions (kg CO_2eq) from ethanol (from molasses based on Sarina plant and using expanded system boundary allocation) production and processing and use in vehicle

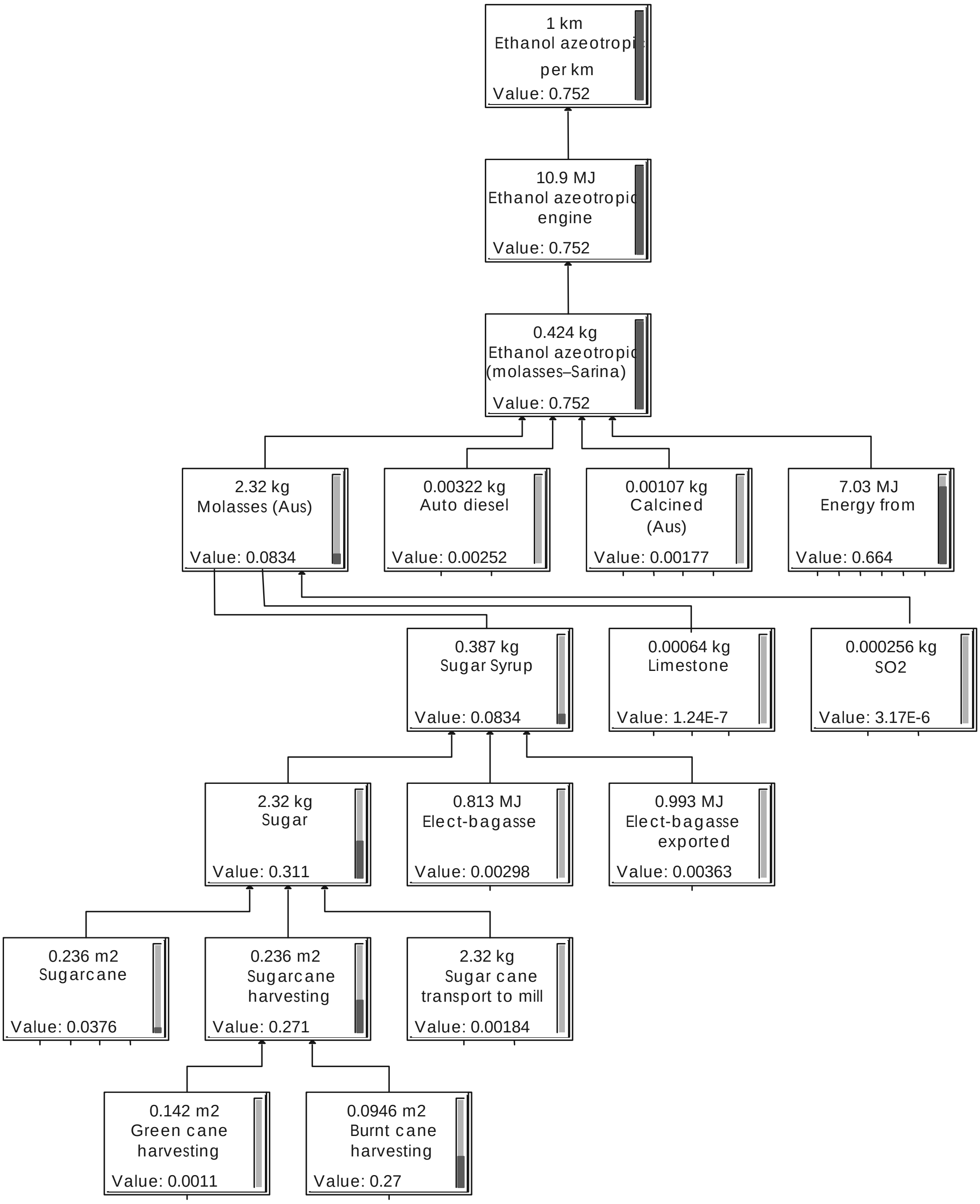

Figure 6.6
Exbodied greenhouse gases emissions (kg CO_2eq) from ethanol (from molasses based on Sarina plant and using economic allocation) production and processing and use in vehicle

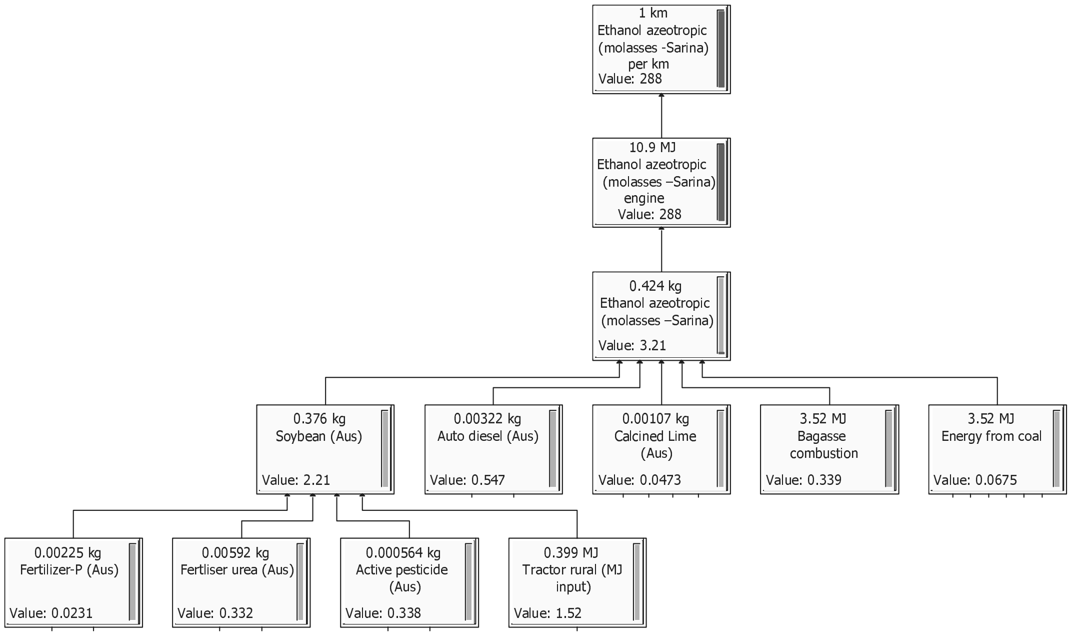

Figure 6.7
Exbodied particulate matter (mg - urban) from ethanol (from molasses based on Sarina plant and using expanded system boundary allocation) production and processing and use in vehicle

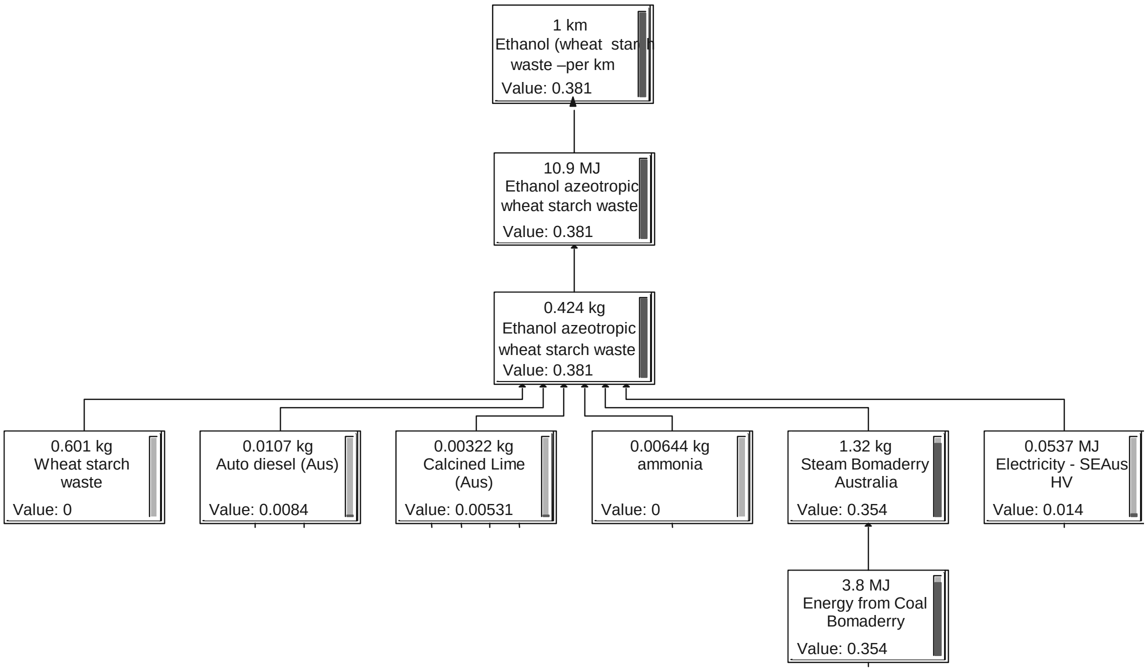

Figure 6.8
Exbodied greenhouse gases emissions (kg CO_2eq) from ethanol (from wheat starch waste based on Manildra plant) production and processing and use in vehicle

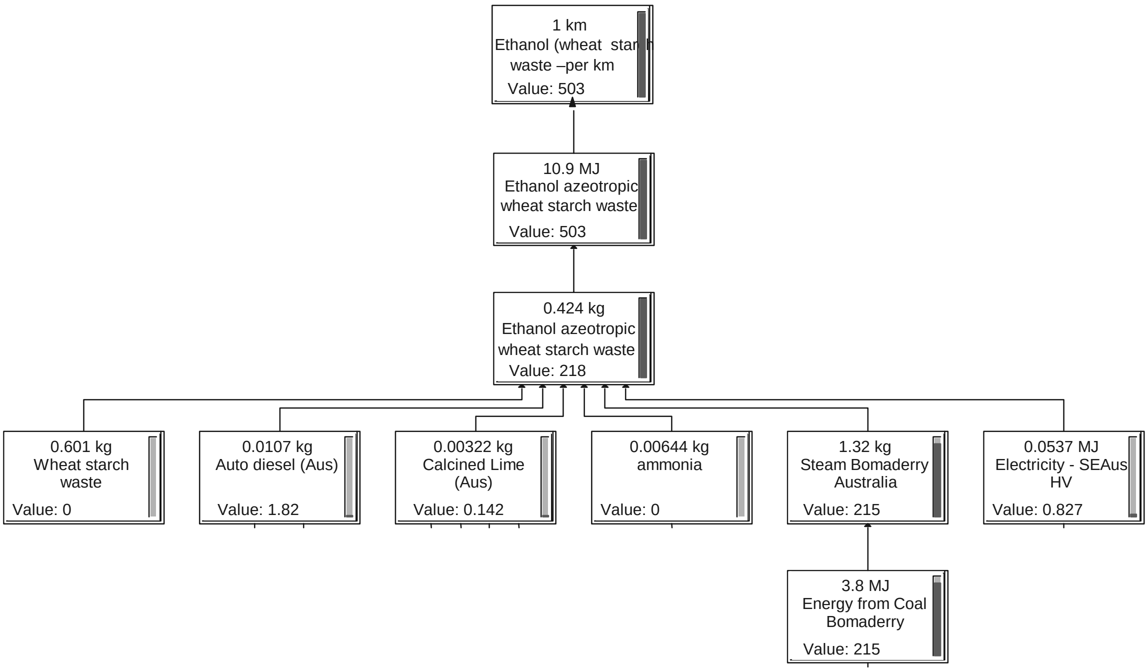

Figure 6.9
Exbodied particulate matter (mg - urban) from ethanol (from wheat starch waste based on Manildra plant) production and processing and use in vehicle

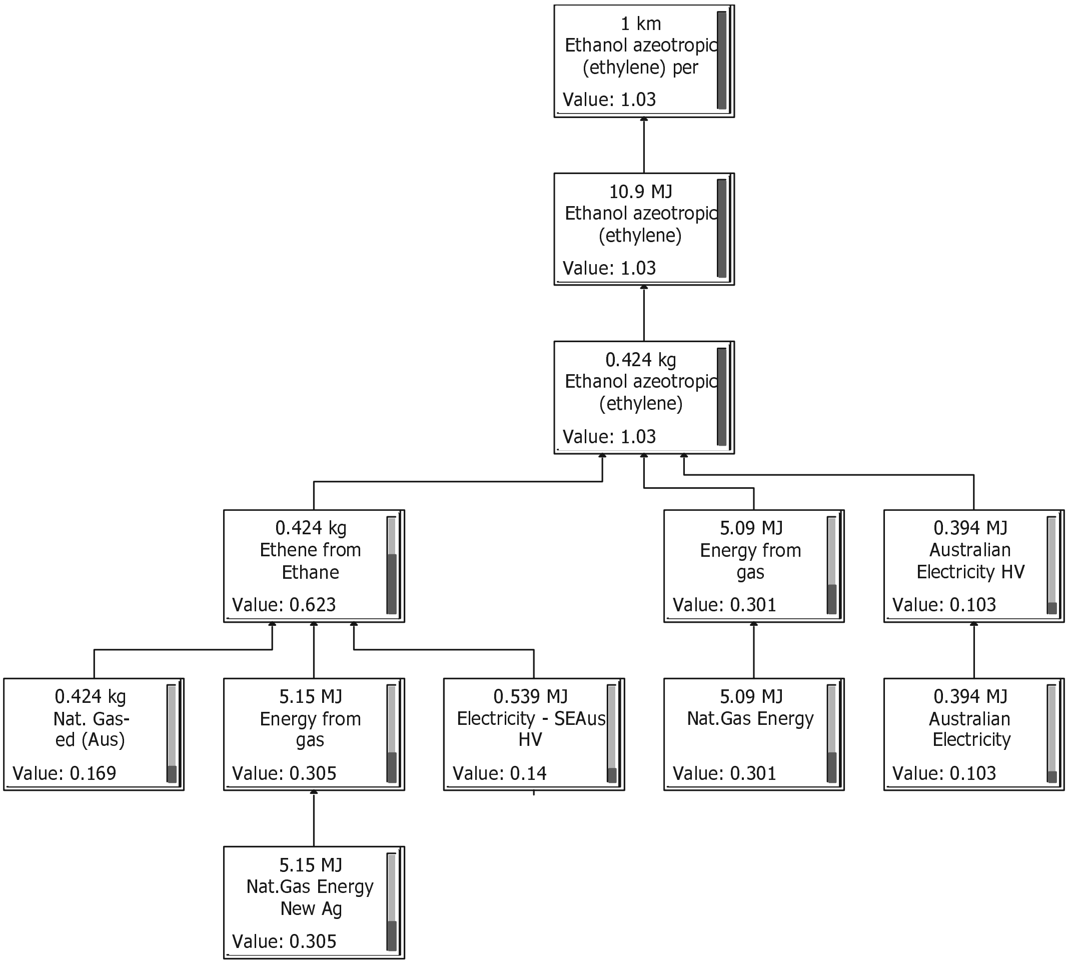

Figure 6.10
Exbodied greenhouse gases in the production of ethanol via ethylene

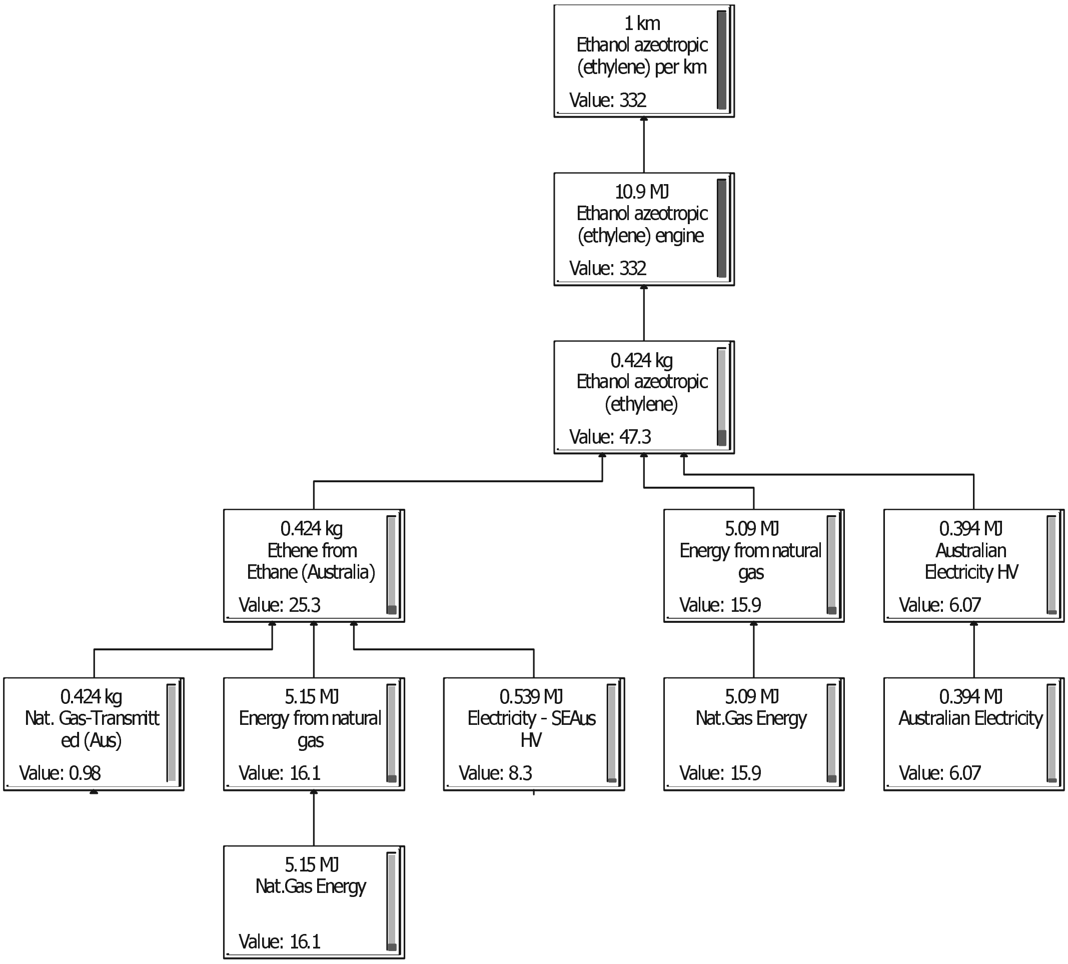

Figure 6.11
Exbodied particulate matter in the production of ethanol via ethylene

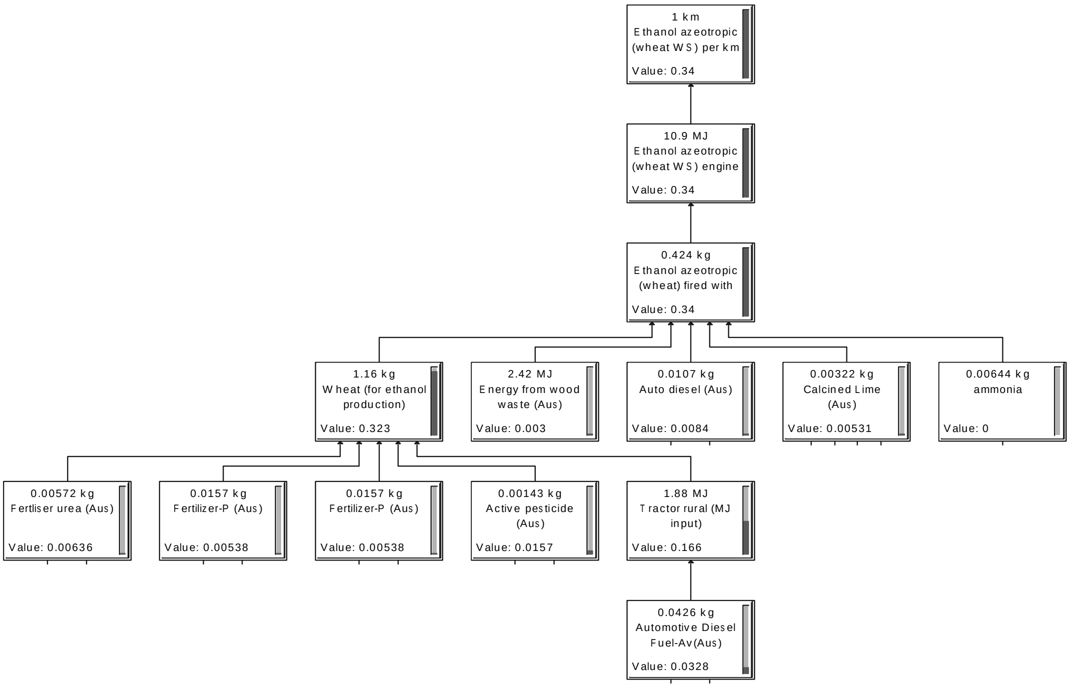

Figure 6.12
Exbodied greenhouse gases in the production of ethanol from wheat using wheat straw for energy

6.4 *Viability and Functionality*

CADDET (1998) notes that third generation ethanol buses have a higher compression ratio (24:1) than the standard diesel engine (18:1) and are equipped with turbo chargers and intercoolers. The third generation fleet also runs with oxidation catalysts. In general, ethanol buses have enlarged holes for the fuel injector, modified injection timing, and increased fuel pump capacity. Gaskets and filters need to be alcohol-resistant. In addition, because ethanol has a tendency to dissolve the oil film on greased metal surfaces, castor oil should be used for fuel pump lubrication. Earlier generations of ethanol buses sometimes emitted an acetic acid smell. The cause was unburned fuel converted into acetic acid in the catalyst and emitted with the exhaust.

On 1 December 2000 Ventura Bus Lines introduced the first two totally renewable fuelled buses into Australia (Figure 6.13). These buses are claimed to operate on 100% ethanol, though as indicated in Table 6.2, it would be more accurate to state that the buses operate on 95% ethanol (by volume) or 90% ethanol (by weight). The ethanol used by Ventura is made from molasses, a by-product of sugar milling by CSR Distilleries. The ethanol is produced at Sarina in the sugar belt of Queensland, shipped to Yarraville for refining, then delivered to the South Oakleigh Depot in the same fashion as diesel. Their web site (www.venturabus.com.au/ven-environmental.html) states:

> **Long Term Supply of Ethanol**
> As ethanol is the base of so many household products, such as Deodorants, Alcoholic Spirits, Methylated Spirits etc, its long term supply is very stable. Therefore there is no issue with future supply of ethanol and costs remain constant as new materials for fermentation are commercialised. Also there is no correlation with the likely substantial escalation of oil prices, as may occur with LPG.
> **Performance of the Ethanol Buses**
> Our customers are aware of the alternative fuel through signage on the buses, promotional literature and our web site editorial. We receive at least one telephone / email or letter each day supporting our recognition of the limited supply of fossil fuel and increasing harmful greenhouse gases. Our Bus Drivers are keen to drive these buses, the responsiveness is better than our newest Euro2 buses and the engine is marginally quieter. The morning bus start-up crews report a huge advantage in starting the ethanol buses compared to the fumes from the modern low emissions Euro2 engines. Given that the engine is so similar to the diesel engine our maintenance staff are happy with the vehicles.
> **The Outlays**
> With a lower energy rating of ethanol than diesel the consumption is much greater than diesel, however after a 20-c/L Commonwealth Government Diesel and Alternative Fuel Grant the operating cost is very similar to the diesel bus. With the assistance of the Commonwealth Vehicle Alternative Fuel Conversion Program the ethanol buses are similar to the current standard Euro3 buses. Ventura has installed a customised fuelling station for the more flammable and corrosive ethanol storage and ethanol pumping, which could cater for another 30 ethanol buses.

There is substantial difference between the Australian experience (based on European technology) and the US experience. The Los Angeles County Municipal Transport Authority (LACMTA, 1999) note that:

> The use of alcohol fuel for transit bus applications was tested by a few transit agencies in the late 1980’s and early 1990’s with less than desirable results. Methanol and ethanol have a very low cetane number, which makes it difficult to compression ignite. Several approaches have been pursued for converting diesel engines to alcohol operation, including conversion to spark ignition, increasing the cetane number with additives, using a dual-fuel system, and direct injection assisted by glow plugs. Several manufacturers developed experimental and prototype heavy-duty methanol engines, however the Detroit Diesel 6V-92 engine has been the only alcohol fuelled engine certified for transit applications.

Figure 6.13
Ethanol bus currently used by Ventura Bus Lines in Melbourne

> The LACMTA and other transit authorities experienced high rates of engine failure and poor engine reliability with their fleet of methanol buses. LACMTA methanol engines required rebuild at intervals of less than 45,000 miles, while comparable diesel engines needed to be rebuilt at intervals of about 135,000 miles. The LACMTA converted the methanol buses to ethanol in 1995/96 in an effort to improve engine reliability. The ethanol engines failed at rates similar to the methanol buses resulting in the decision to convert the entire fleet to diesel as the alcohol engines failed. As of late December 1998, the original alcohol fleet of 333 buses had been reduced to approximately 45 operational buses.
>
> The poor performance and high operating cost of alcohol buses has also resulted in other transit authorities converting their alcohol buses to diesel fuel. Presently, no domestic transit agency has any methanol or ethanol buses on order, and there are currently no certified methanol/ethanol engines available for heavy-duty bus applications.

6.4.1 Ethanol distribution

Difficulties with the distribution of neat ethanol or ethanol blends arise primarily from the solvency effects of ethanol and from ethanol’s affinity for water. Ethanol is capable of dissolving substances accumulated in pipelines, storage tanks and other components of the distribution system, thus introducing impurities into the fuel. These substances are insoluble in gasoline. Ethanol's affinity for water can result in phase separation of blended alcohol/gasoline fuels, resulting in engine damage or poor vehicle performance. Phase separation is a function of water content, ethanol content, temperature and properties of the fuel. Quality controls for dealing with these issues have been developed over the past 23 years in the United States and Brazil.

Most US distribution is inland, with greater use of ‘dry’ pipelines and systems facilitating the handling of oxygenated fuels. In the USA, ethanol is mostly produced in mid-west farm states, by around 50 commercial scale plants. It is shipped by rail car or truck, rather than by pipeline (the least expensive mode), because of the solvency effect problems identified above. Blending occurs in the tanker truck at the distribution terminal prior to distribution to service stations.

6.5 Health and OHS

6.5.1 Production and transport

The ethanol used in Australia is manufactured from biomass from fermentation of sugar derived from grain or sugar crops. There are research activities to examine biomass via the utilisation of the non-sugar lignocellulosic fraction of crops. Production of these feedstock crops would result in a range of particle and air toxic emissions.

Feedstock transport to the ethanol production facility results in a range of particle and air toxic emissions. Emissions of particulate matter and air toxics could be expected from the ethanol production process. The process includes high temperature cooking and fermentation, which emits acetaldehyde.

Particulate Matter
The LCA estimates for ethanol urban precombustion (truck) PM10 emissions are:

- Wheat: 226 mg/km
- Wheat WS: 431 mg/km
- Wheat starch waste: 235 mg/km
- Molasses (expanded systems boundary): 3 mg/km
- Molasses: 2 mg/km
- Woodwaste: 273 mg/km
- Ethylene: 47 mg/km

The LSD estimate is 43 mg/km. Ethanol urban precombustion (truck) PM10 emissions range from substantially lower to higher than LSD emissions depending on the feedstock.

Air Toxics
The LCA estimates for ethanol urban precombustion (truck) NMHC emissions are:

- Wheat: 0.098 g/km
- Wheat WS: 8.66 g/km
- Wheat starch waste: 0.026 g/km
- Molasses (expanded systems boundary): 0.094 g/km
- Molasses: 0.102 g/km
- Woodwaste: 5.72 g/km
- Ethylene: 5.160 g/km

The LSD estimate is 0.292 g/km thus ethanol urban precombustion (truck) NMHC emissions range from substantially lower to substantially higher than LSD emissions depending on the feedstock.

The public health effects of air toxics will be mainly associated with combustion emissions in large urban centres. An accompanying disk to this report provides details of air toxics emissions from upstream activities.

6.5.2 Use

Alcohol does not contain sulfur atoms. An increase in the alcohol content of a fuel will thus automatically reduce emissions of sulfur dioxide. (Vehicles running on 100 per cent alcohol could emit a very small amount of sulfurous compounds via combustion of the lubricating oil).

NO_x emissions from ethanol are lower than from diesel, even without a catalytic converter. This is evident in the results of the US ethanol fleet given in Table 6.1 and from the results in Table 6.13 and 6.17.

Boström et al. (1996) examined the health risks from ethanol used as a bus fuel. They found the health risks associated with ethanol to be less than those associated with diesel. Nevertheless, in their study the emissions of butadiene and NO_2 from ethanol buses were such as to exceed guideline values. They note, however, that improved catalyst technology, especially exhaust gas recirculation, will decrease emissions of NO_2 in future generations of vehicles.

Particulate matter

The LCA estimate for ethanol combustion (truck) PM10 emissions of 285 mg/km (for all feedstocks) is less than the LSD estimate of 380 mg/km.

Air Toxics

VOCs play a role in the formation of photochemical smog. Some VOCs produce a detectable odour; others are carcinogenic. Exhaust emissions of VOCs from alcohol vehicles consist mainly of unburnt ethanol. Also, comparisons of exhaust emissions of VOCs from different vehicles, or the same vehicle in different tests, should be interpreted cautiously, as results can be influenced by a wide range of specific fuel and vehicle factors.

Aldehyde (acetaldehyde and formaldehyde) emissions from ethanol are higher than LSD due to the high emissions of acetaldehyde. (Ahlvik and Brandberg, 2000)

Motor vehicle emissions data indicates that the use of ethanol results in substantial reductions in air toxics emissions. Substantial reduction in benzene, 1,3 butadiene, refuelling vapours and particles would occur, while formaldehyde would be emitted at levels similar to gasoline vehicles. However, acetaldehyde emissions would increase substantially. (USEPA, 1993)

The LCA estimate for ethanol combustion (truck) NMHC emissions of 0.733 g/km (for all feedstocks) is similar to the LSD estimate of 0.900 g/km.

6.5.3 Summary

Ethanol upstream emissions of particles and NMHC range from lower to higher than LSD emissions depending on the feedstock. Ethanol tailpipe emissions of particles and NMHC for all feedstocks are marginally less than LSD. Limited tailpipe emissions data indicate that ethanol is likely to reduce benzene and 1,3 butadiene emissions compared with LSD, formaldehyde emissions would be similar, while acetaldehyde emissions would increase substantially.

No comparative emissions data for ethanol and LSD has been identified for:

- polycyclic aromatic hydrocarbons (PAH)
- toluene
- xylene.

6.6 OHS Issues

Ethanol in solution is hazardous according to Worksafe Australia, with high flammability, moderate toxicity, and is a moderate irritant.

Occupation exposure of drivers to diesohol vapours during HDV refuelling was assessed by Workcover in 1992 (NSW Workcover Authority 1999). Normally refuelling is conducted by keeping the fuel dispensing nozzle in the automatic mode with only the last 10-12 litres added manually. The drivers are normally only exposed to diesohol vapours during manual refuelling. The results indicate that levels of diesohol vapours are low and do not represent a significant health hazard to drivers.

The flash point of the emulsion becomes that of alcohol when the alcohol content exceeds 5% of the volume.

Ethanol fuels increases permeation of elastomers that have been used in automotive applications (e.g.: rubber hoses, plastic fuels tanks). Research is required to quantify the permeation impacts of ethanol. (Harold Haskew & Associates. Emission Effects (Permeation) of ethanol in Gasoline. Harold Heskew & Associates Inc. 2001. www.arb.ca.gov)

The OHS issues in the lifecycle of ethanol are covered by a range of State and Commonwealth occupational health and safety provisions. While there will be different OHS issues involved in the production process associated with ethanol compared with LSD, no OHS issues unique to the production and distribution of ethanol have been identified.

6.7 Vapour Pressure Issues

Diesel fuel has very low vapour pressure, but the addition of alcohol to diesel (for example diesohol) creates a fuel with a vapour pressure similar to that of gasoline. While modern gasoline vehicles have some evaporative emission control measures, diesel vehicles do not. Evaporative emissions may be a significant problem from unmodified vehicles using ethanol based fuels, but this needs to be tested.

To contain evaporative emissions from vehicles using alcohol fuel, measures may need to be implemented to control fuel vapour pressure, and control evaporative emissions from diesel fuel vehicles.

6.8 Environmental Issues

Ethanol is not persistent in the environment. Virtually any environment supporting bacterial populations is believed to be capable of biodegrading ethanol. Atmospheric degradation is also expected to be rapid. Provided that the source of ethanol is not fossil fuels then it satisfies ESD principles.

The present use of ethanol is that of a niche fuel. As such, there are no issues related to sustainability. However, if ethanol were to become a dominant fuel then it would have to be based on ligno-cellulose. Foran and Mardon (1999) contains details of ethanol and methanol production technology and supply constraints, and of the environmental consequences of both crop and fuel production processes. They claim that if ligno-cellulosic ethanol production is used then it would be possible to establish biomass plantations over the next 50 years that meet 90% of Australia’s oil requirements, and specifically to supply all transportation fuels. To do this using ethanol requires biomass production to cover up to 19 million hectares of Australia’s croplands and high rainfall pasture zones. Their modelling approach envisages substantial environmental benefit. In addition to the reduction in greenhouse gas emissions (up to 300 million tonnes by the year 2050), the large scale planting of tree and shrub crops as ethanol feedstock would help to control dryland salinity and associated problems.

Bio-dunder

Bio-dunder (commonly known as dunder) is a by-product of the distilling of ethanol at the CSR Distillery at Sarina. It was once considered a poison, but research into potential uses developed a product that is used by many farmers in the district as a fertiliser and soil conditioner.

Dunder application has been criticised as being the cause of poor water quality in the region. A six-year study concluded that the impacts from application of dunder could not be separated from other agricultural impacts (www.sunfish.org.au/Fishkills/Fishkills.htm). The difficulty in separating the impacts of dunder is perhaps most obvious through observations of creeks and rivers in other regions. Dunder is not used in the Herbert region and yet water quality and habitat impacts are similar.

We also note that Table 6.2 indicates that ethanol when used as a heavy vehicle fuel contains 2.3% MTBE (methyl tertiary butyl ether). This additive has been extensively examined in the US (National Science and Technology Council, 1997) where 15% MTBE (or 7.5% ethanol) was added to petrol to achieve the 2.7% oxygen content required under the Clean Air Act. The use of MTBE is no longer permitted because of concerns in relation to health as a result of groundwater, and hence drinking water, contamination by MTBE.

6.9 Expected Future Emissions

Arcoumanis (2000) developed a model that examines a given alternative fuel relative to the reference diesel engine (Euro2) in terms of a specific regulated pollutant. A value of 1 implies identical performance to the low sulfur diesel/Euro2 combination. A value greater than 1 implies inferior performance, whereas a value less than 1 indicates superior performance.

Table 6.20 lists the estimated emissions factors for ethanol. The columns in bold represent the standards relative to the Euro2 standard. The adjacent column gives the expected performance of ethanol. The estimates of Arcoumanis (2000) indicate that ethanol can be expected to meet all future Australian Design Rules for all pollutants except total hydrocarbon, which may be slightly above Euro3 and Euro4 standards.

Table 6.20
Estimated emission factors for ethanol under future technologies

Technology	**CO**	**CO**	**THC**	**THC**	**NOx**	**NOx**	**PM**	**PM**	**CO_2**	**LCA CO_2**
Euro2	**1.0**	1.1	**1.0**	1.1	**1.0**	0.8	**1.0**	0.6	**1.0**	0.9
Euro3	**0.53**	0.5	**0.6**	0.7	**0.71**	0.6	**0.67**	0.4	**1.0**	0.9
Euro4	**0.38**	0.4	**0.42**	0.5	**0.5**	0.4	**0.2**	0.1	**1.0**	0.9

6.10 Summary

6.10.1 Advantages

- As a renewable fuel, ethanol produces significantly less fossil CO_2 than conventional fuels.
- Particle emissions are lower with ethanol than with conventional fuels.
- 1,3 butadiene and benzene levels decrease as the ethanol concentration increases.
- Ethanol contains less sulfur than conventional fuels.

6.10.2 Disadvantages

- The chemical emulsifiers and ignition improvers used to blend ethanol may contain harmful chemicals.
- There are higher emissions of formaldehyde and acetaldehyde from ethanol vehicles than from diesel vehicles.
- There may be an odour problem.