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PRIMARY ENERGY AND NET GREENHOUSE GAS EMISSIONS FROM BIODIESEL MADE FROM NEW ZEALAND TALLOW - CRL ENERGY REPORT 06-11547b

1 Executive Summary

One of the aims of the government's Biofuels Sales Obligation is to reduce the emission of greenhouse gases. There is potential for this to be achieved through the use of biofuels. However, there is also usually fossil fuel consumed in producing biofuels, which dilutes this advantage. This study, commissioned by EECA, provides a life cycle assessment of one of the more attractive biofuel options for New Zealand, namely biodiesel derived from domestically produced tallow.

This life cycle assessment involved a primary energy and greenhouse gas emissions inventory of the production of tallow-derived biodiesel in New Zealand, from the farmer's paddock to the exit gate of the biodiesel plant. The results of this analysis found tallow-derived biodiesel to have a primary energy input/output of 0.50. This compares to an energy input/output of 1.19 for fossil diesel (at a similar point in the supply chain). Combining these, the use of tallow-derived biodiesel provides a 58% decrease in primary energy.

A similar analysis for greenhouse gas emissions found the domestic production and use of biodiesel from domestically-sourced tallow to have around 51% of the global warming potential of fossil diesel, that is, a 49% decrease over the use of fossil diesel.

Table 1 provides a breakdown of the energy and greenhouse gas emissions associated with the farm to biodiesel production plant life cycle. Rendering accounts for 60% of the total primary energy and 46% of the global warming potential of tallow-derived biodiesel.

Table 1: Primary Energy and Greenhouse Gas Emissions for Tallow-Derived Biodiesel

Stage in Process	Primary Energy MJ/kg biodiesel	As a Percentage of Total	Greenhouse Gas Emissions kgCO_2eq/kg of biodiesel	As a Percentage of Total
Farming and meat processing	1.0	5%	0.77	39%
Rendering	13.9	60%	0.92	46%
Transport to plant	0.3	1%	0.02	1%
Biodiesel production	7.7	34%	0.25	13%
Glycerine credit	-3.0	-	-0.26	-
Total with glycerine credit of 13%	**20.0**	**100%**	**1.75**	**100%**

Note: totals provided may be slightly different to the sum of the components due to rounding.

Sensitivity analysis explored a number of extreme implementation scenarios – mainly related to different by-product values and the different economic allocation that resulted – and found that the reductions in primary energy and greenhouse gas emissions realised for tallow-derived biodiesel decreased, but still provided a clear advantage over the use of fossil diesel. Both the input/output energy ratio and greenhouse gas emissions were found to be reasonably sensitive to the price of tallow due to the relatively high amount of energy expended during rendering – a small increase in the price of tallow can provide significant changes in the energy allocated to it.

Similarly, the greenhouse gas emissions were found to be sensitive to the price of the render material because of the economic allocation of farming emissions.

The transport of tallow to the biodiesel plant is a minor component of the LCA (1% of energy and of greenhouse gases). Hence the analysis provided is applicable to virtually any plant location.

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Contents

List of Abbreviations

Energy and Power

J	joule	basic unit of energy	Factor
kJ	kilojoule	1,000 joules	E3
MJ	megajoule	1,000,000 joules	E6
GJ	gigajoule	1,000,000,000 joules	E9
TJ	terajoule	1,000,000,000,000 joules	E12
PJ	petajoule	1,000,000,000,000,000 joules	E15

W	watt	basic unit of power = 1 joule per second
kW	kilowatt	1,000 watts
kWh	kilowatt-hour	3.6 MJ

Others

ha	hectare	10,000 square metres
kg	kilogram	
t	tonne	1,000 kg
ℓ	litre	
ai	active ingredient	
s.u.	stock unit	
CW	carcass weight	
LW	live weight	
BD	biodiesel	
FD	fossil diesel	
GHG	greenhouse gas	
LCA	life cycle assessment	
MBM	Meat and bone meal	
GWP	Global warming potential	

EECA	Energy Efficiency and Conservation Authority
MAF	Ministry of Agriculture and Forestry
MED	Ministry of Economic Development

Conversions

1 ha = 2.47 acres
1 kJ = 239 calories
1 kW = 1.34 horse-power (HP)

Glossary

Carcass weight

The weight of a freshly dressed animal after slaughter.

Consumer energy

Energy in the state consumed by final users.

Direct energy

Directly added consumer energy, typically in a metered form – mainly in the form of diesel and electricity in this study.

Dressed carcass

The meat and bones of the animal. It excludes the head, feet, hide or pelt, and internal organs.

Dressing out percentage

The carcass weight expressed as a percentage of the pre-slaughter live weight.

Embodied energy

Energy that is used to produce and deliver a product, often used in relation to capital items.

Greenhouse gas emission factors

Emission factors based on consumed energy that combine the global warming potential (calculated over 100 years) of carbon dioxide, methane and nitrous oxide in terms of carbon dioxide equivalents. The emission factors used here (detailed in Appendix E) include fugitive (non-combustion) and indirect emissions estimated for the primary energy.

Indirect energy

Energy added to the system in the form of products such as fertiliser and agrichemicals recognised for their non-energy-related function. For example, fertiliser is added to promote plant growth, not for its energy content.

Live Weight

The weight of the living animal.

Primary energy

MED defines primary energy as energy as it is first obtained from natural sources. It includes upstream energy used to produce electricity, to extract and refine fossil fuels and to manufacture chemicals. In this study, it does not include the solar energy that is transformed through grass into animal fat.

2 Introduction

Biodiesel is a generic name for fuels obtained by the esterification of a vegetable oil or animal fat. An alcohol of low molecular weight, such as methanol or ethanol, is typically used for this process. For New Zealand, the production of biodiesel from domestic tallow appears to be one of the more attractive options for the early provision of biofuels to the New Zealand market. There is also sufficient feedstock of domestic tallow to meet the government's proposed biofuels sales obligation to 2012[1].

One of the reasons for the government's drive to greater use of biofuels is due to the expected lower net greenhouse emissions that would result, the combustion of biofuel releasing carbon that has recently been captured from the atmosphere rather than releasing fossil-stored carbon. This "short-cycled" carbon does not add to the greenhouse effect. However, there is normally other fossil energy involved in the supply chain that produces biofuels. For biodiesel from tallow, there is "fossil energy" consumed in the farming that produces the animals, in processing the animals, in the production of biodiesel and in the transport of products. This study has been conducted to quantify the amount of fossil (and some renewable) energy that is involved and the resulting greenhouse emissions – that is, carry out a life cycle assessment (LCA) for biodiesel from domestic tallow in New Zealand. The results are then compared to those for fossil diesel fuel.

The LCA and reporting for tallow-derived biodiesel has been divided into the following sections:

- Agricultural Production (including meat processing, Section 4).
- Biodiesel Production (Section 5).

Section 6 details the LCA of fossil diesel and Section 7 compares the LCA of tallow-derived biodiesel to that of fossil diesel.

3 Life Cycle Assessment Background

A true LCA requires every input and output to be assessed and traced from their raw resources through to final disposal. There can be thousands of inputs and outputs involved even in a moderately simple system and therefore it is necessary to focus on those that are significant. This focus is aided by defining appropriate *system boundaries*: that is, defining the boundaries within which the study was confined.

There are two main analysis methods used for LCAs: "*system boundary expansion*" and "*allocation method*". In the case of tallow-derived biodiesel, system boundary expansion would consider what the flow-on effect of the new use of tallow is, compared to business as usual, and include consideration of any new products that are also produced, such as glycerine. The system boundary expansion method is preferred by ISO 14040, a standard for LCAs. However, it is not practical to apply a system boundary expansion approach to tallow-derived biodiesel in this project – there is insufficient information to calculate a system boundary expansion for the business-as-usual use of tallow as feedstock for soap manufacture, among others. However, the results from boundary expansion conducted by Beer et al. (2001) have been considered in the discussion.

Instead, the allocation method has been used for this study. The allocation method allocates energy and emissions across co-products according to some meaningful measure. Economic allocation has been used for farm and meat product processing allocation, in keeping with the norm for farm product-related LCA analysis. As the amount allocated to low value by-products can vary dramatically with small price changes, sensitivity analyses were conducted and reported to determine the effect of these on the final result. Energy allocation has been used for energy systems, as is also the norm.

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[1] *Enabling Biofuels, Biofuel Supply Options*, Hale and Twomey, 2006.

There does not appear to be a clear-cut allocation method for LCAs, to the point that Sheehan et al. (1998) note the subject is quite controversial. The result is that there can be study-to-study differences in system boundaries, allocation methods used and others, and these may lead to significant differences in results between studies, not to mention the differences that may arise due to variations in feedstock type, processes and others. For this reason it is important to provide reasonable detail of how the various energy and emission factors were derived. This is not conducive to providing an easily readable document and therefore this report provides summarised data in the forward sections, supported with further detail in appendices.

By way of an introduction to the language of LCAs: LCAs are effectively inventories of resource inputs, product outputs and energy flows. They include accounting for *direct energy*[2] inputs such as diesel and electricity, *indirect energy*[3] inputs such as fertiliser and agrichemicals and *embodied energy*[4] in capital items. LCA analysis tends to account for these in terms of their *primary energy*[5] values which include the sum of *consumer energy* (that energy available to the customer for work) plus the energy required for extraction, processing, transport, etc. *Greenhouse gas emission factors* combine the global warming potential (calculated over 100 years) of carbon dioxide, methane and nitrous oxide in terms of carbon dioxide equivalents. The emission factors used for this study (detailed in Appendix E) include fugitive (non-combustion) and indirect emissions estimated for the primary energy and applied to the consumer energy results to derive greenhouse gas emissions on a carbon dioxide equivalent basis.

Note that almost all studies work in lower heating values (LHV, or net calorific values) because this represents the useful heat available (allowing for the evaporation of steam). However, this study follows the convention used in New Zealand to use higher heating values (HHV, or gross calorific values) (MED, 2006b). This has the advantage that greenhouse gas (GHG) emission factors in New Zealand are normally relative to HHV (MED, 2006a). The difference in using LHV would be negligible when reporting energy input/output ratios as the results are almost identical.

4 Analysis of Agricultural Production

The main source of tallow is the fat from sheep and cattle. This section provides a summary of the assessment of the embodied primary energy and greenhouse gas emissions associated with rearing these farm animals. Further details are provided in Appendix A.

4.1 Embodied Energy

A farm model was developed using the Agriculture Research Group on Sustainability (ARGOS) database for the 2003/04 season. ARGOS is a group that provides expert-verified data on various farm types. Data was chosen to focus on conventional non-cropping farms.

An inventory analysis was carried out for the farm model (detailed in Appendix A) that accounted for:

- Diesel consumed.
- Electricity consumed.
- Agrichemicals – fertiliser and non-fertiliser (e.g., sprays, etc.).
- Purchased feed.
- Embodied energy in capital items.

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[2] That is, directly added energy, for processing, say, and typically in a metered form.

[3] That is, energy added to the system in the form of products recognised for their non-energy-related function. For example, fertiliser is added to promote plant growth, not for its energy content per se.

[4] That is, the energy that is used to produce and deliver a product.

[5] That is, an energy that reflects the energy inputs used to produce the energy product being considered, not only the consumer energy that is available for use. See the Glossary for a more specific definition.

This yielded a primary energy productivity for sheep meat of 13.3 MJ/kgCW and for cattle of 9.9 MJ/kgCW.

The year average livestock slaughter statistics between 2003 and 2005 (MAF, 2005) provide a split for sheep and cattle meat production of 44%:56%. Applying this, the average primary energy content of meat production (of which one output is tallow), was 11.4 MJ/kgCW.

It was assumed that the stock were transported 100 km between the farm and meat processing plant. The energy associated with cartage of the stock to the works was 0.14 MJ/kg *live weight*[6] based on diesel consumption of 1.41 MJ/t-km (Beer et al., 2001). Converted to a *carcass weight* (CW)[7] basis, using the proportion of sheep and cattle meat and their respective *dressing out percentages,*[8] resulted in a cartage energy value of 0.3 MJ/kgCW. Further conversion into primary energy did not change this value at the level of significance reported.

The primary energy related to meat processing was derived from energy consumption data (coal, gas and diesel) provided by Lovatt and Chadderton (1996) for the 1994/95 season (this is the last known comprehensive national study of energy use in New Zealand meat processing plants). This resulted in primary energy values for non-rendering meat plants of 0.7 MJ/kgCW for fuel (gas, diesel or coal) and of 2.2 MJ/kgCW for electricity use.

The results of agricultural production are summarised in Table 2 (note that, for all tables reported, the totals may not equal the sum of the individual components due to rounding off errors).

Table 2: Primary Energy Inputs to Farming and Meat Processing

	Energy Productivity MJ/kg carcass
Farming – Sheep	13.3
Farming – Cattle	9.9
Average farming – Meat[1]	11.4
Transport (100 km)	0.3
Meat processing	2.9
Total Farming & Meat Processing	**14.6**

[1] Weight based on the national slaughter statistics for sheep and cattle

The 14.6 MJ/kgCW figure requires splitting between the main product outputs of meat processing plants, these being meat, hides, offal and raw render material. An economic allocation was used, in keeping with the norms for farming allocation.

Personal communication with Steve Dunn (Rendertech) established that the render material price in New Zealand was from $0.0/kg to $0.09/kg. Using a value of $0.09/kg (assuming that the local market would move to the higher value given the new demand for tallow) and economic allocation results in a 0.94% allocation of farm energy and greenhouse gases to render material (the vast majority of the income coming from meat, hide/skin and offal). A full description of how the allocations were determined is included in Appendix A13. Niederl and Narodoslawsky (2004) found that in the UK rendered products accounted for 1.2% of meat

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[6] That is, the weight of the living animal.

[7] Carcass weight is a standard unit in farming and refers to the weight of a (dressed) carcass.

[8] That is, the dressed weight of the carcass (i.e., less head, viscera, etc.) relative to the live weight.

processing revenue, which shows good agreement. Beer et al. (2001) derived a somewhat higher figure of 3.6% for raw beef render material (compared with this study's finding that beef render material was 1.0% of the animals' value). On the basis of a 0.94% allocation, the primary energy allocated to raw render material is 0.14 MJ/kgCW.

This was converted to a per-kilogram of biodiesel basis by considering the tallow yields from stock and the biodiesel yield from tallow: rendered material yields are approximately 30 to 35% of animal live weight. Tallow yields from sheep and lambs are approximately 15 to 20% of the raw render material and cattle are approximately 20 to 25% (pers. comm. S. Dunn).

Table 3 details how these tallow yields were converted into a kilogram of carcass per kilogram of tallow basis, resulting in the figures of 7.5 kg of lamb carcass or 7.6 kg of cattle carcass per kilogram of tallow. Using the 44%:56% split for sheep and cattle meat production (discussed above), the national weighted average tallow yield is one kilogram of tallow per 7.6 kg of carcass. Therefore the 0.14 MJ/kgCW of farming and meat processing primary energy equals 1.0 MJ/kg tallow (7.6 x 0.14). Biodiesel yields from tallow are 1 kg tallow per kilogram of biodiesel (Hale & Twomey, 2006). On this basis farming and meat processing contribute 1.0 MJ/kg biodiesel to the total primary energy.

Table 3: Conversion of Tallow Yields

	Live weight (LW) kg	**Dressing out %**	**Carcass weight kg**	**Render material (32% of LW) kg**	**Tallow yields (% of render material)**	**Tallow kg**
Lamb	50	42%	21	16.0	17.5%	2.8
Cattle	500	55%	275	160.0	22.5%	36.0
Lamb			7.50	5.71		1.0
Cattle			7.64	4.44		1.0

4.2 Rendering

Lovatt and Chadderton (1996) also provided fuel and electricity use figures for New Zealand rendering plants, the difference between rendering and non-rendering plants being the fuel and energy consumed in the rendering process itself (assuming otherwise similar plant types). The (primary energy) converted values are 5.1 MJ/kgCW for fuel use and 2.0 MJ/kgCW for electricity. GHG emissions are 0.41 kgCO_2eq/kgCW from the fuel and 0.05 kgCO_2eq/kgCW from electricity, totalling 0.47 kgCO_2eq/kgCW (noting a slight difference in this total due to rounding).

Using the March 2006 price data from Meat and Livestock Australia,[9] the income from tallow was assumed to be 22% of the value of rendered lamb product and 28% of rendered beef product (the other product being meat and bone meal, MBM). The weighted average, using a 44%:56% split for sheep and cattle meat production, yields a 26% allocation to tallow. Combining the results for rendering provided above, using an economic allocation of 26% and using a national weighted average tallow yield of one kilogram of tallow per 7.6 kg of carcass and 1.0 kg tallow per kilogram of biodiesel (detailed in Section 4.1) provides a primary energy

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[9] Meat and Livestock Australia website. http://www.mla.com.au/NR/rdonlyres/A64B2323-D807-426D-B84B-55D3E01311B1/0/coproductspricetrendsApril06_march06prices.pdf.

result for rendering of 13.9 MJ/kg of biodiesel. Calculations using a similar procedure produced a greenhouse gas emission factor for biodiesel of 0.90 $kgCO_2$/kg of biodiesel.

4.3 Farm Greenhouse Gas Emissions

The greenhouse gas emissions considered in the analysis are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O).

One-hundred-year global warming potentials (GWPs) were used to convert emissions of each gas to a carbon dioxide equivalent, with CH_4 a factor of 21 higher than carbon dioxide and N_2O 310 times greater (MfE, 2006).

Methane is the main greenhouse gas emitted by livestock, at a rate of 10.6 $kgCH_4$/head/year for sheep and 56.3 $kgCH_4$/head/year for cattle (MfE, 2006). Table 4 provides the resulting carbon dioxide equivalent emissions for the farm model.

Table 4: Farm Methane Emissions

	kg CH_4 /head/yr	**s.u./head**	**kg CH_4 /s.u./yr**	**kg CO_2eq /s.u./yr**	**s.u./ha**	**kg CO_2eq /ha/yr**
Sheep	10.6	1.0	10.6	222.6	7.2	1,603
Cattle	56.3	6.0	9.4	197.1	3.1	611
Total					**10.3**	**2,214**

The Overseer® nutrient budget model (Wheeler et al., 2003) closely matched these methane emission estimates, deriving annual emissions of 2,290 $kgCO_2$eq/ha, providing confidence in the derived farm model results.

An economic allocation was used to proportion sheep emissions into the two products of meat production, at 78.2%, and wool, at 21.8%. Likewise cattle emissions were proportioned into meat production, at 83.2%, and grazing (the grazing of cattle from other farms for a weekly fee), at 16.8%. The farm model annual meat production was 115.8 kgCW/ha for sheep and 102.5 kgCW/ha for cattle. Combined, the annual methane emissions were 10.8 $kgCO_2$eq/kgCW for sheep and 5.0 $kgCO_2$eq/kgCW for cattle. These results are summarised in Table 5.

Table 5: Animal Methane Emissions

	kg CO_2eq /ha/yr	**Meat economic allocation**	**kg CO_2eq /ha/yr**	**kgCW /ha/yr**	**kg CO_2eq /kgCW**
Sheep	1,603	78.2%	1,253	116	10.8
Cattle	611	83.2%	508	103	5.0

Nitrous oxide emissions are associated with the use of fertiliser. The annual emission rate used for this analysis was 720 $kgCO_2$eq/ha, being that derived using Overseer® (Wheeler et al., 2003). This was proportioned between sheep and cattle on the basis of an average stocking rate of 70% sheep and 30% cattle. Using the same allocation methodology described for methane, annual nitrous oxide emissions were 3.4 $kgCO_2$eq/kgCW for sheep and 1.8 $kgCO_2$eq/kgCW for cattle.

Carbon dioxide emissions were calculated from a detailed farm inventory (see Appendix A.9). This found annual carbon dioxide emission to be 184 $kgCO_2$/ha. Again, this was close to the estimate derived using Overseer® of 169 $kgCO_2$/ha. Using the same allocation methodology described for methane, annual carbon dioxide emissions were 0.9 $kgCO_2$/kgCW for sheep and 0.4 $kgCO_2$/kgCW for cattle.

The farm greenhouse gas emission results are listed in Table 6.

Table 6: Farm Greenhouse Gas Emissions

Animal class	kg CO_2eq /kgCW			
	Methane	Nitrous Oxide	Carbon Dioxide	Total
Sheep	10.8	3.4	0.9	15.1
Cattle	5.0	1.8	0.4	7.2

Using the aforementioned 44%:56% split for sheep and cattle meat production, 7.5 kgCW per kilogram of tallow for sheep, 7.6 kgCW per kilogram of tallow for cattle, 1.0 kg of tallow per kilogram of biodiesel and 0.94% economic allocation, the allocated greenhouse gas emissions for farming are 0.77 $kgCO_2$eq/kg of biodiesel.

5 Biodiesel Production

This section summaries the assessment of the primary energy content and greenhouse gas emissions associated with the production of biodiesel. Further details are provided in Appendix B.

The main function of a biodiesel plant is the esterification of tallow (considered in this study) or other animal fats or vegetable oils into mono-alkyl esters – commonly known as biodiesel. This process is normally carried out using methanol in the presence of a catalyst. The intermediate product contains biodiesel in a solution with solids, unused methanol, catalyst and glycerine, among others. This product is neutralised (by the addition of mineral acid) and taken through a number of separating and washing steps before the biodiesel can be used in an engine. Unused methanol is also recovered in an evaporation recovery process.

Most references are for the esterification of vegetable oils. However, the process for esterification of tallow is the virtually same as that for the esterification of vegetable oils. The difference in physical properties between animal fat and vegetable oil (the most obvious being how fluid they are at room temperature) is primarily due to the degree of saturation[10] of base carbon chains. This "end" of the fat or oil molecule does not take part in the esterification reaction and does not have a significant effect on it.

For the analysis it was assumed that a biodiesel plant using tallow feedstock has the same energy and emissions characteristics as one using rapeseed and soybean feedstocks, although factors specifically concerning the production of biodiesel from tallow were used where these were available.

Considerable effort was required in deriving energy and greenhouse gas values for the production of methanol, as a literature search found large variations in these values and quite varying level of detail.

The greenhouse gas emissions that are associated with the production of biodiesel from tallow are primarily due to the source of the alcohol used in the process. Methanol is used in the

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[10] That is, how many double bonds are in the carbon chains. The higher the number, the more fluid the fat or oil and the lower the melting point.

majority of biodiesel plants and is typically derived from natural gas (and natural gas is a carbon-containing fossil fuel). Use of bioethanol or methanol derived from the gasification of biomass is possible, both of which would lessen the greenhouse gases emitted. However, the use of bioethanol is not yet common and "biomethanol" is not yet commercially available. Hence the methanol component of biodiesel production is pivotal to the LCA.

A value of 0.10 kg methanol/kg biodiesel was selected for the analysis, being the average of two studies: 0.11 kg/kg from Natural Resources Canada (2003); and 0.09 kg/kg from Sheehan et al. (1998).

Values provided in the literature for the primary energy content and greenhouse gas emissions for methanol were quite varied in the seven studies considered (Sheehan et al., 1998; Dreier et al., 1998; Beer et al., 2001; Natural Resources Canada, 2003; Mortimer et al., 2003; Nelson and Schrock, 2006; and Delucchi and Lipman, 2003). First principles were applied to derive a New Zealand best estimate of 0.114 MJ per MJ of biodiesel for primary energy input (4.56 MJ per kilogram of biodiesel based on a higher heating value energy density for biodiesel of 39.95 MJ/kg (Mittelbach and Remschmidt, 2004)). Greenhouse gas emissions for NZ methanol manufacture were assessed as 0.12 kg CO_2 equivalent per kilogram of biodiesel. Details of this derivation are provided in Appendix B.

A similar multi-study analysis was required to derive primary energy and greenhouse gas values for the overall esterification process: that is, for other chemicals involved in the process and for overall process energy requirements. This analysis (detailed in Appendix B) resulted in a New Zealand best estimate of 0.193 MJ per MJ of biodiesel for primary energy input (7.72 MJ per kilogram of biodiesel) and 0.25 kgCO_2 equivalent per kilogram of biodiesel.

The primary energy content and GHG emissions from biodiesel plant construction and maintenance are assumed to be negligible. This is in line with the findings of Mortimer et al. (2003), who estimated that construction and maintenance added 1.8% and 1.1% respectively to primary energy and 1.4% and 0.5% respectively to GHG emissions for the esterification process.

It is assumed for transport calculations that a biodiesel plant would be built near the Marsden Point refinery. This considers a scenario where biodiesel could be blended with diesel before distribution – chosen more to provide a worst-case transportation scenario than to model a perceived option. From the location of output of processing plants in New Zealand, as provided by Hale & Twomey (2006), the weighted average distance travelled by domestic tallow is 930 km by sea (it was assumed that the current sea-going facilities would be utilised). It is assumed that sea transport consumes 0.3 MJ/t-km (consumer energy), including heating of tallow for transfers. Using this, a factor of 1.0 kg of tallow producing 1 kilogram of biodiesel (Hale & Twomey, 2006) and a primary energy factor for fossil diesel of 1.193, the primary energy relating to the transport of tallow is 0.33 MJ/kg of biodiesel. Applying a greenhouse gas emissions factor of 82.55 gCO_2eq/MJ of diesel (Appendix C) results in a value of 0.03 kgCO_2eq/kg of biodiesel. Note a road and rail scenario gave a two-fold increase in the energy consumed for transport, but this is still relatively insignificant.

Glycerine is a by-product of biodiesel production that requires allocation of the energy and greenhouse gases associated with biodiesel production, providing biodiesel with a by-product credit. A 13% credit is provided, based on Mortimer et al. (2003), using economic allocation. This appears to be of similar order to that which would be expected for production in New Zealand (as based on a 1:10 production ratio with methyl ester and a range of prices in Europe from $500 to $1000 per tonne[11] resulting in a by-product credit of glycerine to the order of $0.05-$0.10 per litre of biodiesel compared to a value of biodiesel to the order of $0.70 per litre). Hale & Twomey (2006) noted that under a scenario of large-scale worldwide production of biodiesel, the excess supply of glycerine could cause its price to fall significantly. This

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[11] Hale and Twomey (2006).

would have an unfavourable impact on biodiesel production economics and consequently cause a small increase in the allocation of primary energy and GHG emissions to biodiesel.

6 Fossil Diesel Fuel Model

6.1 Fossil Diesel Primary Energy

The primary energy content of diesel delivered to the customer includes the higher (*gross)* heating value of the fuel (the energy available to the customer[12]), plus all the energy that has been used to extract, process, refine and transport the diesel. Analysis of several studies and consideration of New Zealand's mix of domestic and foreign oil derives a factor of 1.193 MJ/MJ to be applied to the consumer energy value of diesel to provide its primary energy value. This analysis is detailed in Appendix C. Using a consumer energy content of 38.67 MJ/ℓ (MED, 2006b), this results in a primary energy value of 46.14 MJ/ℓ diesel.

6.2 Fossil Diesel Greenhouse Gas Emissions

The direct GHG emission factor used in the study for NZ diesel is 70.73 ktCO_2eq/PJ (or gCO_2eq/MJ) (MED 2006a).

Including the indirect GHG emissions from upstream primary energy (see Appendix C), the total GHG emission factor used for NZ diesel is 82.55 gCO_2eq/MJ.

7 Biodiesel Fuel Model

This section combines the various results provided to date to deduce primary energy and greenhouse gas emission factors for tallow-derived biodiesel in New Zealand. These are then compared to those for fossil diesel. Energy referred to in this section is primary energy, unless otherwise stated.

Table 7 lists the allocations derived for primary energy and greenhouse gas emissions for the various steps from the farm to the biodiesel production plant exit gate. Total farm to biodiesel plant gate primary energy for tallow-derived biodiesel was 20.0 MJ/kg of biodiesel with a credit for glycerine, and 23.0 MJ/kg of biodiesel without a credit for glycerine. Note that a world-wide increase in biodiesel production is expected to reduce the international price for glycerine and hence the use of a value between the two, but closer to 20.0 MJ/kg, would be appropriate. Comparing it to a consumer energy of 39.95 MJ/kg for tallow-derived esters (Mittelbach and Remschmidt, 2004), the biodiesel MJinput/MJoutput (the I:O relationship) is 0.50 (with glycerine credit).

Also as shown in Table 7, the highest source of energy consumed in the farm to biodiesel production plant gate life cycle is in rendering, at 60% of the total energy consumed. Rendering is also the highest source of greenhouse gas emissions, at 46%. Note that farming has relatively high greenhouse gas emissions, but in this model the render material is allocated only 0.9% of farm emissions.

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[12] In theory, the gross heating value of energy is available but as most machines are not capable of extracting the heat relating to the vaporisation of water in exhaust gases, only the net heating value of energy is available, which is around 10% less than the gross heating value for gas and around 5% less for coal and liquid fuels.

Table 7: Primary Energy and Greenhouse Gas Emissions for Tallow-Derived Biodiesel

Stage in Process.	Primary Energy MJ/kg biodiesel	As a Percentage of Total with Credit	Location of Derivation	Greenhouse Gas Emissions $kgCO_2eq/kg$ of biodiesel	As a Percentage of Total with Credit	Location of Derivation
Farming and meat processing.	1.0	5%	Section 4.1	0.77	39%	Section 4.3
Rendering.	13.9	60%	Section 4.2	0.90	46%	Section 4.2
Transport to plant.	0.3	1%	Section 5.	0.02	1%	Section 5.
Biodiesel production.	7.7	34%	Section 5.	0.25	13%	Section 5.
Total without glycerine credit.	23.0		-	1.95		-
Glycerine credit (13%).	3.0	-	Section 5.	0.25	-	Section 5
Total with glycerine credit of 13%.	**20.0**	**100%**	-	**1.70**	**100%**	-
I:O relationship with glycerine credit.	0.50		-	-		-
I:O relationship w/o glycerine credit.	0.58		-	-		-

7.1 Comparison of Biodiesel and Fossil Diesel

The input/output energy ratio (MJprimary/MJconsumer) for biodiesel is 0.50 (with glycerine credit) compared with 1.19 for fossil diesel, that is, 58% lower.

There is not expected to be any significant difference in the efficiency of using biodiesel in an engine over the use of fossil diesel, 1 MJ of biodiesel providing the same work output as 1 MJ of fossil diesel. However, biodiesel is less energy dense, on a weight basis – it takes 1.15 kg of biodiesel to provide the same energy as for 1 kg of fossil diesel – and this must be taken into consideration when comparing the performance of fuels on an equivalent work basis.

Comparing on an equivalent work (MJ) basis, the greenhouse gas emissions from biodiesel equivalent to 1 kilogram of fossil diesel are 1.70 $kgCO_2eq/kg$ biodiesel (total with glycerine credit as given in Table 7) x 1.15 kg biodiesel/kg diesel (mass ratio for same energy) = 1.95 $kgCO_2eq$. The greenhouse gas emissions for 1 kilogram of fossil diesel, including upstream emissions, are 3.80 $kgCO_2eq$. Hence New Zealand tallow-derived biodiesel is expected to have around 51% of the greenhouse warming potential of fossil diesel, that is, a 49% reduction over the use of fossil diesel.

Table 8 provides primary energy savings and greenhouse gas reductions for the system boundaries: biodiesel production only (which assumes that tallow has no value at the production plant entry gate); plus rendering, plus farming and meat processing (the base case analysis provided by this study). Note that the savings achieved from restricting the system boundary to just the biodiesel production are not considered entirely valid as the energy relating to providing a replacement to tallow (perhaps palm oil for soap manufacture or animal feed) has not been considered.

Table 8: Effect of Different System Boundaries (With Glycerine Credit)

Stage Number and Description	Stages included	Input output ratio	Energy Saving %	Greenhouse Gas Reduction
1. Biodiesel production & transport	1	0.18	85%	93%
2. Plus rendering	1 + 2	0.48	60%	69%
3. Plus farming & meat processing	1 + 2 + 3	0.50	58%	49%

Note that many factors used in this study's analysis have been based on national averages. An alternative is to consider consequential scenarios, for example, additional electricity is sourced from new generation rather than the national average. This may slightly alter the base factors that are used.

7.2 Sensitivity Analysis

Table 9 provides the results of sensitivity analysis carried out on the base biodiesel model. Both the input/output energy ratio and greenhouse gas emissions were found to be somewhat sensitive to both the price of tallow and to the glycerine credit amount. The tallow sensitivity is due to the relatively high amount of energy expended during rendering plus the relatively small share of this that is first allocated to tallow – a small increase in the price of tallow can provide significant changes in the energy allocated to it.

The greenhouse gas emissions were found to be sensitive to the price of the render material, primarily due to high greenhouse gas emissions associated with farming plus the small share that is allocated to the render material on an economic basis (0.94%). A small increase in the price of render material can produce significant changes in the emissions allocated to it (but not in the relatively low primary energy content).

The last sensitivity analysis set out in Table 9 (Scenario 7) is an attempt at providing what is arguably a more likely scenario than those based on current prices, namely, a 25% decrease in the glycerine price plus a 25% increase in the price of tallow. This still results in a 52% saving in primary energy and a reduction in greenhouse warming potential of 42%.

The transport of tallow to the biodiesel plant is a minor component of the LCA (1% of energy and of GHG) so the base case provides a suitable indicator for virtually any plant location.

Table 9: Results of Sensitivity Analysis on Base Biodiesel Model

Sensitivity Considered	Model Value Changed	I:O Relationship	Greenhouse Gas Emissions Reduction (%)
0. Base case model (with glycerine credit).	Nil	0.50	49%
1. Base case model without glycerine credit.	Allocation of 100% rather than 87% to biodiesel.	0.58	41%
2. Base case plus 100% increase in price of render material.	Increase value of render products from 0.94% to 1.9% of income from animals.	0.52	29%
3. Base case plus high estimate of biodiesel plant energy and emissions.	Increase biodiesel plant's energy requirements from 7.72 to 9.68 MJ/kg biodiesel and increase emissions 0.25 to 0.35 kgCO_2eq/kg biodiesel.	0.70	40%
4. Base case plus low estimate of biodiesel plant energy and emissions.	Decrease biodiesel plant's energy requirements from 7.72 to 5.77 MJ/kg biodiesel and decrease emissions 0.25 to 0.15 kgCO_2eq/kg biodiesel.	0.62	45%
5. Base case plus increase in the price of tallow by 50%.	Increase the allocation of energy and emissions to tallow from 26% to 34%.	0.60	41%
6. Base case plus a combination of 50% decrease in price of glycerine plus 50% increase in price of tallow.	Reduce glycerine credit from 13% to 7% and increase allocation of energy and emissions to tallow from 26% to 34%.	0.64	36%
7. Base case plus 25% decrease in the price of glycerine plus 25% increase in the price of tallow.	Reduce glycerine credit from 13% to 10% and increase allocation of energy and emissions to tallow from 26% to 30%.	0.57	42%

7.3 Uncertainty Analysis

Another method to consider the robustness of the analysis is to carry out an uncertainty analysis. The result provided here were from the use of a similar method to that used to consider uncertainty analysis in the National Greenhouse Gas Emissions Report (MfE 2006), with estimates made of the 95% confidence limits for each of the primary energy LCA components. As discussed in the sensitivity analysis, the largest relative uncertainties arise from the allocation methodology. Prices of render material, tallow and glycerine were all considered to be ±50% while the total animal values were assessed to be ±20%. Combining uncertainties is more accurate using the root mean square method rather than by simple addition.[13] Note that the variables considered in this way are supposed to be independent, whereas some are dependent in this study. For example, if the total animal value increases, the render material and the tallow prices would tend to follow. As a result, the uncertainties are likely to be over-estimated to some degree.

The weighted average of primary energy figures relating to sheep and cattle farming was made up of relative uncertainties of ±34% for farming, ±50% for the transport component and ±25% for meat processing, totalling ±27% for farming energy before allocation. After combining with the render material and total animal value uncertainties, the relative uncertainty of farming energy was assessed to be ±60%.

The uncertainty for rendering energy was ±25% before allocation and ±59% after allocation. The uncertainties on the primary energy for biodiesel processing and transport were ±25% and ±50%, respectively.

Combining all of these primary energy components, the total uncertainty was ±38% with a glycerine credit and ±37% without a glycerine credit.

Uncertainties in the fossil fuel diesel model would be relatively low in comparison.

Greenhouse gas emission uncertainties would be quite similar with the exception of a higher uncertainty from the farming emissions component.

7.4 International Comparison

Niederl and Narodoslawsky (2004) calculate a greenhouse gas emissions figure for tallow processing to biodiesel, with no upstream emissions except transport to the plant and no allocation/substitution, of 0.017 kgCO_2eq/MJ compared with 0.084 kgCO_2eq/MJ for fossil diesel (converted to a higher heating value basis for comparison with this study's findings). The equivalent figures from the current study were very similar for fossil diesel (0.0825 kgCO_2eq/MJ) but 60% lower (0.007 kgCO_2eq/MJ) for tallow-derived biodiesel. There was insufficient detail provided in their report to analyse this discrepancy further. Niederl and Narodoslawsky did not offer an energy figure and hence this comparison cannot be made for energy.

Nelson and Schrock (2006), in a study of the embodied energy relating to the conversion of beef tallow to biodiesel, concluded that tallow should be regarded as an inevitable by-product of meat production because their analysis showed that tallow ester would not be produced intentionally for energy purposes alone. This conclusion resulted from their use of a mass allocation method that suggested that twice as much energy input was needed for farming, rendering and esterification compared with the biodiesel output. They calculated an input/output energy ratio for the esterification process of 0.35, which we believe is unusually high compared with the ratio of 0.19 (without glycerine credit) used in our study. They calculate an input/output ratio of 0.44 for the rendering process (from a single rendering company, and without appearing to include meat processing) compared with the biodiesel energy output, significantly lower than the average that we calculate at a more detailed level and taking into consideration a wide range of rendering plants in New Zealand, at 1.35 before economic allocation. This study illustrates the importance of the allocation method and the need for detailed analysis to be included to allow meaningful comparison.

Beer et al. (2001) obtained a greenhouse gas emissions figure for their full upstream tallow biodiesel with economic allocation of 0.047 kgCO_2eq/MJ (noting this figure has been converted to a higher heating value basis, to allow comparison with our findings) and this compares favourably with the 0.042 kgCO_2eq/MJ from our study. However, Beer et al.'s input/output ratio for this option is 0.18 compared with 0.50 calculated by this current study. In part, the

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[13] Noting that simple addition assumes that the worst of all the componential errors align, which would be unlikely to occur within 95% confidence limits.

difference in these calculated energy input/output ratios is due to Beer et al. (2001) using a much lower rendering energy value, at just 40% of the figure used in our study. The similarity in the greenhouse gas emissions yet different energy ratios is due in part to the impact that the different allocation rates have on each part of the system combined with the different rendering energy values.

In addition to the economic allocation method, Beer et al. (2001) also conducted a system boundary expansion analysis – avoiding allocation between different animal by-products. The approach used assumed that tallow will be taken from current users to meet the demand for tallow used in biodiesel production. The replacement for tallow in soap and cosmetic applications was assumed to be vegetable oil, with canola used as a proxy for mixed vegetable oils. The impact of diverting tallow to biodiesel is therefore modelled as the production of canola to replace tallow displaced into biodiesel. The greenhouse gas emissions from this system boundary expansion approach were 0.039 kgCO2eq/MJ, compared to 0.042 kgCO2eq/MJ calculated by our study. The energy ratio calculated by Beer et al. was 0.43 compared to our study's figure of 0.50. Beer et al. provided insufficient detail for us to explain this latter discrepancy.

8 Conclusions

The use of domestically-produced biodiesel from locally-sourced tallow, as a replacement for fossil diesel, is expected to decrease total primary energy by around 50% and have around 51% of the global warming potential.

The highest source of energy consumed in the life cycle from farm to biodiesel production plant exit gate is in rendering, at 60% of the total energy consumed. Rendering is also the highest source of greenhouse gas emissions, accounting for 46% of these emissions.

Sensitivity analysis explored a number of extreme implementation scenarios, mostly related to less favourable by-product values. Despite the higher allocation of primary energy and greenhouse gas emissions to biodiesel that resulted, the use of biodiesel still provided a clear advantage over the use of fossil diesel.

This sensitivity analysis also found that both the input/output energy ratio and greenhouse gas emissions were sensitive to the price of tallow and the greenhouse gas emissions were found to be sensitive to the price of the render material. The primary energy and greenhouse gas emissions relating to the transport of tallow to the biodiesel plant was found to be relatively minor.

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Appendix A - Agriculture Production Detail

A.1 Tallow Carbon

The carbon in the tallow is ultimately released as carbon dioxide whichever manner it is used – whether it is used to produce biodiesel and then combusted in an engine or used to make soap which eventually biodegrades. However, this is carbon that has been recently sequestered from the atmosphere – by the grass or other plants eaten by the animals the tallow was produced from – and is considered to result in zero net emissions of carbon dioxide. Note, however, there is other carbon involved in farming processes that must also be considered, including that relating to energy embodied in capital equipment (vehicles, buildings, water supply etc.). Capital equipment to the farm gate (i.e., to the pick-up of product from the farm gate) accounts for 9% of farm energy inputs.[14] The contribution from capital beyond the farm gate is likely to be very small due to the high flow of product[15] and has been taken as nil for this analysis. This includes the capital contribution for petroleum diesel.

A.2 Farm Description

The farm-related inventory of resource and energy use that is used in this report's analysis has been based on the Agriculture Research Group on Sustainability (ARGOS) database for the 2003/04 season. This database has had expert input from economists, sociologists, farm management experts and ecologists and provides sustainability and socio-ecological resilience assessments of farms and orchards participating in organic, integrated management, conventional, and Māori farming systems. A description of the ARGOS project that developed this, and of the energy aspect of the programme, is provided in *Total Energy Indicators: Benchmarking Organic, Integrated and Conventional Sheep and Beef Farms* (Barber and Lucock, 2006).

For this report's analysis the farm-related *inventory of resources* has been derived from combining the data from 10 non-cropping, conventional and integrated ARGOS sheep and beef farms that derive more than 10% of their income from net cattle sales. This method excludes cropping farms in the ARGOS database – to match data provided in the MAF national average sheep and beef model (MAF, 2004) – and provides a "farm model" that matches closely the ARGOS database national farm model, which has net income from cattle sales of 19%.

Note that the ARGOS farms are all in the South Island. While these farms do not represent a national average for New Zealand sheep and beef farms, the benefits of having an extremely detailed inventory outweighs the disadvantages. A project is currently being conducted to create a national average model, but this is not due to be completed until mid 2007 and preliminary results are not available. However, a significant difference in result is not expected for a "national farm model", as the energy intensity (which is derived from the inventory of resources) appears relatively insensitive to different farming methods. For example, the results from a study on high country farming (*Merino Study*, Barber and Pellow, 2005) found the total energy use per tonne of product was around 13.5 MJ/kg (capital excluded), similar to that found for low land sheep and beef farms (ARGOS database), at 12.1 MJ/kg, using the same analysis methods. This is despite likely large differences in the energy intensity on a per hectare basis.[16]

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[14] Barber and Lucock (2006)

[15] Boustead (1997) states that flows from large equipment and facilities construction are less than 0.01% for any product.

[16] For example, Smith and McChesney (1979) found the national average energy intensity for sheep and beef farms (meat and wool only) was 1,300 MJ/ha/yr, the energy intensity for intensive fattening (class 7) farms was 3,800 MJ/ha/yr and for mixed cropping (class 8) farms (those most like the ARGOS farms) was 4,700 MJ/ha/yr. The ARGOS-derived farm model used for this project's analysis had an energy intensity of 2,760 MJ/ha. Despite these large differences, there is balancing between energy intensity and product output that results in a relatively insensitive energy intensity.

For this study it is the sheep and cattle energy productivity data that is used to model biodiesel energy and greenhouse gas emissions.

A.3 Agricultural Inventory Analysis

A.3.1 Diesel

The gross energy content or consumer energy of fossil diesel is 38.4 MJ/ℓ or 45.6 MJ/kg (MED Energy Data File July 2004, the period that most closely matches the ARGOS farm survey period). The primary energy content, which includes an allowance for the fuel's production and delivery, adds an extra 19.3%. For a full description of the primary energy content see Appendix C. Therefore the primary energy content of fossil diesel is 45.8 MJ/ℓ or 54.4 MJ/kg.

Farm fuel use, which includes tractors, road vehicles and contractors, developed from the ARGOS database was found to be 2.3 ℓ/s.u. or 99.2 MJ/s.u. Based on the ARGOS farm budgets the cost of fuel was $2.03/s.u. This is 50% higher than compared to the MAF Model (MAF, 2004) for the same period at $1.35/s.u.

A.3.2 Electricity

The consumer energy content of electricity is 3.6 MJ/kWh. The primary energy content has been calculated as 2.14 kWh of primary energy to supply 1 kWh to the consumer. This is based on the electricity generation in the 12 months to June 2004 (the period that most closely matches the ARGOS farm survey period). The primary energy supply figure for electricity generation (including cogeneration) in 2003/04 was 304 PJ and consumption was 142 PJ (MED, 2006b). In addition to the primary energy supply figure energy described by the MED Energy Data File (293 PJ), additional energy is added to take into account coal mining and distribution plus gas extraction, treatment and distribution (10.9 PJ).

The additional 10.9 PJ of coal and gas energy has been calculated based on the energy coefficients of 1.04 MJ/MJ for coal and 1.13 MJ/MJ for gas (Alcorn and Wood, 1998). This adds 1.9 PJ and 9.3 PJ to the coal and gas electricity generation supplies respectively.

The direct GHG emission factor for average electricity use (MED 2006a Table 1.1.1 and 2006b Table G.3 for 2005) is:

7,148,000 tCO_2eq /41,245 GWh = 173.3 gCO_2eq/kWh.

Divide by 3.6 = 48.1 gCO_2eq/MJconsumer.

The total GHG emission factor for average electricity use is:

197.2 gCO_2eq/kWh or 54.8 gCO_2eq/MJconsumer or 26.0 gCO_2eq/MJprimary.

This includes 0.162MtCO_2eq from diesel used to mine coal, 0.110MtCO_2eq from coal fugitive methane emissions, 0.250MtCO_2eq from half (to minimise double counting) the extra 13% upstream primary energy (using the direct gas emission factor) and 0.464MtCO_2eq from gas fugitive CO_2 and methane emissions. All coal used at Huntly Power Station is assumed to have the same primary energy content as the average NZ coal because there was no information available on the amount of Indonesian coal or its primary energy content including mining, shipping and trucking.

A.4 Agrichemicals[17]

A.4.1 Fertiliser

The energy required to manufacture fertiliser has been calculated from the sum of its constituent nutrient components. Table 10 lists the average energy to manufacture each component (i.e., the average of a range of fertiliser production methods) and their carbon dioxide emissions, from Wells (2001).

Table 10: Energy Requirements to Manufacture the Components of Fertiliser

Component	Energy Use (MJ/kg)	Carbon dioxide (gCO_2/MJ)	Use (kg/ha/yr)	Use (kg/s.u.)
Nitrogen (N)	65	46.2	10.2	1.0
Phosphorus (P)	15	60.0	18.4	1.8
Potassium (K)	10	60.0	0.0	0.0
Sulphur (S)	5	60.0	21.2	2.2
Magnesium (Mg)	5	60.0	0.1	0.0
Limestone	0.6	466.0	78.2	11.0

Nitrogen use dominates the embodied energy in fertiliser due to the combination of high energy content and high use. Total fertiliser energy use is 107.4 MJ/s.u. (noting that farm outputs are often referred to in terms of stock units, "s.u.", which is the ewe equivalent) and carbon dioxide emissions are 8.3 $kgCO_2$/s.u. In the absence of information about methane and nitrous oxide emissions from the fertiliser manufacture, these must be assumed to be negligible for the purpose of the current study.

From the ARGOS database the farm model used for analysis spends $6.04/s.u. on fertiliser and $0.35/s.u. on lime. The MAF National Model is slightly higher at $7.38/s.u. and $0.49/s.u., respectively, and is used in sensitivity analysis.

A.4.2 Non-fertiliser Agrichemicals

The energy required to manufacture non-fertiliser agrichemicals was adapted from Green (1987) for different agrichemical-type categories, and ranged between 97 to 210 MJ/kg of *active ingredient*[18](ai). Note that Green (1987) did not have a figure for animal remedies, which were assumed to have a total energy input of 210 MJ/kg ai based on work of Wells (1998).

Energy costs were added for formulation (at 20 to 30 MJ/kg, Green, 1987), packaging (at 2 MJ/kg, Green, 1987) and transport.

The sum of all non-fertiliser agrichemical active ingredients was 0.1 ℓ/s.u. with a total embodied energy of 7.5 MJ/s.u. Carbon dioxide emissions at 60 gCO_2/MJ equates to 0.5 $kgCO_2$/s.u. In the absence of information about methane and nitrous oxide emissions from the manufacture of non-fertiliser agrichemicals, these must be assumed to be negligible for the purpose of the current study.

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[17] An umbrella term used to encompass any chemicals used in agriculture including fertilisers and pesticides.

[18] That is, the ingredient that is active in providing a cure and not the holding medium.

A.5 Purchased Feed

Most farms produce their own silage or hay as supplementary feed. A small amount is sometimes also purchased and there is energy expended in providing this, which is also taken into account. Silage and hay has an energy content of 1,500 MJ/t DM (Wells, 2001) and grain is 3,200 MJ/t DM (Barber, 2004). From the ARGOS database, the spend on feed in the farm model used for analysis is \$1.46/s.u. This compares to the MAF model at \$1.27/s.u.

A.6 Farm Capital Energy Inputs

Capital items have energy embodied in them due to the energy expended in their materials extraction, manufacture and maintenance, which is estimated by multiplying the mass of each component by an appropriate energy coefficient. The embodied energy of vehicles and implements was derived using a simplification of the approach used by Audsley et al. (1997) resulting in an embodied energy for vehicles of 65.5 MJ/kg and for implements of 51.2 MJ/kg. Note this incorporates New Zealand data for steel and rubber, a working life for vehicles of 15 years and a working life for implements of 20 years.

Other capital items included in the analysis were: buildings with an embodied energy coefficient of 590 MJ/m^2; races with an embodied energy of 75 MJ/m and a working life of 30 years (Wells, 2001); conventional, deer and electric fences with embodied energies of 20 MJ/m, 32 MJ/m and 4.5 MJ/m respectively (from Barber and Lucock, 2006); and stock water reticulation systems with embodied energy calculated on the length, diameter and type of pipes used.

A.7 Farm Production

The proportion of total farm resources allocated to sheep and cattle meat production was based on their proportion of net revenue. Sheep meat production is 54% of net farm revenue and cattle 24%. The other main farm economic output is wool at 15%.

The sale of stock on each ARGOS farm was recorded and the live weights converted into carcass weight based on a *dressing out percentage*[19] for sheep of 42% and cattle at 55% (Barber and Lucock, 2006).

A.8 Greenhouse Gas Emissions

The greenhouse gas emissions considered in the analysis are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O).

Global warming potentials (GWPs) are used to convert emissions of each gas to a CO_2 equivalent. The 100-year GWPs have been used for the analysis which has CH_4 a factor of 21 higher than CO_2 and N_2O 310 times greater (MfE, 2006).

Methane is the main greenhouse gas emitted by livestock at a rate of 10.6 kg CH_4/head/yr for sheep and 56.3 kg CH_4/head/yr for cattle (MfE, 2006). Table 11 provides the resulting CO_2 equivalent emissions for the analysis farm model.

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[19] That is, the weight of the slaughtered animal without the head, gastro-intestinal system, pluck (heart, lungs and liver) and skin.

Table 11: Farm Methane Emissions

	kg CH_4 /head/yr	s.u./head	kg CH_4 /s.u./yr	kg CO_2eq /s.u./yr	s.u./ha	kg CO_2eq /ha/yr
Sheep	10.6	1.0	10.6	222.6	7.2	1,603
Cattle	56.3	6.0	9.4	197.1	3.1	611
Total					**10.3**	**2,214**

The Overseer® nutrient budget model (Wheeler et al., 2003) closely matched these methane emission estimates, deriving annual emissions of 2,290 kgCO_2eq/ha, providing confidence in the derived farm model results.

An economic allocation was used[20] to divide the sheep emissions into the two products of meat production, at 78.2%, and wool, at 21.8%. Likewise cattle were divided into meat production, at 83.2%, and grazing (the grazing of cattle from other farms for a weekly fee), at 16.8%. The farm model annual meat production was 115.8 kgCW/ha[21] for sheep and 102.5 kgCW/ha for cattle. Combined, the methane emissions were 10.8 kgCO_2eq/kgCW for sheep and 5.0 kgCO_2eq/kgCW for cattle. These results are summarised in Table 12.

Table 12: Animal Methane Emissions

	kg CO_2eq /ha/yr	Meat economic allocation	kg CO_2eq /ha/yr	kgCW /ha/yr	kg CO_2eq /kgCW
Sheep	1,603	78.2%	1,253	116	10.8
Cattle	611	83.2%	508	103	5.0

Nitrous oxide emissions are associated with the use of fertiliser. The annual emission rate used for this analysis was 720 kgCO_2eq/ha, being that derived by Wheeler et al. (2003) using Overseer®. This was proportioned between sheep and cattle on the basis of an average stocking rate of 70% sheep and 30% cattle. Using the same allocation methodology described for methane, annual nitrous oxide emissions were 3.4 kgCO_2eq/kgCW for sheep and 1.8 kgCO_2eq/kgCW for cattle.

Carbon dioxide emissions were calculated from a detailed farm inventory (see A.9). This found annual CO_2 emission to be 184 kgCO_2/ha. Again, this was close to the estimate derived using Overseer® of 169 kgCO_2/ha. Using the same allocation methodology described for methane, annual carbon dioxide emissions were 0.9 kgCO_2/kgCW for sheep and 0.4 kgCO_2/kgCW for cattle.

Manure management has been assessed as a negligible source of agricultural greenhouse gas emissions for this study, based on the national inventory for 2004 (MfE, 2006) which estimated it was just 2.2% compared with 33.4% for soils (mainly nitrous oxide) and 64.3% for enteric fermentation methane.[22]

The farm greenhouse gas emission results are listed in Table 13.

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[20] Noting that a weight-based allocation is not sensible as there is a large disparity between the values of farm outputs. The adjustment for cattle grazing is needed because the farm model does not calculate the hectares used to feed the farmer's own cattle.

[21] kgCW: kg of carcass weight.

[22] i.e. of the gut.

Table 13: Farm Greenhouse Gas Emissions

	kg CO_2eq /kgCW			
	Methane	**Nitrous Oxide**	**Carbon Dioxide**	**Total**
Sheep	10.8	3.4	0.9	15.1
Cattle	5.0	1.8	0.4	7.2

A.9 Sheep and Beef Farm Resource Inputs

Table 14: Annual Farm Resource Use

Direct Energy	**Amount**	**Unit**	**Amount**	**Unit**
Diesel	2.1	ℓ/s.u.	22.3	ℓ/ha/yr
Contractors	0.1	ℓ/s.u.	1.2	ℓ/ha/yr
Electricity	3.3	kWh/s.u.	34.1	kWh/ha/yr
Indirect Energy				
Fertiliser				
Nitrogen	1.0	kg/s.u.	10.2	kg/ha/yr
Phosphorous	1.8	kg/s.u.	18.4	kg/ha/yr
Potassium	0.0	kg/s.u.	0.0	kg/ha/yr
Sulphur	2.2	kg/s.u.	21.2	kg/ha/yr
Magnesium	0.0	kg/s.u.	0.1	kg/ha/yr
Lime	11.0	kg/s.u.	78.2	kg/ha/yr
AgriChemicals	0.07	ℓ/s.u.	0.8	ℓ/ha/yr
Purchased Feed	0.00	kg DM/s.u.	0.0	kg DM/ha/yr
Capital Energy				
Vehicles	0.1	kg/s.u./yr	1.4	kg/ha/yr
Buildings	0.0	m2/s.u./yr	0.1	m2/ha/yr
Fences	0.4	m/s.u./yr	3.7	m/ha/yr
Races	0.0	m/s.u./yr	0.7	m/ha/yr

Table 15: Farm Primary Energy and Greenhouse Gas Intensity

	Primary Energy		GHG	
	MJ/s.u.	MJ/ha/yr	$kgCO_{2eq}/s.u$	$kgCO_{2eq}/ha/yr$
Direct Energy				
Diesel	90.5	945	6.10	63.7
Contractors	5.0	51	0.34	3.4
Electricity	25.5	264	0.59	6.1
Sub-total	**121.0**	**1,259**	**7.03**	**73.2**
Indirect Energy				
Fertiliser				
Nitrogen	62.5	664	2.89	30.6
Phosphorous	27.3	276	1.64	16.6
Potassium	0.1	0	0.00	0.0
Sulphur	10.8	106	0.65	6.4
Magnesium	0.0	0	0.00	0.0
Lime	6.6	47	3.08	21.9
AgriChemicals	7.5	83	0.45	5.0
Purchased Feed	9.6	103	0.56	6.0
Sub-total	**124.5**	**1,280**	**9.27**	**86.5**
Capital Energy				
Vehicles	8.2	89	0.76	8.3
Buildings	6.0	66	0.60	6.6
Fences	6.7	69	0.53	5.6
Races	3.4	52	0.23	3.5
Sub-total	**24.3**	**276**	**2.13**	**23.9**
TOTAL	**269.7**	**2,815**	**18.42**	**183.6**

A.10 Transport

For the base case, animals were assumed to be transported an average of 100 km between the farm and meat processing plant. The diesel fuel used for transport was 1.41 MJ/t-km (Beer et al. 2001, noting that this was a primary energy figure for operation in Australia), or approximately 0.031 ℓ/t-km. This has been used as a primary energy (higher heating value) figure. Calculations using fuel consumption from a (single) New Zealand trucking operation, that also accounted for return-empty operation, derived transport energy consumption figure of 1.26 MJ/t-km (1.50 MJ/t-km for primary energy).

A.11 Meat Processing

The Meat Industry Research Institute of New Zealand, now AgResearch, has published information on the energy used in meat processing plants from the 1973/74 season to the 1994/95 season. Lovatt and Chadderton (1996) found that, for the 1994/95 season, fuel use (coal, gas and oil) in non-rendering meat plants was 0.68 MJ/kgCW and electricity use was 1.03 MJ/kgCW. These consumer energy values need to be converted into primary energy to fit into the LCA methodology used in the analysis.

Lovatt and Chadderton (1996) did not include the fuel mix, so it is not possible to directly determine the primary energy values that account for both consumer energy and *fugitive*[23] emissions. However, an earlier report by Wee and Kemp (1992) included both fuel type and quantities used. This fuel mix is described in Table 16, along with the consumer and primary energy values. It has been assumed that the fuel mix in the 1989/90 and 1994/95 seasons were the same; therefore the specific fuel consumption figures in Lovatt and Chadderton (1996) were multiplied by 1.07 to account for fugitive emissions. Likewise the specific electricity consumption figures were adjusted using a fugitive multiplier of 2.11 (see Appendix E). Therefore, on a primary energy basis, fuel use in non-rendering meat plants was 0.73 MJ/kgCW (0.68 x 1.07) and electricity use was 2.2 MJ/kgCW (1.03 x 2.11).

Table 16: Fuel Type and Quantity used by NZ Meat Export Plants in the 1989/90 Season

Fuel Type	**Quantity**	**units**	**GJ/unit**	**Energy** **consumer** (GJ)	**Fugitive Multiplier**	**Energy** **primary** (GJ)
Coal	120,000	tonnes	24.1	2,892,000	1.04	3,007,680
Gas	1,215	TJ	1,000	1,215,000	1.13	1,372,950
Oil	3,500,000	litres	0.0383	134,050	1.19	159,962
Total				**4,241,050**	**1.07**	**4,540,592**
				GJ/t		**GJ/t**
Meat processed	866,000	tonnes		**4.90**		**5.24**

Adapted from Wee and Kemp (1992)

The fuel mix and resulting GHG emissions from meat processing are described in Table 17.

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[23] That is, releases not confined to a stack, duct or vent.

Table 17: GHG Emissions by NZ Meat Export Plants in the 1989/90 Season

Fuel Type	Consumer energy (GJ)	GHG emission factors* (g CO_{2eq}/MJ $_{consumer}$)	GHG emissions (t CO_{2eq})
Coal	2,892,000	96.8	279,900
Gas	1,215,000	62.0	75,300
Oil	134,050	82.6	11,100
Total	**4,241,050**	**86.4**	**366,300**

* From Appendix E and assuming light fuel oil same upstream emissions as diesel.

Based on fuel use in non-rendering meat processing plants being 0.68 $MJ_{consumer}$/kgCW GHG emissions using this weighted average GHG emission factor of 86.4 $gCO_2/MJ_{consumer}$ are 58.7 gCO_2eq/kgCW. Electricity use is 1.03 $MJ_{consumer}$/kgCW and at 54.8 $gCO_2eq/MJ_{consumer}$, GHG emissions are 56.4 gCO_2eq/kgCW. Total GHG emissions are 115.2 gCO_2eq/kgCW.

A.12 Meat Rendering

Lovatt and Chadderton (1996) found that, for the 1994/95 season, fuel use (coal, gas and oil) in rendering meat plants was 5.44 MJ/kgCW and electricity use was 1.99 MJ/kgCW again, expressed in consumer energy values. Based on their energy use in non-rendering plants (described above), the energy attributable to the rendering operation is 4.78 MJ/kgCW for fuel and 0.96 MJ/kgCW for electricity (consumer energy).

On a primary energy basis (using the process described above) fuel use was 5.12 MJ/kgCW and electricity use was 2.03 MJ/kgCW. GHG emissions from the fuel were 412.9 gCO_2eq/kgCW (4.78 x 86.4) and electricity emissions were 52.6 gCO_2eq/kgCW (0.96 x 54.8), totalling 465.5 gCO_2eq/kgCW.

A.13 Render and Tallow Resource Allocation

Where there are multiple economic outputs in the production chain, resources need to be allocated to each output. Consistent with the ISO 14041:1999 standard, where allocation cannot be avoided and where there is no suitable underlying physical relationship between them, economic allocation is used.

Lamb and beef allocations are described in Tables 18 and 19. Lamb- and beef-sourced rendering material, the raw product for tallow, is allocated 0.87% and 0.99% of the meat processing plant resource inputs respectively. The weighted national average based on the slaughter statistics is 0.94%. The rendering process produces tallow and meat and bone meal (MBM). Tallow from sheep is allocated 22% of the rendering inputs and beef 28%. Even though the price of tallow is the same irrespective of the animal source, the difference in resource allocation is caused by beef having a higher yield of tallow per kilogram of raw render material.

Table 18: Lamb Meat Processing Allocation

Meat Processing – Lamb						Allocation	
		kg/kgLW	kg/head	$/head	$/kg	Mass	Economic
	Lamb meat	0.42	15.0	105.75	$7.05 [a]	42%	87.2%
	Sheep skin	0.10	3.6	5.00 [b]		10%	4.1%
	Render material	0.33 [c]	11.8	1.06	0.09 [d]	33%	0.9%
	Offal	0.15	5.4	9.45	1.76 [e]	15%	7.8%
	Total	1.00	35.7	121.26		100%	100%
Rendering – Lamb						Allocation	
		kg/kg render	kg/head	$/head	$/kg	Mass	Economic
	Tallow	0.18 [f]	2.1	1.18	0.57 [g]	18%	22.3%
	MBM	0.83	9.7	4.11	0.42 [h]	83%	77.7%
	Total	1.00	11.8	5.30		100%	100%

Sources:

[a] *Situation and Outlook for New Zealand Agriculture and Forestry* (SONZAF) 2005. MAF Policy.

[b] Anonymous. Meat processing industry participant

[c] S. Dunn, personal communication, range between 30 to 35% of live weight (LW)

[d] S. Dunn, personal communication, range between free to $0.09.

[e] Meat and Livestock Australia website. http://www.mla.com.au/NR/rdonlyres/A64B2323-D807-426D-B84B-55D3E01311B1/0/coproductspricetrendsApril06_march06prices.pdf. Range $A1.25 - $1.75. Exchange rate 0.85

[f] S. Dunn, personal communication, range between 15 – 20%

[g] Meat and Livestock Australia web site. $A527 <1FFA and $A448 <2FFA

[h] Meat and Livestock Australia web site. $A359. Exchange rate 0.85

Table 19: Beef Meat Processing Allocation

Meat Processing - Beef					Allocation	
	kg/kgLW	kg/head	$/head	$/kg	Mass	Economic
Beef meat	0.55	300	1,380	$4.60 [a]	55%	84.4%
Hides	0.06	33	65 [b]		6%	4.0%
Render material	0.33 [c]	180	16	0.09 [d]	33%	1.0%
Offal	0.06	33	174	5.32 [e]	6%	10.6%
Total	1.00	545	1,635		100%	100%
Rendering - Beef					Allocation	
	kg/kg render	kg/head	$/head	$/kg	Mass	Economic
Tallow	0.23 [f]	40.5	23.21	0.57 [g]	23%	28.2%
MBM	0.78	139.5	58.96	0.42 [h]	78%	71.8%
Total	1.01	180.0	82.17		100%	100%

Sources:

[a] *Situation and Outlook for New Zealand Agriculture and Forestry* (SONZAF) 2005. MAF Policy.

[b] Anonymous. Meat processing industry participant

[c] S. Dunn, personal communication, range between 30 to 35% of live weight (LW)

[d] S. Dunn, personal communication, range between free to $0.09.

[e] Meat and Livestock Australia website. Range $A0.61 – 21.58/kg. Exported 123,910 tonnes valued at $A560 million.

[f] S. Dunn, personal communication, range between 20 – 25%

[g] Meat and Livestock Australia website. $A527 <1FFA and $A448 <2FFA

[h] Meat and Livestock Australia website. $A359. Exchange rate 0.85

Appendix B Biodiesel Production

Many references were consulted to in deriving energy and emission factors for biodiesel production. They include:

Beer at al. (2001) from CSIRO and other Australian research groups studied a wide range of alternative fuels for heavy duty vehicles including biodiesel from rapeseed, canola, soybeans, waste cooking oil and tallow. Their comprehensive report is sufficiently detailed to provide useful information on the GHG emissions (but not the primary energy inputs) for the esterification process.

Niederl and Narodoslawsky (2004) undertook a substantial life cycle assessment of tallow biodiesel for the UK Department of Environment, Food and Rural Affairs (DEFRA). The results for their Sustainable Production Index and Global Warming Potential index are not sufficiently detailed to allow a comparison with other studies. The authors did not respond to an email enquiry for further detail.

Sheehan et al. (1998) of the US National Renewable Energy Laboratory carried out a very comprehensive study that included primary energy inputs and GHG emissions figures for each of the soybean oil esterification process components.

Dreier et al. (1998) included primary energy input figures for each of the rapeseed oil esterification process components.

Natural Resources Canada (2003) commissioned an economic study of biodiesel from tallow and other sources that is useful for a discussion of methanol and energy requirements.

Mortimer et al. (2003) of UK Sheffield Hallam University carried out for DEFRA a very thorough and frank critical review of 11 existing life cycle assessment studies for rapeseed biodiesel, particularly focusing on inconsistencies and allocation methods for primary energy inputs and GHG emissions. For relevance to UK esterification (and for transparent data) they relied mainly on Kaltschmitt el al. (1997).

Delucchi and Lipman (2003) included primary energy inputs for some of the soybean oil esterification process components and usefully quoted a 1994 study that contrasted current figures with industry potential in both the US and Europe.

Nelson and Schrock (2006) carried out a detailed economic and energy study of biodiesel derived from beef tallow. The esterification energy from natural gas is unusually high.

B.1 Quantity of Methanol Used in the Production of Biodiesel.

A value of 0.01 kg methanol/kg biodiesel was selected for the analysis, being the average of two studies: an economic study of biodiesel (Natural Resources Canada, 2003) based its methanol consumption of 0.12 litre per litre of biodiesel (0.11 kg/kg) on data from a Tennessee plant, with the comment that the requirements were found in practice to be 10% greater than the theoretical amount; Sheehan et al. (1998) based its consumption data of 0.09 kg methanol/kg biodiesel on a Missouri plant. They stated that an excess of methanol is usually used in order to obtain high yields and reasonable reaction times, although the excess methanol is recovered later in the process. Beer et al. (2001) also used a figure of 0.09 kg methanol/kg biodiesel in their modelling, and while the source was not stated, it may have been Sheehan et al. as there are other references to this work.

Those studies that were sufficiently detailed showed that methanol manufacture is the main source of input primary energy and greenhouse gas emissions for the esterification process. Consequently, considerable effort was taken to seek a range of information about inputs to methanol manufacture and to apply this to the New Zealand situation.

The other main variable was the primary energy content of methanol, which on an input/output megajoule basis ranged over a factor of two for six studies. The two low results (both 0.06

MJ/MJ) were rejected as too low on the basis that they appeared to include just the direct energy content of methanol rather than the upstream energy input. After correcting to 100% mass allocation and economic allocation respectively, the Sheehan et al. (1998) figure was 0.098 MJ/MJ biodiesel while Mortimer et al. (2003) used 0.116 MJ/MJ biodiesel (and cited a figure 20% lower for a 1996 UK study). Nelson and Schrock's 2006 figure of 0.122 MJ/MJ biodiesel and the "industry potential" figure in Delucchi and Lipman (2003) of 0.114 MJ/MJ biodiesel both suggest a consensus towards the higher figures.

Methanex confirmed that it does not release data on the output, energy use or carbon dioxide emissions from its two methanol plants in Taranaki. However, it was reported as achieving 0.9% better than its voluntary agreement target of 0.823 tonne CO_2 per tonne methanol in 2000 (G. Kennedy, 2006), although these have been deduced from MED publications and are presented in Table 20 as the best estimates. They were calculated from average output (2.2 million tonnes) from 1999-2002 before production declined with increasing gas feedstock prices. Average energy consumption then increased from a reasonably consistent 39.7 MJ/kg methanol to a highly variable quantity averaging 62.2 MJ/kg from 2003-2005. This suggests that the primary energy input and consequent carbon dioxide emissions for methanol would be highly dependent on the scale of operation and the methanol source if the Taranaki plants close down with increasing gas prices.

Methanex indicated that methanol is currently trucked to Auckland in tankers for New Zealand uses and this would probably be used if a biodiesel plant was developed in Northland. A transport component has been included in the best estimate (adding 2% to primary energy content and 5% to GHG emissions) and it is assumed such a component was included in the Sheehan et al., Beer et al. and Mortimer et al. studies.

The New Zealand best estimate for primary energy input (including the transport component and 13% extra for upstream gas energy) is remarkably close to the figures for three other studies Mortimer et al 2003, Delucchi & Lipman 2003, Nelson & Schrock 2006 (although some may also include sodium methoxide primary energy). It is about 15% higher than the Sheehan et al. figure, which was used as the estimated lower limit in the uncertainty range.

In comparison with the two-fold range of primary energy inputs, there is a much broader seven-fold range of GHG emissions for the three studies that published these figures. The Sheehan et al. figure was rejected as unreasonably low and the Mortimer et al. was rejected as unreasonably high despite the detailed breakdown of individual GHG in each study. Beer et al. did not include a breakdown of individual GHG but their figure was only 14% lower than the New Zealand best estimate. A broad range of uncertainty was chosen to reflect this issue, composed of ±10% for the methanol quantity and for the transport, ±30% for the plant emissions and ±50% for the upstream emissions.

Table 20: Energy Input and Greenhouse Gas Emissions from Methanol Manufacture

Study		Primary energy input[1] (MJ/MJ BD)	Primary energy input (MJ/kg BD)	Greenhouse gas emissions ($kgCO_2eq./kg$ BD)
Sheehan et al 1998		0.098	3.93	0.042
Dreier et al 1998		0.061	-	-
Beer et al 2001		-	-	0.102
NRC 2003		0.057	-	-
Mortimer et al 2003		0.116	4.61	0.296
Delucchi et al 2003		0.114	4.56	-
Nelson et al 2006		0.122	4.89	-
NZ estimate 2006	Low	0.097	3.88	0.070
	High	0.131	5.24	0.171
	Best	0.114	4.56	0.120

[1] Primary energy inputs for most studies were calculated in reference to a range of (net) lower heating values for biodiesel that have been approximately converted here to (gross) higher heating values for comparison. The NZ estimates are calculated in reference to a higher heating value of 39.95 MJ/kg for tallow biodiesel (Appendix A).

B.2 Other Chemicals

Sheehan et al. (1998) and Beer et al. (2001) included figures for manufacturing the sodium methoxide catalyst[24], adding 57% and 38% respectively to the GHG emissions from methanol. If this is added to the methanol figures above, the Beer et al. figure would then be 16% higher than the New Zealand best estimate but the Sheehan et al. figure would still be 45% lower. It has been assumed that Mortimer et al. (2003) included the catalyst in its methanol and caustic soda figures for primary energy input and GHG emissions. The relatively low Sheehan et al. (1998) figures (as the only complete set) have been used for the New Zealand best estimate with an uncertainty range of ± 50%.

Mortimer et al. (2003) used primary energy and GHG figures for caustic soda that were more than 6 times higher than those used by Sheehan et al. (1998) and Beer et al. (2001) (and Dreier et al. (1998) for energy). These are all figures based on esterification of rapeseed and soybean oil and it is unclear if there is the same need for caustic soda treatment of tallow. Therefore the Mortimer et al. (2003) figure has been considered an upper limit with a very wide uncertainty range of 20% of that level as the lower limit.

For hydrochloric acid primary energy content, the Sheehan et al. (1998) figure was chosen as the appropriate one (more than double the Dreier et al. (1998) value). For GHG emissions, Beer et al. (2001) was very similar to (perhaps derived from) Sheehan et al. (1998) so an average was used with uncertainty ranges of ± 20% for both quantities.

Dreier et al. (1998) included (negligible) primary energy figures for sodium carbonate and phosphoric acid used in rapeseed oil esterification but there is no indication that these are needed for processing tallow.

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[24] In commercial practice, Sheehan et al. (1998) reported that a variety of base catalysts has been used for the esterification reaction, including sodium hydroxide and potassium hydroxide, as well as sodium methoxide.

B.3 Energy Requirements

Sheehan et al. (1998) stated that their base case estimate of the energy requirements for soybean oil conversion was from a preliminary engineering design loosely based on data from an existing esterification plant in Missouri. Their energy budget proved to be much lower than that reported for this facility yet a review of the literature on (then) recent esterification technology revealed that their design estimate was at the high end of the range of published literature values. They chose baseline estimates of 1.53 MJ/kg biodiesel for steam consumption and 1.99 MJ/kg biodiesel for primary energy content with a high uncertainty range of around ±70%. For electricity consumption, they chose 0.37 MJ/kg biodiesel for primary energy content again with a high uncertainty range of around ±70%.

Nelson and Schrock (2006) used a similar electricity figure, of 0.39 MJ/kg biodiesel for primary energy content, but a figure of 9.0 MJ/kg biodiesel for the primary energy content for natural gas which we feel is too high for our study. Delucchi and Lipman (2003) quoted a more useful "industry potential" figure of 1.32 MJ/kg biodiesel compared with an average industry figure nearly five times higher.

Beer et al. (2001) used primary energy content figures for steam and electricity that were 80% and 30% of the respective Sheehan et al. (1998) figures. Mortimer et al. (2003) used primary energy figures for steam and electricity that were 108% and 77% of the respective Sheehan et al. (1998) figures. For the NZ uncertainty range for steam consumer energy in a new plant (presumably close to "industry potential"), the Sheehan et al. (1998) figure was chosen as the upper limit and 50% of that level as the lower limit. The NZ primary energy calculation assumed this to be generated from natural gas at 80% net efficiency and 13% upstream energy. For the purpose of calculating NZ GHG emissions, upstream emissions were assumed to have the same emission factor as Maui gas with an estimate of upstream emissions (Appendix E). For the NZ uncertainty range for consumed electricity in a new plant, the Sheehan et al. (1998) figure was chosen as the upper limit and 40% of that level as the lower limit. For the purpose of calculating NZ GHG emissions, a kilowatt-hour was assumed to have the same emission factor as the average for the NZ electricity sector (Appendix E) with an estimate of upstream emissions.

Table 21: Total Energy Input and Greenhouse Gas Emissions from Esterification

Study		**Primary energy input[1] (MJ/MJ BD)**	**Primary energy input (MJ/kg BD)**	**Greenhouse gas emissions (kgCO$_2$eq/kg BD)**
Sheehan et al 1998		0.189	7.57	0.181
Beer et al 2001		-	-	0.265
Mortimer et al 2003		0.183	7.29	0.432
Delucchi et al 2003		0.174	6.98	-
Nelson et al 2006		0.363	14.52	-
NZ estimate	Low	0.144	5.77	0.152
	High	0.242	9.68	0.356
	Best	0.193	7.72	0.254

[1] Primary energy inputs for most studies were calculated in reference to a range of (net) lower heating values for biodiesel that have been approximately converted here to (gross) higher heating values for comparison. The NZ estimates are calculated in reference to a higher heating value of 39.95 MJ/kg for tallow biodiesel (Appendix A).

Appendix C Fossil Diesel Fuel Model

The **direct GHG emission factor** for NZ diesel (MED 2006a Tables A1.3, A2.1, A2.2) is:

$69.5\ CO_2 + 0.080*21$ for CH_4 + $0.001149*310$ for N_2O

= **70.73 ktCO_2eq/PJ or gCO_2eq/MJ$_{consumer}$**.

Including the **indirect GHG emissions** from upstream primary energy, the total GHG emission factor for NZ diesel is:

70.73 + 11.82 = **82.55 gCO_2eq/MJ$_{consumer}$.**

This is based on the following analysis. Using the fuel mix described by Sheehan et al. (1998), an analysis was conducted to determine the GHG released from the upstream diesel energy. Table 22 shows the fuel mix for NZ diesel. Half of the electricity use occurs in NZ during refining and domestic transport and the other half during foreign oil extraction. Greenhouse gas emissions from NZ electricity generation are 25.2 gCO_2eq/MJ$_{primary}$ (see below). The carbon dioxide emissions from foreign electricity generation were based on Saudi Arabia's electricity being mostly oil fired generation plants at a rate of 74.8 gCO_2eq/MJ. In addition to the emissions from burning fossil fuels, advanced onshore oil extraction techniques use carbon dioxide directly at a rate of 0.6 g/MJ (Sheehan et al., 1998).

Table 22: NZ Fossil Diesel's Primary Energy Fuel Mix and Greenhouse Gas Emissions

Fuel Type	**MJ$_{primary}$ /MJ$_{consumer}$**	**gCO_2eq/MJ$_{primary}$**	**gCO_2eq/MJ$_{consumer}$**
CO_2 for oil extraction	-	0.6	0.73
Electricity – NZ	0.026	26.0	0.68
Electricity – Foreign	0.026	74.8	1.94
Natural gas	0.091	52.4	4.77
Heavy fuel oil	0.044	74.8	3.29
Diesel (Road transport of diesel in NZ)	0.006	70.73	0.42
Diesel (consumer)	1.000	70.73	70.73
Total	**1.193**		**82.55**

Appendix D Biodiesel Heating Value

Literature figures for heating values for biodiesel appear to be highly inconsistent and in at least one case may be wrongly cited or calculated from another publication.

The most consistent source of heating values for biodiesel in general (no vegetable oil source was stated) was found through the US Alternative Fuels Data Center (www.afdc.doe.gov) reference to "Exhaust Emissions Performance of Diesel Engines with Biodiesel Fuels," C.A. Sharp, Southwest Research Institute, summer 1998.

Heat of Combustion, gross (HHV) 39.8 MJ/kg; net (LHV) 37.2 MJ/kg

Checked by calculating the LHV/HHV ratio 37.2 / 39.8 = 0.935

This is almost identical to the 0.937 ratio we have calculated using the Sheehan et al. (1998) analysis for soybean methylester (Table 109: 77.2% carbon, 11.9% hydrogen, 10.8% oxygen) with their LHV of 37.5MJ/kg. ISO 1928-1976(e) uses the equation:

HHV = LHV + 0.212*hydrogen (%) + 0.0008*oxygen (%) + 0.0245*moisture (%) MJ/kg

= 37.5 + 2.52 + 0.01 + 0 MJ/kg

= 40.03 (37.5/40.03 = 0.937) MJ/kg

Beer et al. (2001) used LHV in some places and HHV in others and their report is generally unclear despite a statement in Appendix 8 that they used HHV for stoichiometric calculations. Their flow diagrams containing their only base data used the same value of 37.8 MJ/kg for biodiesel from rapeseed, canola, soybeans, waste cooking oil and tallow and this is consistent with LHV from other studies. Their Table 4.1 included a HHV value for tallow methylester of 39.9 MJ/litre (and 39.8 MJ/litre for soybean methylester) that are very unlikely and should instead be MJ/kg.

Mortimer et al. (2003) based their rapeseed oil methylester analysis on a comprehensive pair of UK studies that used a LHV of 37.27 MJ/kg. However, they also quote the Beer at al. (2001) figure of 37.84 MJ/kg for FAME (fatty acid methylester) without commenting on the contradiction of the consequent LHV/HHV ratio of 0.985 (instead of the 0.937 we derived from the ISO equation above).

The HHV value of 39.95MJ/kg from Mittelbach for tallow methylester used for this study was chosen for its consistency with other methylesters (soybean methylester 39.8 MJ/kg).

Applying the 0.937 ISO factor for LHV = 37.43 MJ/kg.

The *New Zealand Energy Information Handbook* (Baines, 1993) quotes in Table 9.3 Sims et al. (1982) LHV figures of 40.4 MJ/kg for tallow methylester and 39.1 MJ/kg for rapeseed oil methylester. Applying the 0.937 ISO factor gives derived HHV figures of 43.1 and 41.7 MJ/kg respectively. These are considered unreasonably high in comparison with other studies and could mean they are wrongly quoted as LHV instead of HHV (which would then be consistent with other studies).

Conversion to HHV for biodiesel primary energy is approximate for some components because LHV/HHV ratios for energy mixes are not known.

Appendix E Greenhouse Gas Emissions Factors

All greenhouse gas emission factors have been based on HHV (gross calorific value).

Diesel (summary of Appendix C)

The direct GHG emission factor for NZ diesel (MED 2006a Tables A1.3, A2.1, A2.2) is:

= 69.5 CO_2 + 0.080*21 for CH_4 + 0.001149*310 for N_2O

= **70.73 ktCO_2eq/PJ or gCO_2eq/MJ**.

Including the **indirect GHG emissions** from upstream primary energy, the total GHG emission factor for NZ diesel is:

70.73 + 11.82 = **82.55 gCO_2eq/MJ.**

Natural Gas

The direct GHG emission factor for Maui gas in industrial boilers (MED 2006a Tables A1.1, A2.1, A2.2) is:

52.3 CO_2 + 0.0013*21 for CH_4 + 0.00009*310 for N_2O = 52.35 ktCO_2eq/PJ or gCO_2eq/MJ

The total GHG emission factor for Maui gas in industrial boilers is assumed to include the indirect GHG emissions from half (to minimise double counting) of the extra 13% upstream primary energy (using the direct gas emission factor) plus fugitive CO_2 and methane emissions (MED 2006a Tables 6.1.1 and 6.1.2 and MED 2006b total gas supply):

52.35*1.065 + (649+15.573*21kt)/154.86PJ = 55.75 + 6.30 = 62.05 gCO_2eq/$MJ_{consumer}$.

Coal

The direct GHG emission factor for the average sub-bituminous coal in industrial boilers (MED 2006a Tables A1.4, A2.1, A2.2) is:

91.2 CO_2 + 0.00066*21 for CH_4 + 0.00015*310 for N_2O = 91.26 ktCO_2eq/PJ or gCO2eq/$MJ_{consumer}$.

The total GHG emission factor for the average sub-bituminous coal in industrial boilers is assumed to include the indirect GHG emissions from the extra 4% upstream primary energy (using the diesel emission factor) plus fugitive coal mining methane emissions:

91.26 + 5.55 = 96.81 gCO_2eq/$MJ_{consumer}$.

From the Coal Corporation (later Solid Energy) voluntary agreement, it can be calculated that diesel use (and electricity use) were targeted at 0.066 GJ (and 0.0054 kWh) per tonne of coal or cubic metre of overburden. The weighting between coal and overburden is highly variable depending on the development stages of different mines and whether the mining is opencast (using more diesel) or underground (using more electricity). Nevertheless, for the average coal, the sum of these energy consumption figures represents only 0.0039MJ input per MJ output. This is only one tenth of the 4% upstream energy figure used by Alcorn and Wood (1998) and suggests this may be an over-estimate for NZ coal.

Electricity

The primary energy content has been calculated from MED data (2006b) as 2.11 kWh of primary energy to supply 1 kWh to the consumer. This is based on the primary energy supply figure for electricity generation (including cogeneration) in 2005 of 312 PJ and consumption of 148 PJ (MED, 2006b). In addition to the primary energy supply figure energy described by the MED Energy Data File (300 PJ), additional energy is added to take into account coal mining and distribution plus gas extraction, treatment and distribution (11.5 PJ).

The additional 11.5 PJ of coal and gas energy has been calculated based on the energy coefficients of 1.04 MJ/MJ for coal and 1.13 MJ/MJ for gas (Alcorn and Wood, 1998). This adds 1.96 PJ and 9.56 PJ to the coal and gas electricity generation supplies respectively.

The direct GHG emission factor for average electricity use (MED 2006a Table 1.1.1 and 2006b Table G.3 for 2005) is:

7148000 tCO$_2$eq /41245 GWh = 173.3 gCO$_2$eq/kWh.

Divide by 3.6 = 48.1 gCO$_2$eq/MJ$_{\text{consumer.}}$

The total GHG emission factor for average electricity use is:

197.2 gCO$_2$eq/kWh or 54.8 gCO$_2$eq/MJ$_{\text{consumer}}$ or 26.0 gCO$_2$eq/MJ$_{\text{primary}}$.

This includes 0.162MtCO$_2$eq from diesel used to mine coal, 0.110MtCO$_2$eq from coal fugitive methane emissions, 0.250MtCO$_2$eq from half (to minimise double counting) the extra 13% upstream primary energy (using the direct gas emission factor) and 0.464MtCO$_2$eq from gas fugitive CO$_2$ and methane emissions. All coal used at Huntly Power Station is assumed to have the same primary energy content as the average NZ coal because there was no information available on the amount of Indonesian coal or its primary energy content including mining, shipping and trucking.