Department of Chemical Engineering

Energy Balance of Biodiesel Production from Rapeseed in Western Australia

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Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

Signature:

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Executive Summary

Increasing energy consumption in Australian transport sector, rapidly depleting amount of Australian oil reserves, and the environmental concerns that arise from the associated greenhouse gas emissions produced by the combustion of large amount of fossil fuels during transport activities have increased the interest in using renewable transport fuels, especially ethanol and biodiesel, as replacements for petrol and diesel fuels, respectively, in the transport sector.

In Western Australia, there is a potential for replacing diesel fuel consumed in its transport sector by biodiesel produced from rapeseed (canola) grown as one of the break crops between cereal crops. Apart from the availability of raw material, sustainable biodiesel production from rapeseed needs to be analysed from, among other factors, its energy efficiency, which can be determined from the energy ratio of the overall biodiesel production process, defined as the ratio of energy output from biodiesel to the total primary energy consumed during rapeseed growing and processing into biodiesel.

In this study, the energy ratio of biodiesel production from rapeseed in Western Australia is evaluated through an energy balance analysis, considering typical Western Australian rapeseed growing practices and rapeseed processing parameters. The energy ratio is then used to evaluate the land, water, and labour requirements of a large scale biodiesel production to analyse its feasibility as a replacement for fossil diesel fuel consumption in Western Australian transport sector. The energy ratio and feasibility of the biodiesel production process are then compared to those of ethanol production from mallee in Western Australia since both biofuels are produced as alternative transport fuels and an assessment is therefore needed to decide which fuel is more feasible to produce, considering the competition for limited resources, e.g. arable land, during their production

Without by-products utilisation, the energy ratio of biodiesel production from rapeseed is found to be less than 1, indicating a negative energy return. The most significant improvement to the energy ratio is achieved when all by-products are utilised, resulting in an energy ratio of 1.70.

A feasibility analysis using the net energy approach with an energy ratio of 1.70 shows that the land and labour requirements of a large scale biodiesel production are the major constraints to its realisation as an alternative to diesel fuel in Western Australian transport sector. Replacement of a significant fraction of diesel fuel consumption in the transport sector would cause severe competition for arable land with production of other crops. The net biodiesel production rate is also lower than that required to maintain the current transport activities that are supported by diesel fuel produced by Western Australian energy sector.

Feasibility analysis of large scale ethanol production shows, on the other hand, that there is potential to replace approximately 15% of the total petrol fuel consumption in Western Australian transport sector with ethanol produced from mallee grown in Western Australian wheatbelt to tackle dryland salinity problem. The net ethanol production rate would also be sufficient to maintain the current transport activities that are supported by petrol fuel produced by Western Australian energy sector. The feasibility of the large scale ethanol production is, however, dependent on the availability of sufficient water, and hence rainfall, to maintain a consistent mallee yield per hectare of agricultural area.

The results of energy balance and feasibility analyses in this study imply that wide implementation of rapeseed-based biodiesel in Western Australia is unsustainable. Possible future implementation should be directed at smaller and more specific targets and should be supported by development of key strategies in both rapeseed growing and rapeseed processing stages aimed at increasing rapeseed yield and reducing main energy input contributors to improve the energy ratio and productivity of the whole production process. The results also show that ethanol production from mallee grown in Western Australian wheatbelt to tackle dryland salinity problem provides an option for a large scale biofuel production to play significant role in future energy security in Western Australian transport sector.

Chapter 1

Introduction

The transport sector is shown to be one of the most energy intensive sectors in Australia, where, in 2006-2007, it consumed 1359.2 PJ, which is approximately 24% of the total annual domestic energy consumption of 5770 PJ in the same period (ABARE, 2008a). Approximately 74% of the energy consumed in the transport sector was in the form of automotive fuels, i.e. petrol and diesel fuels, which are manufactured from fossil fuel resources. In the face of rapidly depleting fossil fuel resources, the large amount of automotive fuels consumed in the Australian transport sector poses a significant challenge to the future energy security in Australia. Additional concerns also arise from the associated greenhouse gas emissions produced by the combustion of such a large amount of fossil fuels during transport activities.

1.1 Challenge for Future Australian Energy Security

The aforementioned automotive fuel consumption was approximately 51% of the total domestic refinery feedstock and petroleum products availability of 1989.7 PJ in the same period (ABARE, 2008b). This domestic availability is supplied, in part, by the production from Australian proved oil reserves, which, by the end of 2005, was estimated to last for just approximately another 20 years (Table 1-1) (BP, 2006). Considering the large contribution of automotive fuel consumption to the depletion of proved oil reserves, finding an alternative transport fuel that is renewable is of significant urgency to ensure future energy security in Australia.

Table 1-1 Proved oil reserves and their consumption in Australia and the world at the end of 2005 (BP, 2006).

	Proved oil reserves[a] **(barrels)**	**Consumption**[b] **(barrels/year)**	**Reserve to usage ratio**[c] **(year)**
Australia	4.00E+09	2.02E+08	19.8
World	1.20E+12	2.96E+10	40.6

[a] Proved oil reserves are the amount of remaining oil reserves that geological and engineering information indicates with reasonable certainty can be recovered in the future from known reservoirs under existing economic and operating conditions. [b] The amount of oil from proved oil reserves that are exploited in a given year. [c] Indicates how long proved oil reserves would last if exploitation continued at the same rate.

1.2 Importance of Reducing Greenhouse Gas Emissions

The large energy consumption in the Australian transport sector has also led to significant greenhouse gas emissions from the sector, which, in 2005, were estimated to be 80.4 million tonnes of CO_2 equivalent (Pink, 2008c), or approximately 14.4% of the total net national greenhouse gas emissions in 2005. A large proportion of these greenhouse gas emissions are produced by the combustion of fossil fuels during transport activities. In view of the Australian government's ratification of the Kyoto Protocol, which came into force for Australia on 11 March 2008 (Wong, 2008), reducing greenhouse gas emissions from consumption of fossil automotive fuels is of critical importance in an effort to comply with emission reduction target committed by Australia under the Protocol.

1.3 The Role of Renewable Energy

As a result of the need to ensure future energy security and to reduce greenhouse gas emissions from the combustion of fossil fuels, interest in renewable energy sources for automotive fuels has increased recently in Australia. There has been a growing trend in Australia to use biofuels, especially ethanol and biodiesel, as replacements for petrol and diesel fuels, respectively. Interests in using these biofuels mainly stemmed from the claim of their renewability and CO_2 neutrality. Biofuels can be produced from renewable raw materials, i.e. fermentation of sugar crops (e.g. sugarcane, sugarbeet, sweet sorghum) or of starchy crops (e.g. corn and cassava) in the case of ethanol and extraction and transesterification of oil from oilseed crops (e.g. rapeseed, soybean, sunflower, palm) in the case of biodiesel (Giampietro et al., 1997). Ethanol and biodiesel are also often claimed to be "CO_2 neutral" on the basis that the carbon dioxide given out during their combustion is equivalent to that taken up during growing stages of the raw materials from which they are produced. Replacing fossil automotive fuels with ethanol and biodiesel therefore has the potential of relieving some pressure on the very limited amount of the remaining Australian proved oil reserves and helping to reduce greenhouse gas emissions from combustion of fossil fuels.

1.4 Western Australian Situation

In Western Australia, where a considerable amount of cereal crops are grown annually, the advantages of replacing fossil diesel fuel with biodiesel have the potential to be realised. Rapeseed is included in the cereal crop rotation as a break crop to help manage and control diseases and pests during cultivation of cereal crops (Duff et al., 2006). Apart from being a means of disease and pest control for cereal crops, rapeseed is a raw material from which rapeseed oil is produced through extraction of the oilseeds. The extracted oil can then be processed further to produce biodiesel. Managed with good cultivation practice and rotation programme, rapeseed growing in Western Australia has the potential of providing the source of biomass necessary for sustainable production of biodiesel to meet the increasing future energy demand in Western Australian transport sector.

Apart from the availability of rapeseed as raw material, sustainable biodiesel production in Western Australia also depends upon, among other factors, the energy ratio of the overall biodiesel production process. The energy ratio is defined as the ratio of the total energy output from biodiesel and any utilised by-products to the total non-renewable primary energy consumed during the whole production process, which includes the energy consumed during rapeseed cultivation and rapeseed oil extraction and conversion into biodiesel. This output/input energy ratio must be greater than 1 for any biodiesel production process to be sustainable. An evaluation of this energy ratio under typical Western Australian rapeseed cultivation practices and rapeseed processing parameters is an integral part of a sustainability assessment of biodiesel production from rapeseed in Western Australia.

1.5 Objective of This Thesis

The main objective of this study is to determine energy ratio of biodiesel production from rapeseed in Western Australia by conducting an energy balance analysis under typical Western Australian rapeseed growing practice and commercial rapeseed processing (rapeseed oil extraction and conversion into biodiesel) parameters. The energy ratio will then be used to evaluate the land, water, and labour requirements of a large scale biodiesel production from rapeseed to analyse its feasibility as an alternative to diesel fuel consumption in Western Australian transport sector.

A literature review on the energy balance analysis of biodiesel production will be discussed in the next chapter, followed by a methodology chapter, in which the method of accounting of the energy requirements and energy outputs of the overall biodiesel production from rapeseed, and also the method of its feasibility analysis, are described. The results of the energy balance analysis are described in the subsequent chapter, including a discussion on the evaluation of the feasibility analysis. The conclusions that can be derived from the energy balance and feasibility analyses and some recommendations for future work are then summarised in the concluding chapter.

Chapter 2

Literature Review

The process chain of biodiesel production from rapeseed under typical Western Australian conditions is described in this chapter. The energy balance analyses of biodiesel production from rapeseed and also from other raw materials that have been done by previous studies are also discussed in this chapter. This chapter is concluded by the summary of the findings of the previous studies and the objectives of this current study on the energy balance and feasibility analyses of biodiesel production from rapeseed under typical Western Australian rapeseed growing practices and rapeseed processing parameters.

2.1 Process Chain of Biodiesel Production from Rapeseed

The process chain of biodiesel production from rapeseed typically consists of three main stages described in Figure 2-1. In the first stage, the raw material, rapeseed, is produced in an agricultural process of rapeseed cultivation, by the end of which rapeseed is harvested. In the next stage, rapeseed oil is extracted and then refined from the harvested rapeseed. In the last stage, the refined rapeseed oil is then transesterified into biodiesel, which is the main product of the biodiesel production process, and glycerol, which is a by-product of the production process. The agricultural process of rapeseed cultivation also produces rapeseed straw, an agricultural residue which can also be considered as a by-product of the biodiesel production process. Another by-product of the process is the rapeseed meal that is left over after extraction of the oil. Between the main stages of the process chain, transport activities are required to transfer the rapeseed and rapeseed oil to their respective processing plants. The product biodiesel also needs to be distributed to filling stations and any utilised by-products are collected and transferred to their respective utilisation sites. The transport arrangements usually vary according to the infrastructure of the process chain.

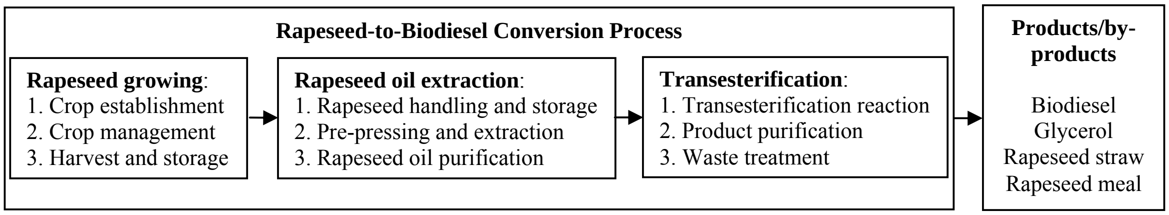


Figure 2-1 Process chain of biodiesel production from rapeseed.

2.1.1 Rapeseed Growing

In Western Australia, rapeseed is grown as a break crop between cereal crops to help manage and control diseases and pests (weeds and insects) during cultivation of cereal crops (Duff et al., 2006). Rapeseed growing practices in Western Australia usually vary between growers and depend on, among other factors, the rapeseed variety sown, the amount of rainfall, soil condition, and the prevailing farm pests (weeds/insects) and diseases in a region. A typical agricultural region in the Western Australian wheat belt where rapeseed can be grown as a break crop is the Great Southern and Lakes District (Carmody and Herbert, 2001), where both conventional and herbicide tolerant varieties of rapeseed can be sown. Due to weed management issues, however, more than 90% of rapeseed grown in the Great Southern and Lakes District are the herbicide tolerant varieties, particularly the triazine tolerant (TT) varieties (Carmody and Herbert, 2001). Growing TT rapeseed varieties in this region typically involves pre-seeding knockdown (pest control) and fertiliser application, followed by seed planting, post-seeding (pre and post-emergence) pest control, additional fertiliser application, and also crop monitoring throughout the growing season (Carmody and Herbert, 2001, Duff et al., 2006, Knight, 2006, Singh et al., 2008). At the end of growing season, rapeseed is harvested and stored temporarily before being transported using trucks to an oil extraction plant, where the next stage of the biodiesel production process takes place. The typical activities associated with growing TT rapeseed along with their input quantities are described in a later chapter in Table 4-1. The rapeseed straw, i.e. parts of the rapeseed plant other than the oilseed, which is left over after harvesting is usually ploughed back into the soil. However, it also has potential utilisation in energy production by combustion and gasification (Quaak et al., 1999, Wachendorf, 2008), and, when utilised it also needs to be transported to its utilisation site.

2.1.2 Rapeseed Oil Extraction

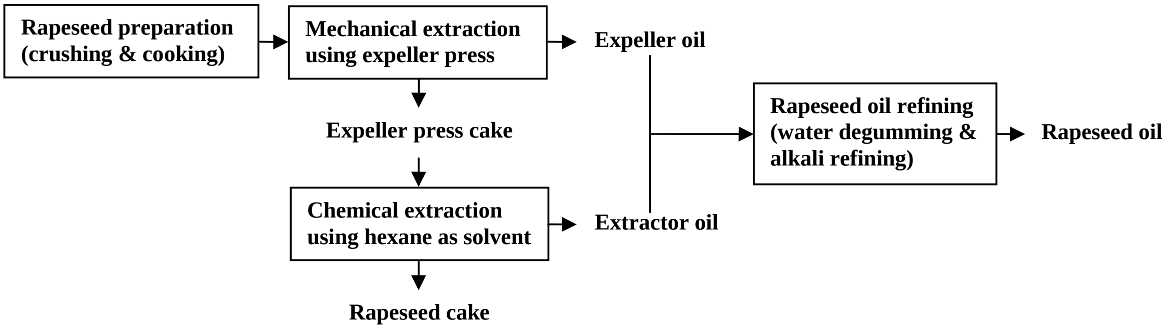


Figure 2-2 Rapeseed oil extraction by pre-pressing in an expeller press followed by solvent extraction using hexane (Anjou, 1972).

The rapeseed oil extraction process involves the separation of oil from the oil-bearing material. This can be achieved by mechanical means (pressing), chemical means (solvent extraction), or a combination of both (Anjou, 1972). In Western Australia, a rapeseed oil extraction plant, which is located in Pinjarra and is operated by Riverland Oilseed Processors Pty. Ltd. (RiverlandOilseeds, 2007b), utilises the combined extraction method (Figure 2-2), where the rapeseed is pre-pressed using an expeller press prior to solvent extraction of the press cake. To facilitate extraction of the oil, rapeseed is crushed by roller mills and then subjected to a heat treatment in a stack cooker prior to the mechanical extraction using expeller press, where some of the rapeseed oil is extracted. The left over press cake is then sent to the solvent (hexane) extractor, where the remaining rapeseed oil is extracted and combined with the expeller oil prior to refining. For fuel-grade rapeseed oil, the refining process consists of degumming with water and removing the remaining water-insoluble impurities using an alkali solution. After refining, the oil is transported using oil tankers to a transesterification plant, where it is converted into biodiesel. As a by-product, the rapeseed cake from the solvent extractor can be utilised, mainly as animal feed (Bonnardeaux, 2007). An alternative utilisation of rapeseed meal in energy production by combustion has also been suggested (Bostrom et al., 2008). Whenever utilised, the rapeseed meal also needs to be transported to its utilisation sites.

2.1.3 Rapeseed Oil Transesterification

Rapeseed oil is converted into biodiesel through the transesterification reaction (Figure 2-3). The transesterification reaction is a reversible chemical reaction in which the triglycerides (triacylglycerols) in rapeseed oil react with an alcohol to produce biodiesel and, as a by-product, glycerol.

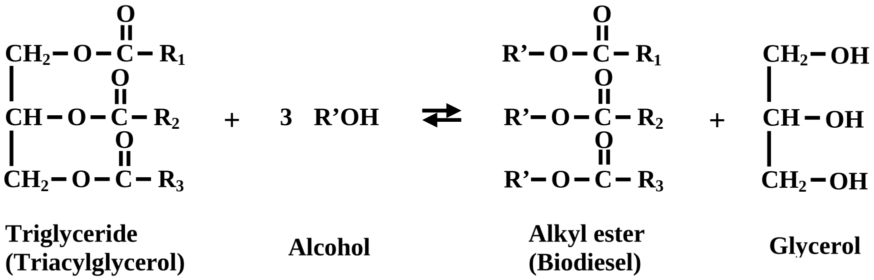


Figure 2-3 Transesterification reaction. R_1, R_2, and R_3 are a mixture of various fatty acid alkyl chains. The alcohol used is usually methanol ($R'=CH_3$) (Gerpen and Knothe, 2005, Ma and Hanna, 1999).

The transesterification process is a process where the transesterification reaction is utilised to produce biodiesel on a commercial basis. The predominant transesterification process in use for industrial scale biodiesel production is the homogeneous alkali-catalysed transesterification process (Haas and Foglia, 2005), in which the transesterification reaction is catalysed by sodium or potassium hydroxide dissolved in an excess amount of the reacting alcohol (usually methanol). In this process (Figure 2-4), the crude products from the reactor are separated in a gravity settler. The crude biodiesel is then purified further by water washing followed by drying, whereas crude glycerol is purified by evaporation of volatile impurities followed by neutralisation of the catalyst, which remains in the glycerol stream after reaction. The excess alcohol that is also removed during the purification processes is recovered in a distillation column and is then recycled back to the reactor.

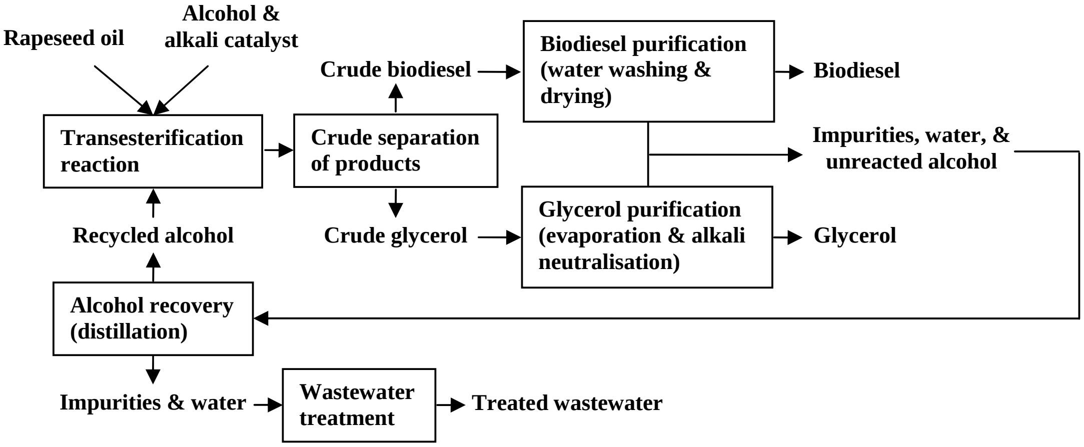


Figure 2-4 Homogeneous alkali-catalysed transesterification process (adapted from Chau et al., 2002).

Apart from the homogeneous alkali-catalysed transesterification process, there are also alternative transesterification processes, which include both catalytic and non-catalytic processes. Alternative catalytic transesterification processes are carried out using solid catalyst (heterogeneous catalysis), usually metal oxide or carbonate, or using the enzyme lipase as catalyst (enzymatic catalysis). The non-catalytic process is carried out by reaction with supercritical alcohol, usually methanol, i.e. supercritical methanol (SCM) process. These alternative transesterification processes have been reviewed elsewhere (Haas and Foglia, 2005). Their advantages and disadvantages in comparison to the homogeneous alkali-catalysed transesterification process are summarised in Table 2-1.

Table 2-1 Alternative transesterification processes and their advantages and disadvantages compared to homogeneous alkali-catalysed transesterification (Haas and Foglia, 2005, Kiwjaroun et al., 2009).

	Catalytic process		**SCM process**
	Heterogeneous	**Enzymatic**	
Catalyst	Solid metal oxide or carbonate	Immobilised lipase methyl ester	None
Reaction condition	0.1-5 MPa, 30-200^{0}C	0.1 MPa, 35-40^{0}C	>8.09 MPa, >239.4^{0}C
Reaction time	0.5-3 h	1-8 h	120-240 s
Advantages	Simpler product purification process and less waste material	Catalyst reuse, higher glycerol purity, flexibility towards free fatty acid content of rapeseed oil	Very fast reaction, much higher yield and purity of products, no waste water generated
Disadvantages	Moderate biodiesel yield	High cost of catalyst, inactivation of catalyst by contaminants in oil and by short-chain alcohols	Very high reaction temperature and pressure leading to high energy and equipment costs

Despite their advantages, these alternative processes are largely in developmental stage, with little or no actual current application in the biodiesel industry (Haas and Foglia, 2005), leaving the homogeneous alkali-catalysed transesterification process as the most common transesterification process in use for industrial scale biodiesel production. The homogeneous alkali-catalysed transesterification process is also utilised by an oil transesterification plant in Western Australia, which has been built in Picton and is operated by Australian Renewable Fuels Pty. Ltd. (ARF, 2008a). For these reasons, the homogeneous alkali-transesterification process is used in this energy balance and feasibility study of biodiesel production from rapeseed in Western Australia.

The biodiesel product from the transesterification plant is transported using oil tankers to a terminal operation site of a fuel provider, where the biodiesel is blended with conventional petroleum diesel prior to distribution to service stations operated by the fuel provider. Biodiesel is sold as B20 blend (20%vol biodiesel in petroleum diesel) in Western Australia by Gull Petroleum (Batten and O'Connell, 2007, O'Connell et al., 2007), which has a terminal operation in Kwinana and 23 of its service stations selling the B20 blend around Western Australian metropolitan area (GullPetroleum, n.d.).

2.2 Energy Requirements of Biodiesel Production from Rapeseed

The energy requirements of biodiesel production from rapeseed have been evaluated in several previous studies. These studies evaluated the total direct and indirect energy requirements of the production process in terms of primary energy requirements and accounted for the utilisation of by-products by allocating some of the energy requirements to the utilised by-products. Most of these studies compared the total primary energy requirement to that of the production of conventional fossil diesel fuel and/or of other biofuels, mainly ethanol, in an attempt to assess the energetic advantage of producing biodiesel from rapeseed over that of producing conventional fossil diesel fuel and/or other biofuels. The total primary energy requirements of different scales of biodiesel production process and of different transesterification technologies used in the production process chain have also been compared in some other studies.

2.2.1 Direct and Indirect Energy Requirements

The total primary energy requirement of biodiesel production from rapeseed evaluated in the previous studies consists of direct and indirect energy requirements. Direct energy requirements are those in the form of fuels, electricity, and/or process heat directly consumed by the process. These direct energy requirements are accounted for by considering not only their inherent energies, but also the energies used in their provision. Indirect energy requirements are those accumulated in the materials and chemicals, farm machineries/equipments, transport vehicles, processing plants equipments, and/or services (e.g. labour), etc., that are consumed or needed by the biodiesel production process chain. These indirect energy requirements are accounted for by considering all energies involved in their supply and, in case of machineries/equipments (e.g. farm machineries, plant equipments, and vehicles), the energies involved in the maintenance.

2.2.2 Allocation of Energy Requirements

The biodiesel production process generates by-products, i.e. rapeseed straw, rapeseed meal, and glycerol, which can be utilised for various different purposes. In previous studies, utilisation of the by-products is accounted for by allocating some of the energy requirements to the utilised by-products. Different allocation methods, e.g. allocation by mass, market price, energy (calorific) value, and also by substitution, have been adopted in the previous studies, depending on the utilisation of the by-products.

Allocation by market price and by energy value are the most common allocation methods used in previous studies evaluating energy requirements of the biodiesel production process and are considered to be suitable to represent utilisation of the by-products when they are sold for various (usually non-fuel) purposes and when they are used as fuels or energy sources, respectively. The applications of allocation by market price in the evaluation of energy requirements of biodiesel production from rapeseed and also of production of other biofuels have been exemplified in some previous studies (Elsayed et al., 2003, Mortimer et al., 2003, Mortimer and Elsayed, 2006). Allocation by substitution, in which the energy requirements associated with the production of other products that can be displaced by the by-products are used to displace some of the energy requirements of the biodiesel production process, is the more preferred method. However, since the substitution procedure requires the by-products be utilised to displace existing products which are the main products of other production processes, whereas in many cases, the products displaced are, in fact, joint products or by-products of other production processes, the alternative allocation methods are usually adopted (Mortimer et al., 2003, Mortimer and Elsayed, 2006).

2.2.3 Comparison with Total Energy Requirement of Fossil Diesel Production

Elsayed et al. (2003) and Mortimer et al. (2003) evaluated the total primary energy requirement of biodiesel production from rapeseed in the UK. Similar biodiesel production process chains were used in their evaluation. By-products (rapeseed straw, rapeseed meal, and glycerol) were sold for other uses and energy requirements were allocated by market prices. The total primary energy requirement was then compared to that of ultra low sulphur diesel production from crude oil. Similar evaluation and comparison of total primary energy requirement of biodiesel production from rapeseed to that of fossil diesel was conducted in Germany (Kaltschmitt et al., 1997), using allocation of energy requirements by energy value on rapeseed meal and glycerol. Their results (Table 2-2) showed that the total primary energy requirement of biodiesel production from rapeseed is smaller than that of fossil diesel production, suggesting that primary energy savings could be obtained when biodiesel is used to replace fossil diesel.

Table 2-2 Total primary energy requirements of biodiesel production from rapeseed and of fossil diesel production.

Author(s)	Elsayed et al. (2003) Mortimer et al. (2003)	Kaltschmitt et al. (1997)
Total energy requirement		
Biodiesel	0.44 MJ/MJ biodiesel[a]	16204 MJ/(ha year)[d]
Fossil diesel	1.26 MJ/MJ diesel[b]	47096 MJ/(ha year)[e]
Energy saving	0.82 MJ/MJ[c]	30892 MJ/(ha year)

[a] Total primary energy requirement of producing 1 MJ of biodiesel (based on net calorific value of biodiesel of 37.27 MJ/kg). [b] Total primary energy requirement of producing 1 MJ of ultra low sulphur diesel from crude oil (based on net calorific value of ultra low sulphur diesel of 42.38 MJ/kg). [c] Comparison is made between total primary energy requirement of biodiesel production and that of conventional ultra low sulphur diesel production on the basis of equivalent net energy content of biodiesel and ultra low sulphur diesel. [d] Total primary energy requirement of biodiesel production from 1 hectare of rapeseed produced in an average growing season. [e] Total primary energy requirement of producing fossil diesel that can be substituted by biodiesel produced from 1 hectare of rapeseed.

Mortimer and Elsayed (2006) showed that different by-products utilisation scenarios, which were accounted for by different allocation procedures, could affect the total primary energy requirement of the production process and hence the primary energy saving that can obtained from producing biodiesel from rapeseed in the UK. Their study considered two options for utilisations of rapeseed meal, i.e. sold as animal feed and as co-firing fuel in a coal-fired power station. When sold as animal feed, allocation by market price was used on both rapeseed meal and glycerol (which was sold for other uses). When used as co-firing fuel, allocation by substitution for energy inputs associated with average electricity supply that was displaced by co-firing was used on the rapeseed meal and allocation by market price was used on the glycerol. Their results (Table 2-3) showed that utilisation of rapeseed meal as co-firing fuel greatly increased the potential primary energy saving that can be obtained from replacing fossil diesel with biodiesel.

Table 2-3 Effect of different by-product utilisation scenarios on the total primary energy requirement of biodiesel production from rapeseed (Mortimer and Elsayed, 2006).

	Allocation	
Rapeseed straw	Waste (no allocation)	Waste (no allocation)
Rapeseed meal	Market price	Substitution
Glycerol	Market price	Market price
	Total energy requirements	
Biodiesel (MJ/MJ biodiesel)[a]	0.54	0.042
Fossil diesel (MJ/MJ diesel)[b]	1.26	1.26
Energy saving (MJ/MJ)[c]	0.72	1.22

[a] Total primary energy requirement of producing 1 MJ of biodiesel (based on net calorific value of biodiesel of 37.27 MJ/kg). [b] Total primary energy requirement of producing 1 MJ of ultra low sulphur diesel from crude oil (based on net calorific value of ultra low sulphur diesel of 42.38 MJ/kg). [c] Comparison is made between total primary energy requirement of biodiesel production and that of conventional ultra low sulphur diesel production on the basis of equivalent net energy content of biodiesel and ultra low sulphur diesel.

Some studies evaluated the total fossil fuel consumption associated with biodiesel production from rapeseed in Belgium (Halleux et al., 2008, Spirinckx and Ceuterick, 1996). The total fossil fuel consumption, which is related to the total primary energy requirement, was found to be lower than that of fossil diesel production. It is interesting to note, however, that the total fossil fuel consumption was evaluated in these studies as one of the environmental impact categories of biodiesel production and the lower fossil fuel consumption does not necessarily lead to lower overall environmental impact of biodiesel production compared to fossil diesel production (Spirinckx and Ceuterick, 1996), and that the overall environmental impact of biodiesel production is markedly affected by allocation to the by-products (Halleux et al., 2008).

2.2.4 Comparison with Total Energy Requirement of Ethanol Production

The total primary energy requirement of biodiesel production from rapeseed has also been compared to that of the production of ethanol in some studies. The comparison is deemed necessary when both biofuels are produced for similar purposes (alternative transport fuels) and therefore an assessment is needed to decide which fuel is more energetically beneficial to produce, since their productions are in competition for arable land use, which is a limited resource.

Elsayed et al. (2003) calculated the total primary energy requirements of ethanol production processes from 3 different raw materials, i.e. lignocellulosics (wheat straw), sugar beet, and wheat in the UK. The ethanol production process chain considered for each raw material consisted of cultivation and/or harvesting of raw material, pre-treatment (e.g. milling, shredding, hydrolysis, etc), followed by fermentation and distillation to produce ethanol. Transport between the cultivation area and the processing plant was also included in the process chain. The results showed that the total primary energy requirements of ethanol production from sugar beet and wheat (0.50 MJ/MJ ethanol and 0.46 MJ/MJ ethanol, respectively) were slightly higher than the total primary energy requirement of biodiesel from rapeseed (0.44 MJ/MJ biodiesel). Production of ethanol from lignocellulosics (wheat straw), however, resulted in a net production of energy (0.028 MJ/MJ ethanol), mainly because the residue from pre-treatment and hydrolysis of the wheat straw could be utilised to not only provide all the heat and electricity in processing plant, but also produce surplus electricity, for which substitution energy credit was given for the displacement of average grid electricity by the surplus electricity.

Halleux et al. (2008) evaluated and compared the environmental impacts of biodiesel production from rapeseed to those of ethanol production from sugar beet in Belgium. Impact categories which are related to the total primary energy requirements of both production processes, such as fossil fuel consumptions, were included in the evaluation. It was found that, without allocation of environmental impacts to the by-products (i.e. rapeseed meal and glycerol for biodiesel production and sugar beet pulps for ethanol production), the total fossil fuel consumption, and also the overall environmental impact, associated with biodiesel production were only slightly lower than those associated with ethanol production. When the environmental impacts were allocated to the by-products, however, the overall environmental performance of the biodiesel production process was significantly improved relative to that of the ethanol production process, implying the relative environmental significance of the by-products of the biodiesel production process compared to those of the ethanol production process.

2.2.5 Comparison of Total Energy Requirements of Different Scales of Biodiesel Production from Rapeseed

In order to study the effect of production scale on the total primary energy requirement, Stephenson et al. (2008) compared total primary energy requirements of large scale (≥100000 tonnes/year) and small scale (≤10000 tonnes/year) biodiesel production from rapeseed in the UK. The process chains of both production scales are shown in Figure 2-5. For large scale production, rapeseed was cultivated in farms all over UK, whereas for small scale production, rapeseed was cultivated locally in East Anglia, UK. Also, for small scale production, drying and storage of rapeseed and oil extraction occurred on the farm, whereas for large scale production, harvested rapeseed had to be transported to an extraction plant. Rapeseed oil was extracted by combined mechanical and solvent (hexane) extraction and was refined in the large scale production, whereas in the small scale production, it was extracted mechanically without further refining.

Their results (Table 2-4) showed that, under the same allocation procedure, the scale of production had little effect on the total primary energy requirement of the production process. The results also showed that, within a production scale (the small scale in Table 2-4), different by-products utilisation scenarios, accounted for by different allocation procedures, could affect the total primary energy requirement of the production process, similar to the finding of Mortimer and Elsayed (2006) aforementioned. When either the rapeseed meal or glycerol was assumed to be utilised as co-firing fuel in a coal-fired power plant or a combined heat and power (CHP) plant, allocation by substitution for primary energy inputs associated with average electricity supply or average heat and power supply that were displaced by co-firing was used and the total primary energy requirement of the biodiesel production process was lower than when both rapeseed meal and glycerol were sold for non-fuel purposes and allocation by market prices was used. It is interesting to note that the utilisation of rapeseed meal in a power station or a CHP plant led to the production process being a net energy producer (noted by negative primary energy requirements in Table 2-4), indicating that the primary energy inputs associated with average electricity supply or heat and power supply that were substituted for by the co-firing were higher than the energy requirements of the biodiesel production process.

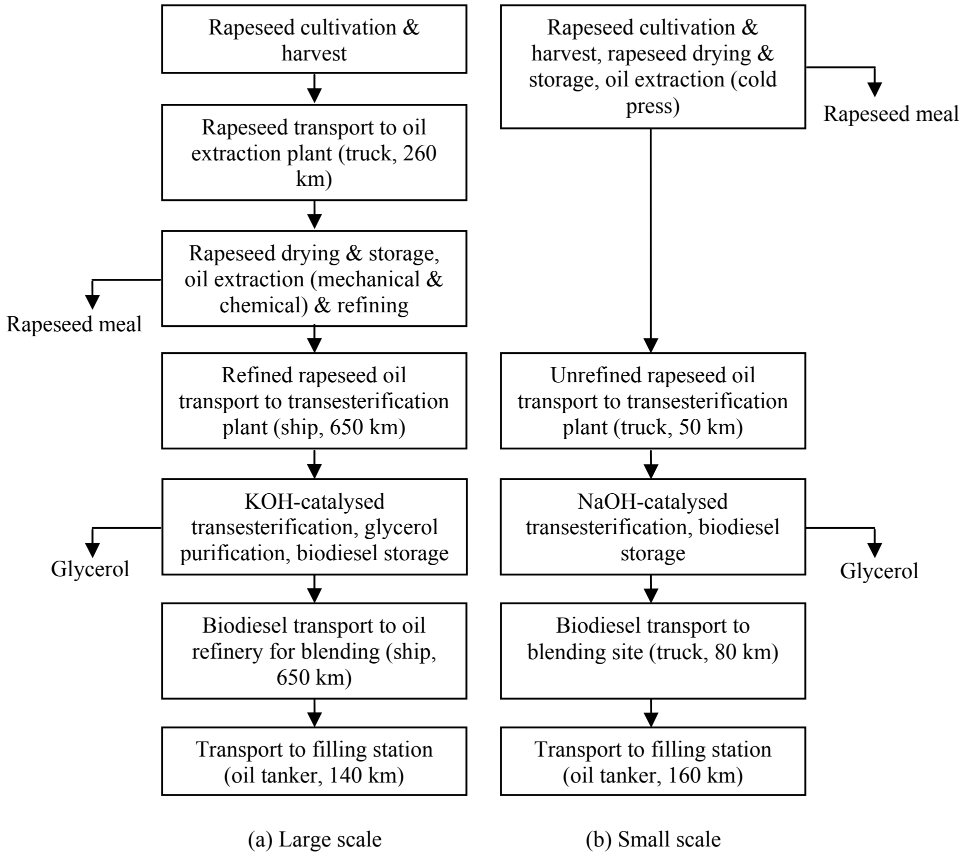


Figure 2-5 Process chains for large and small scale biodiesel production from rapeseed in the UK (adapted from Stephenson et al. (2008)).

Table 2-4 Total primary energy requirements of large and small scale biodiesel production from rapeseed in the UK (Stephenson et al., 2008)

	Scale					
	Large	Small	Small	Small	Small	Small
	Allocation					
Rapeseed straw	No allocation		No allocation		No allocation	
Rapeseed meal	Market price[a]		Substitution[c] (power plant)	Substitution[d] (CHP plant)	Market price[a]	
Glycerol	Market price[b]		Market price[b]		Substitution[e] (power plant)	Substitution[f] (CHP plant)
	Total energy requirements (MJ/MJ biodiesel)[g]					
	0.55	0.54	-0.25	-0.62	0.43	0.39

[a] Rapeseed meal was sold as animal feed. [b] Glycerol was sold to pharmaceutical industry. [c] Rapeseed meal was used for co-firing in a coal-fired power station with substitution credit for primary energy inputs associated with average electricity supply that was displaced by co-firing. [d] Rapeseed meal was used for co-firing in a CHP plant with substitution credit for primary energy inputs associated with average power and heat supply that was displaced by co-firing. [e] Glycerol was used for co-firing in a coal-fired power station with substitution credit for primary energy inputs associated with average electricity supply that was displaced by co-firing. [f] Glycerol was used for co-firing in a CHP plant with substitution credit for primary energy inputs associated with average power and heat supply that was displaced by co-firing. [g] Total primary energy requirement of producing 1 MJ of biodiesel (based on net calorific value of biodiesel of 37.3 MJ/kg).

Bernesson et al. (2004) compared total energy requirements of small, medium, and large scale biodiesel production from rapeseed in Sweden. The process chains for the three biodiesel production scales are shown in Figure 2-6. A combined oil processing plant (extraction and transesterification) was assumed to process rapeseed harvested from 40 ha, 1000 ha, or 50000 ha farm for the small, medium, and large scale production, respectively. For small scale production, the processing plant was located on the farm. Oil extraction was carried out mechanically in the small and medium scale production, whereas combined mechanical and solvent extraction was used by the large scale production. Alkali-catalysed transesterification was used to convert rapeseed oil into biodiesel for all production scale. The rapeseed meal and biodiesel produced were transported back to the farm for large and medium scale production. Glycerol was, however, transported by a tank lorry to the consumer in all cases.

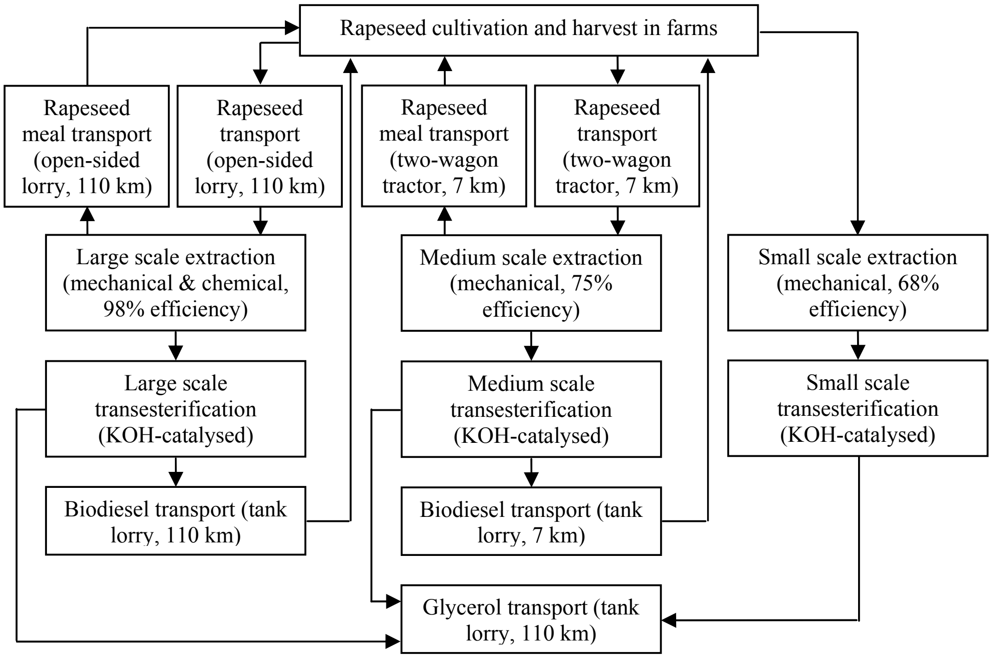


Figure 2-6 Process chains for large, medium, and small scale biodiesel production from rapeseed in Sweden (adapted from Bernesson et al. (2004))

Their results (Table 2-5) showed that when the energy requirements were allocated to the by-products using allocation by energy value and market price, the scale of production has little effect on the total primary energy requirement. When the energy requirements were solely burdened on the biodiesel product (i.e. no allocation in Table 2-5), however, the total primary energy requirement decreased as the production scale increased. Similar to the findings of Mortimer and Elsayed (2006) and Stephenson et al. (2008), the total primary energy requirement was affected by the allocation methods used. It is interesting to note that when the substitution method was used, the biodiesel production process became a net energy supplier at all scales studied (noted by the negative total primary energy requirements in Table 2-5). However, this result should be taken with caution since soybean meal that was replaced by rapeseed meal was likely to be produced as a by-product of another production process and, as mentioned by Mortimer and Elsayed (2006), application of substitution credit in this situation might give unrealistic result.

Table 2-5 Total primary energy requirements of large, medium, and small scale biodiesel production from rapeseed in Sweden (Bernesson et al., 2004).

Scale	**Allocation**[a]		**Total energy requirements (kJ/MJ biodiesel)**[b]
	Rapeseed meal	**Glycerol**	
Small	Energy value	Energy value	295
Medium			277
Large			284
Small	Market price	Market price	355
Medium			327
Large			313
Small	No allocation	No allocation	569
Medium			497
Large			407
Small	Substitution (production of soybean meal mixed with soybean oil)[c]	Substitution (production of glycerol from propane)[e]	-367
Medium			-342
Large	Substitution (production of imported soybean meal)[d]		-147

[a] No allocation was made to rapeseed straw which was assumed not to be utilised. [b] Total primary energy requirement of producing 1 MJ of biodiesel (based on the lower heating value of biodiesel of 38.5 MJ/kg). [c] Substitution credit for primary energy inputs associated with production of soybean meal mixed with soybean oil that is replaced by rapeseed meal. [d] Substitution credit for energy inputs associated with production of imported soybean meal that is replaced by rapeseed meal. [e] Substitution credit for primary energy inputs associated with glycerol production from fossil propane gas that is replaced by glycerol from transesterification.

2.2.6 Comparison of Total Energy Requirements of Biodiesel Production from Rapeseed Utilising Different Transesterification Technologies

The different transesterification technologies discussed previously can also affect the total energy requirement of the biodiesel production process. An insight into the effect of the different transesterification technologies can be gained from some studies that evaluated and compared the environmental impacts of the different transesterification technologies and included impact categories that are related to total primary energy requirement of the production process, such as fossil fuel consumption, in their evaluation.

The environmental impacts of a conceptual enzyme-catalysed transesterification were compared to those of the homogeneous alkali-catalysed transesterification (Harding et al., 2007). It was found that the conceptual enzyme-catalysed transesterification had a lower impact in the abiotic depletion category, which included the fossil fuel consumption, than the homogeneous alkali-catalysed transesterification. This was attributed to the lower process heating (steam) requirements in the enzyme-catalysed transesterification.

Kiwjaroun et al. (2009) compared the environmental impacts of a conceptual non-catalysed transesterification under supercritical methanol to those of the homogeneous alkali-catalysed transesterification. It was found that the fossil fuel consumption, and also the overall environmental impact, of the supercritical methanol process were higher than the homogeneous alkali-catalysed transesterification. This was attributed to the much larger excess amount of methanol used in the supercritical process, requiring larger energy expenditure in the methanol recovery system, and also to the much higher process temperature and pressure than in the homogeneous alkali-catalysed transesterification.

2.2.7 Energy Requirements of Biodiesel Production from Other Oilseeds and Raw Materials

The energy requirements of biodiesel production from other oilseeds and raw materials have also been studied in several previous studies, which evaluated and compared the total primary energy requirement of the biodiesel production to that of conventional fossil diesel production.

The total primary energy requirements of biodiesel production from soybean in China (Hu et al., 2008), Italy (Carraretto et al., 2004), and USA (Sheehan et al., 1998) were evaluated, taking into account soybean cultivation, soybean oil extraction and transesterification, transport of soybean and/or soybean oil, and biodiesel distribution in the production process chain. The results are shown in Table 2-6. Hu et al. (2008) and Sheehan et al. (1998) found that more primary energy was required to produce biodiesel from soybean than to produce conventional fossil diesel, implying that no primary energy saving was obtained from replacement of fossil diesel by soybean based biodiesel. This is contrary to most of the results for total primary energy requirements of biodiesel production from rapeseed discussed in the previous sections, which indicated net primary energy saving obtained from replacement of fossil diesel by biodiesel. Furthermore, Carraretto et al. (2004) also conducted e*m*ergy analysis to evaluate the environmental support required to produce biodiesel from soybean and found that larger amount of environmental resources was required to convert soybean to biodiesel than was required to produce fossil fuels.

Table 2-6 Total primary energy requirements of biodiesel production from soybean and of fossil diesel production.

Author(s)	Hu et al. (2008)	Carraretto et al. (2004)	Sheehan et al. (1998)
Allocation	Mass	Mass	Mass
Total energy requirement			
Biodiesel (MJ/MJ$_{biodiesel}$)	1.31	1.40	1.24
Fossil diesel (MJ/MJ$_{diesel}$)	1.26	n.s.*	1.20

*** Not specified.**

Elsayed et al. (2003) calculated the total primary energy requirement of biodiesel production from recycled vegetable oil in the UK, considering the cleaning and transesterification of the recycled vegetable oil in the production process chain and allocating the energy requirements between biodiesel and glycerol by their market prices. This study reported a total primary energy requirement of 0.19 MJ/MJ biodiesel, indicating a net primary energy saving when compared with the total primary energy requirement of conventional ultra low sulphur diesel production (1.26 MJ/MJ diesel). The ecological footprint of biodiesel production from recycled vegetable oil has also been evaluated (Niederl and Narodoslawsky, 2004) and it was found that the ecological footprint of the biodiesel production process was lower than that of fossil diesel production.

2.3 Energy Ratios of Biodiesel Production from Rapeseed

The output/input energy ratio of the biodiesel production from rapeseed, defined as the ratio of the total energy value of biodiesel and any utilised by-products to the total non-renewable primary energy consumed during the whole production process, has been evaluated in several previous studies. These studies evaluated the output/input energy ratio under different parameters of a given production process chain in an attempt to assess the feasibility of the production process. An output/input energy ratio of higher than 1 has been considered necessary in the previous studies for the biodiesel production process to be feasible, since only then there would not be a net loss of energy in the production process, which would otherwise negate its status as a renewable energy source (Batchelor et al., 1995).

2.3.1 Energy Input and Output Accounting

Previous studies evaluating the output/input energy ratio of biodiesel production from rapeseed calculate the total energy requirement (input) of the production process and account for the utilisation of by-products by calculating the useful energy obtained from their utilisation rather than allocating some of the total energy requirement to the utilised by-products. Depending on the utilisation, the useful energy obtained from the by-products can be added to the energy output obtained from biodiesel or be substituted as energy credit to replace some of the total energy requirement of the process.

By-products utilisation as fuels has been assumed in many previous studies evaluating the energy ratio, in which case the useful energy obtained from the utilised by-products is calculated from their respective energy contents and yields and is added to the energy output from biodiesel. Other utilisations of by-products than as fuels are also common. Rapeseed meal is commonly utilised as animal feed (Bonnardeaux, 2007, Braid, 2007), in which case an energy credit is assigned to the rapeseed meal and is evaluated from the replacement value, that is the energy value of the substitute product replaced in animal nutrition (Culshaw and Butler, 1992). Glycerol from the biodiesel production process is also usually utilised to replace glycerol produced from conventional method, e.g. as the by-product of soap production process, in which case an energy credit, equal to the energy required to produce the same amount of glycerol in the conventional method as that replaced by the glycerol from transesterification, is assigned to the glycerol from transesterification process

2.3.2 Energy Ratios of Biodiesel Production from Rapeseed under Different Process Parameters

Culshaw and Butler (1992) calculated the output/input energy ratios of biodiesel production from two different rapeseed cultivars, i.e. winter and spring rapeseed, in the UK. The harvested rapeseed was transported to and processed in a combined oil extraction and transesterification plant, where rapeseed oil was mechanically extracted, refined, and converted into biodiesel, which was then distributed to consumers. Typical agricultural energy input data under UK conditions and typical rapeseed processing and transport energy input data from a processing plant were used to calculate the total primary energy requirement. Assuming that the by-products (rapeseed straw, rapeseed meal, and glycerol) were used as fuels, the results (Table 2-7) showed that the energy ratios were higher than 1 for all different combination of biodiesel and utilised by-products and were found to be very similar for both winter and spring rapeseed, because although spring rapeseed required less nitrogen fertiliser during cultivation, it gave lower yield of rapeseed, and hence lower yields of biodiesel and other by-products contributing to the energy output from the production process.

Table 2-7 Output/input energy ratios of biodiesel production from rapeseed in the UK (Culshaw and Butler, 1992).

Outputs included	**Energy ratio**
Biodiesel	1.35
Biodiesel + rapeseed meal	2.55
Biodiesel + rapeseed meal + glycerol	2.62
Biodiesel + rapeseed meal + glycerol + straw	3.77
Biodiesel + straw	2.5

Table 2-8 Output/input energy ratios of biodiesel production from winter rapeseed in the UK under different conditions (Batchelor et al., 1995).

Outputs included*	Batchelor et al. (1995)			
	Best case scenario	Intermediate		Worst case scenario
		Good	Poor	
1	2.23	1.58	1.12	0.674
2	3.83	2.22	1.6	0.88
3	3.95	2.3	1.65	0.91
4	9.18	5.46	3.92	2.22

*** 1 = biodiesel only; 2 = biodiesel + rapeseed meal; 3 = biodiesel + rapeseed meal + glycerol; 4 = biodiesel + rapeseed meal + glycerol + straw.**

Batchelor et al. (1995) further evaluated the output/input energy ratio of biodiesel production from winter rapeseed in the UK using a similar process chain to that of Culshaw and Butler (1992). A range of energy values was calculated for each energy requirement and output to account for different soil and weather conditions, variation in yield, and different estimates of energy required for various processes in the UK. The results (Table 2-8) showed that the energy ratio was dependent on the prevailing conditions under which biodiesel was produced, as shown by the large variation of energy ratio between best case (very high yields with very low energy requirements) and worst case scenarios (very low yields with very high energy requirements). The variation was attributed mainly to the difference of the amount of nitrogen fertiliser applied during rapeseed cultivation between best case (small amount) and worst case (large amount), which was identified as the biggest single factor, with respect to energy requirement, affecting the energy ratio. It was also shown that utilisation of rapeseed meal and, particularly, rapeseed straw gave significant improvement to the energy ratio. Utilisation of glycerol only gave little impact on the energy ratio.

Output/input energy ratio of biodiesel production from rapeseed in Lithuania was calculated by Janulis (2004), comparing the energy ratio obtained from utilisation of conventional technologies under Lithuanian conditions to that obtained if new low energy input and environmentally friendly technologies were implemented in the biodiesel production process. Rapeseed growing, oil extraction, and transesterification were included in the process chain. Assuming utilisation of by-products (rapeseed meal, straw, and glycerol) as fuels, the results (Table 2-9) showed that the application of the new technology increased the energy ratio by approximately 1.6 times. Similar to the finding of Batchelor et al. (1995), the results also showed that utilisation of rapeseed straw gave significant improvement to the energy ratio.

Table 2-9 Output/input energy ratios of biodiesel production from rapeseed in Lithuania (Janulis, 2004).

Outputs Included*	**Output/input energy ratio**	
	Conventional technology	**New technology**
1	1.04	1.66
2	1.76	2.82
3	3.80	6.08

*** 1 = biodiesel only; 2 = biodiesel + rapeseed meal + glycerol; 3 = biodiesel + rapeseed meal +glycerol + straw.**

2.3.3 Comparison with Energy Ratios of Ethanol Production

By comparing their results for biodiesel production from rapeseed to those for ethanol production from wheat under similar range of conditions, Batchelor et al. (1995) pointed out that the energy ratios of biodiesel production were more favourable than those of ethanol production. It was mentioned that when only ethanol was considered as the energy output, a net loss of energy (energy ratio < 1) resulted from the production of ethanol under all scenarios (c.f. energy ratios of biodiesel production in Table 2-8). Also, when utilisation of all by-products of the ethanol production, i.e. wheat straw and distillers grains, were considered, the maximum possible energy ratio was considerably lower than the maximum energy ratio of biodiesel production.

Another study (Richards, 2000) also found a more favourable output/input energy balance for biodiesel production from rapeseed compared to that of ethanol production from wheat in the UK. When no by-products were utilised, an energy ratio of 1.78 could be achieved for biodiesel production and only a marginal net energy gain (energy ratio = 1.11) was obtained for ethanol production. When utilisations of by-products were considered, the energy ratios for biodiesel and ethanol production were 3.71 and 2.51, respectively. Utilisation of rapeseed straw and wheat straw as fuels was found to make a strong contribution to the energy ratios of the biodiesel and ethanol production, respectively.

Table 2-10 Typical output/input energy ratios of biofuel production systems from agricultural crops (Giampietro et al., 1997).

Biofuel production system	**Output/input energy ratio**
Biodiesel (from sunflower, soybean, rapeseed)	0.6 - 1.3
Ethanol in temperate areas	0.5 - 1.7
Ethanol in (sub)tropical areas	2.5 - 3.0

Giampietro et al. (1997) summarised a range of typical output/input energy ratios of biodiesel production from several oilseed crops (rapeseed, sunflower, and soybean) and also of ethanol production from crops grown in temperate areas and from crops grown in tropical/subtropical areas which had been evaluated previously from energy requirements and outputs data reported in the literature for the three biofuel production systems. The results (Table 2-10) showed that, contrary to the aforementioned comparisons, ethanol production from crops in tropical/subtropical areas showed more favourable energy ratios compared to those of biodiesel production, which shared similar energy ratios with ethanol production in temperate areas. It was further mentioned that the best performing system for biodiesel production was that from rapeseed, while the best performing system for ethanol production in temperate areas and in tropical/subtropical areas were that from corn-sorghum and sugarcane, respectively.

2.3.4 Energy Ratios of Biodiesel Production from Other Raw Materials

Output/input energy ratios of biodiesel production from soybean and sunflower seed in the USA were evaluated (Pimentel and Patzek, 2005) and were found to be 0.76 and 0.46, respectively, when only the energy output from biodiesel is considered. In the case of biodiesel production from soybean, the energy ratio was still lower than 1 (0.93) even when energy credit was assigned to the soybean meal co-product. The negative energy returns were attributed to the relatively low yields of oilseed crops and the highly energy intensive nature of oil extraction and transesterification processes.

Output/input energy ratio was also calculated for biodiesel production from animal fat in the USA (Nelson and Schrock, 2006). Cattle (cows) were bred and grown in farms and were transported from the farm to the feedlot before being slaughtered to obtain the animal fat, which was then transported to a rendering plant to render the fat into tallow. The tallow was then transported to a transesterification plant where it was converted into biodiesel by alkali-catalysed transesterification. In the study, energy ratios were evaluated for three different system boundaries including firstly the transesterification process only, followed by including the rendering operation, and then the growth and maintenance of the beef animal. It was found that favourable energy ratios (larger than 1) were obtained only when the animal growth stage was not included in the system boundaries. The choice of the system boundary and hence the various energy ratios for the production system was attributed to tallow being a by-product of the meat production system and hence was not intentionally produced as a feedstock for biodiesel, complicating the energy analysis of the production process.

2.4 Feasibility of Large Scale Biodiesel Production

The increasing trend of energy consumption in the transport sector, particularly in the form of automotive fuels, means that a large scale biofuel production is necessary to contribute significantly to the future energy security in the transport sector. Giampietro et al. (1997) proposed that the feasibility analysis of such a large scale biofuel production should be performed by relating the performance of the production process, as indicated by its output/input energy ratio, to the characteristics of both the socioeconomic and environmental system in which the biodiesel production and consumption take place. Specifically, it was suggested that the biophysical (land and water) and labour requirements of a biofuel production process, as evaluated from its energy ratio, be compared with actual land and fresh water availability and existing socioeconomic constraints, such as the energy consumed by society per hour of labour in the primary sectors of the economy, to indicate whether a large scale biofuel production as an alternative to fossil fuel is feasible.

In their study, Giampietro et al. (1997) used the output/input energy ratios of the three most common biofuel production systems, i.e. biodiesel production from oilseed crops (rapeseed, sunflower, and soybean), ethanol production from crops grown in temperate areas, and ethanol from crops grown in tropical/subtropical areas (Table 2-10), to analyse the feasibility of the biofuel production systems as alternatives to fossil fuels in 21 countries and found that, to produce the biofuels, considerably larger land areas than the available arable land areas were required and the water requirement was considerably larger than the then current fresh water withdrawal. More importantly, the amount of energy delivered to the society per hour of labour should the biofuel production process become an alternative to fossil fuel was considerably lower than the energy throughput per hour of labour in the energy sector that was required to support the society and was supplied by fossil fuels.

Giampietro and Ulgiati (2005) performed similar analysis to analyse the feasibility of biodiesel production from sunflower seeds in Italy. A large scale biodiesel production under the conditions considered in their study was also found to be unfeasible due to excessive land and water demands which compete with other land uses (e.g. food production), low energy throughput per hour of labour, and also the environmental impacts associated with large scale sunflower cultivation and waste streams from sunflower conversion into biodiesel. The same conclusion was also found for other large scale biofuel production systems under Italian conditions analysed in the study i.e. ethanol production from corn and methanol production from fast growing woody crops.

2.5 Summary of Literature Review and Objectives of This Study

The total primary energy requirement of biodiesel production from rapeseed has been evaluated in several previous studies and was compared to those of conventional fossil diesel production and of ethanol production. The results of the studies suggested that primary energy savings could be obtained when biodiesel from rapeseed was used to replace fossil diesel and that less primary energy was mostly required to produce biodiesel from rapeseed than that to produce ethanol, hence the energetic advantage of producing biodiesel from rapeseed over ethanol. While the results of these studies have important significance in determining the advantage of producing biodiesel from rapeseed over producing conventional fossil diesel or another biofuel, they did not directly indicate the feasibility of the biodiesel production process.

As an indicator of the feasibility of biodiesel production from rapeseed, the output/input energy ratio has been evaluated in some previous studies. An output/input energy ratio of higher than 1 has been considered necessary in the previous studies for the biodiesel production process to be feasible, since only then there would not be a net loss of energy in the production process, which would otherwise negate its status as a renewable energy source. The energy ratios were evaluated under different parameters of a given biodiesel production process chain The results of these studies showed that the energy ratios depended on the parameters of both rapeseed (raw material) production and rapeseed processing stages (oil extraction and transesterification) of the process chain (e.g. nitrogen fertiliser application rate during rapeseed growing, rapeseed yield, efficiency of processing plant equipments) and also on the utilisation of the by-products of the biodiesel production process. High energy ratios were usually obtained in the results of the previous studies under good case scenario, i.e. low energy input and high yield, and also when rapeseed straw and rapeseed meal were utilised as fuels.

While the studies evaluating the output/input energy ratios of biodiesel production from rapeseed give important indications on the energetic viability of the production process under certain process chain parameters and by-products utilisation, these studies did not consider relating the biophysical (land and water) and labour requirements of the production process, which can be derived from its energy ratio, to the actual land and fresh water availability and the labour constraint in the society in which the biodiesel production and consumption take place as has been suggested in some previous studies to analyse the feasibility of a large scale biodiesel production necessary for the biodiesel to contribute significantly as an alternative to fossil diesel fuel.

Only few of the previous studies analysing the feasibility of a large scale biofuel production has analysed the feasibility of a large scale biodiesel production as an alternative to fossil diesel fuel. Specifically, the feasibility of a large scale biodiesel production from rapeseed in Western Australia as an alternative to fossil diesel transport fuel has not been analysed before, despite the availability of rapeseed as raw material for biodiesel production. The aim of this study is to analyse the feasibility of a large-scale biodiesel production from rapeseed in Western Australia as a potential renewable future energy source for Western Australian transport sector by performing an energy balance analysis to determine the output/input energy ratio of the production process under typical Western Australian agricultural practice in rapeseed growing and commercial rapeseed processing (rapeseed oil extraction and conversion into biodiesel) parameters and relating the energy ratio to the characteristics of Western Australian socioeconomic and environmental system, especially the land and water availability and labour constraint. The specific objectives of this study are:

- To obtain typical rapeseed growing field data and statistics and rapeseed processing (oil extraction and transesterification) parameters applicable to Western Australian conditions, and also the transport means and distances involved in the transport and/or distribution of rapeseed, rapeseed oil, biodiesel, and any utilised by-products during biodiesel production from rapeseed in Western Australia.

- To evaluate the total primary energy requirement of biodiesel production from rapeseed in Western Australia from the data obtained and also the biodiesel energy output and energy credits from by-products utilisation to enable the calculation of energy ratio, and also the energy productivity, of the biodiesel production process.

- To analyse the feasibility of a large scale biodiesel production from rapeseed in Western Australia by evaluating its land, water, and labour requirements from the energy ratio and comparing them to the actual Western Australian land and water availability, and labour constraint in Western Australian energy sector.
- To suggest some key biodiesel and biofuel production strategies in Western Australia from the comparison of the energy ratio and energy productivity of biodiesel production from rapeseed in Western Australia evaluated in this study to those evaluated in other countries/regions in the world and from the comparison of the feasibility of the large scale biodiesel production to that of a large scale ethanol production from mallee in Western Australia.

Chapter 3

Methodology

This chapter outlines the methodology by which the energy requirements and energy outputs of the biodiesel production from rapeseed under typical Western Australian conditions are accounted for, facilitating the evaluation of the output/input ratio of the production process. The methodology by which the feasibility of the production process is analysed using the result of the energy balance analysis is also described in this chapter.

3.1 Biodiesel Production System and Life Cycle Energy Inputs and Outputs

The process chain of biodiesel production from rapeseed considered in this study is shown with the energy requirements (inputs) involved in the production process in Figure 3-1. The energy requirements consist of direct energy requirements in the form of fuels, electricity, and/or process heat directly consumed by the process, and indirect energy requirements accumulated in the materials and chemicals, farm machineries/equipments, transport vehicles, processing plants equipments, and/or services (e.g. labour), etc., that are consumed or needed by the biodiesel production process. As mentioned previously, in the evaluation of the total energy requirement of the biodiesel production process, the direct energy requirements are accounted for by considering not only their inherent energies, but also the energies used in their provision. For example, fuel consumption is accounted for by taking into account its inherent energy value and the energy used for its production and delivery. The indirect energy requirements are also accounted for by considering all energies involved in their supply and, in case of machineries/equipments (e.g. farm machineries, plant equipments, and vehicles), the energies involved in the maintenance. For example, the chemicals (e.g. fertilisers, alkali catalyst) consumed by the biodiesel production process are accounted for by considering all the energies involved in their manufacturing process and delivery.

The energy output is the energy contained in the product biodiesel and the useful energy obtained from the utilisation of the by-products (rapeseed straw, rapeseed meal, and glycerol), which, depending on their utilisation, can be added to the energy output obtained from biodiesel or be substituted as energy credit to replace some of the total energy requirement of the process. The methods used to account for the energy requirements of biodiesel production from rapeseed and energy outputs and/or energy credits from the biodiesel and by-products are discussed in the following sections.

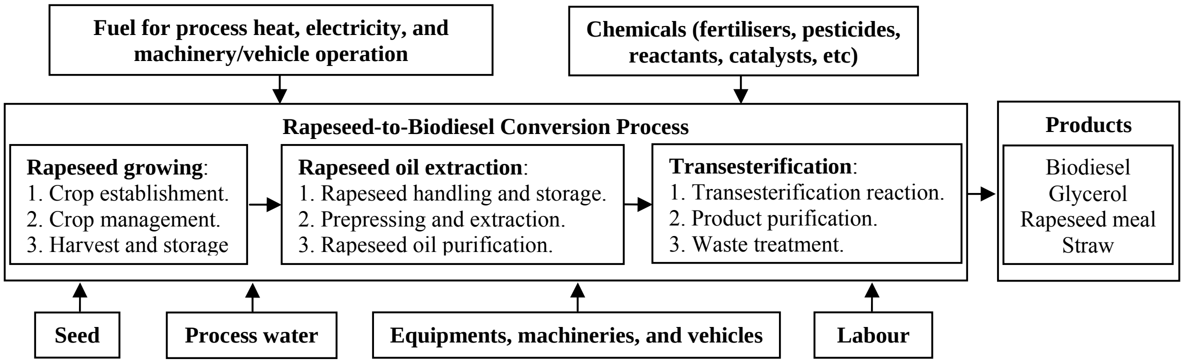


Figure 3-1 Process chain of biodiesel production from rapeseed with its various energy requirements.

3.2 Specific Energy Densities

The specific energy density is defined as the total accumulated non-renewable primary energy in a unit quantity of an item (Wu et al., 2008, Wu et al., 2006). Wherever possible the specific energy density of an item is calculated using

Australian statistical data, direct first-hand process data, process analysis, or sample analysis. Otherwise, data published in the literature are considered.

3.2.1 Specific Energy Density of Fuels

The specific energy density of a unit amount of fuel is the total of its inherent energy and the energy required to extract, process, and transport/distribute the unit amount of fuel. The specific energy density can be calculated by multiplying the inherent energy with the inverse of the fuel efficiency (Leach, 1976). The efficiencies of various delivered fuels have been evaluated in previous publications (Cervinka, 1980, Leach, 1976) and are used in this study to calculate the specific energy densities of the fuels relevant to the biodiesel production process. The specific energy densities of these fuels are shown in Table 3-1.

Table 3-1 Energy efficiencies and specific energy densities of various delivered fuels (Cervinka, 1980, Leach, 1976).

Fuel	Unit	Inherent energy (MJ/unit)	Efficiency (%)	Energy density (MJ/unit)
Petrol/gasoline	Litre	34.22	80.91	42.30
Diesel	Litre	38.64	80.91	47.76
L. P. gas	Litre	26.08	80.91	32.24
Natural gas (offshore)	m^3	41.36	83.68	49.43
Manufactured gas	m^3	38.56	76.34	50.51
Coal	kg	30.22	92.77	32.57
Coke	kg	28.04	84.75	33.09

3.2.2 Specific Energy Density of Electricity

The specific energy density of electricity is calculated by considering the electricity generation efficiency. In Western Australia, electricity is most commonly generated in a steam cycle by a coal-fired power station, with an efficiency of approximately 35% (Diesendorf, 2005). Combining this electricity generation efficiency with the energy efficiency of coal (Table 3-1), the overall energy efficiency of a unit amount of electrical energy is 32.47%. Using the inverse of this overall energy efficiency as a multiplier, the specific energy density of electricity equals 11.09 MJ/kWh electrical energy.

3.2.3 Specific Energy Density of Process Heat

Process heat is delivered as direct energy input mainly in the form of steam. The specific energy density of steam is calculated by considering the efficiency of the steam boiler that is used to generate the steam. A typical Australian steam boiler efficiency of 85% (based on the lower heating value of the fuel used by the boiler) is used in this study (ROAMConsulting, 2000). Combining the efficiency of the steam boiler with the efficiency of the fuel used by the boiler gives the overall efficiency of the energy delivered by the steam, which can be used to calculate its energy density. Using coal as the fuel for the boiler, the overall efficiency is 78.86%, giving an energy density of 1.27 MJ/MJ delivered by steam. The specific energy density of process heat delivered in other forms (e.g. heat for drying) is calculated using similar procedure, i.e. by considering the efficiency of the equipment generating the heat (e.g. dryer) and the efficiency of the fuel (Table 3-1) used by the equipment.

3.2.4 Specific Energy Density of Agricultural Machineries and Equipments

The specific energy density of the tractor used for various agricultural field activities is accounted for by considering the energy inputs required for its depreciation (manufacture) and maintenance (repair parts, oils, and greases). Following the method adopted by a previous publication (Leach, 1976), these energy inputs are calculated as the tractor performs various field operations (work-load basis) and are close to 40% of the fuel energy inputs for all sizes of tractors. The specific energy density of the tractor is correspondingly obtained by multiplying the total primary energy input associated with tractor fuel consumption when performing field operations, which will be discussed in a later chapter, by a factor of 0.4.

The specific energy densities of other agricultural field machineries and equipments (e.g. self-propelled harvester/swather, application equipments, tillage equipments etc.) are adapted from a previous publication (Leach, 1976) and are shown in Table 3-2.

Table 3-2 Specific energy densities of various agricultural field machineries and equipments (Leach, 1976).

Field machinery/equipment	Specific energy density
Plough	120 MJ/ha
Harrow	18 MJ/ha
Fertiliser application equipment	45 MJ/ha
Pesticide application equipment (e.g. sprayer)	34 MJ/ha
Seeding/sowing equipment	158 MJ/ha
Self-propelled harvester/swather	820 MJ/ha
Straw baler	330 MJ/ha
Drying & storage equipment	130 MJ/t rapeseed dried

3.2.5 Specific Energy Density of Processing Plants and Equipments

The specific energy densities of the rapeseed oil extraction and transesterification plants and equipments are calculated from the capital costs of the processing plants using a monetary to energy conversion factor (Table 3-3), according to the method used by a previous publication (Batchelor et al., 1995). The monetary to energy conversion factor represents the primary energy consumption per unit of Gross Domestic Product (GDP) and is calculated based on Australian statistics on national total energy consumption and GDP. It is noted (Batchelor et al., 1995, Leach, 1976) that although many industries have MJ/$ performances close to the national average, the accuracy of the method is variable and energy values calculated using this method should be regarded as estimates.

Table 3-3 Australian total energy consumption and GDP (Trewin, 2006).

	Energy consumption (PJ)[a]	GDP (10^6\$)	Energy consumption/GDP (MJ/\$)
1998-1999	4884.7	667780	7.315
1999-2000	1971	692889	7.174
2000-2001	5034.1	707140	7.119
2001-2002	5110.8	734575	6.957
2002-2003[b]	5145.1	758147	6.879

[a] Primary plus derived energy. [b] The data of year 2002-2003 is used in this study.

3.2.6 Specific Energy Density of Transport Vehicle

The specific energy density of transport vehicle is accounted for by considering the energy inputs required for vehicle manufacture and maintenance (spare parts, tyres, etc.). Following the method adopted by a previous publication (Leach, 1976), these energy inputs are estimated as 25% of the fuel energy input consumed by the vehicle during transport activities. The specific energy density of the transport vehicle is correspondingly obtained by multiplying the total primary energy input associated with vehicle fuel consumption during transport activities, which will be discussed in a later chapter, by a factor of 0.25.

3.2.7 Specific Energy Density of Chemicals, Fertilisers, Pesticides, and Seed

Chemicals, fertilizers, and/or pesticides are accounted for by considering the primary energy requirements of the typical industrial process that produces the chemicals, fertilizers, or pesticides, which include the energy embodied in the required raw materials and the energy consumed in the manufacturing process. The specific energy densities of various chemicals consumed in the biodiesel production from rapeseed are shown in Table 3-4. The specific energy densities of pesticides (herbicides, insecticides, and fungicides) and various NPK fertilisers are shown in

Table 3-5 and Table 3-6, respectively. The specific energy density embedded in graded seed that is sown during the seeding operation in the rapeseed growing process is estimated from its cost using the monetary to energy conversion factor (Table 3-3), according to the method used in the previous publication (Wu et al., 2008). The typical cost for open pollinated rapeseed seed in Western Australia is A$ 3 – 8/kg seed (FarmWeekly, 2008). Taking an average cost of A$ 6/kg seed, the specific energy density of seed is estimated to be 41.27 MJ/kg seed.

Table 3-4 Specific energy densities of various chemicals.

	MJ/kg	**References**
Methanol	39.67	(LeBlanc et al., 1994, Cervinka, 1980)
KOH	42.33	(Worrell et al., 2000, Cervinka, 1980)
H_2SO_4	2.62	(Boustead and Hancock, 1979)
NaOH	42.33	(Worrell et al., 2000, Cervinka, 1980)
Process water	0.00925	(Boustead and Hancock, 1979)
Hexane	52.05	(Kaltschmitt and Reinhardt, 1997)
H_3PO_4	12.93	(Bhat et al., 1994, Cervinka, 1980)
$Al_2(SO_4)_3$	2.61	(Chau et al., 2002, Leach, 1976, Trewin, 2006)

Table 3-5 Specific energy densities of various pesticides (Bhat et al., 1994, Wu et al., 2008, Wu et al., 2006).

	Specific energy density* (MJ/kg active ingredient)
Herbicides	
2,4,D	108
Amitrol	213
Atrazine	213
Dicamba	318
Glyphosate	477
Metolachlor	299
Oxyfluorfen	238
Simazine	213
Other	238
Insecticides	
Carbaryl	186
Chlorpyrifos 500 g a.i./L	273
Other	268
Fungicides	
Benomyl	420
Fluometuron	378
Other	379

*** Includes the energy consumed for formulation, packaging and distribution of the pesticides.**

Table 3-6 Specific energy densities of various NPK fertilisers (Bhat et al., 1994, Kongshaug, 1998, Wu et al., 2006).

Fertilisers	**Composition**			**Specific energy density* (MJ/kg)**
	N%	**P%(as P_2O_5)**	**K%(as K_2O)**	
Urea	46			40.98
Urea Ammonium Nitrate	30			22.90
Ammonia	82			55.33
Ammonium nitrate	34			27.64
Ammonium sulphate	21			14.84
Calcium ammonium nitrate	27			19.83
Mono-ammonium Phosphate	11	54		15.34
Di-Ammonium phosphate	18	46		19.26
Single superphosphate		21.8		3.09
Triple superphosphate		46		7.92
Muriate of Potash			60	7.11
Sulphate of Potash			49.4	5.85
Flexi-N (liquid fertiliser)®	32			21.64
CSBP Agras No. 1®	17.5	17.4		15.42
CSBP Agyield®	17.5	40.1		18.78
CSBP Agrich®	12	26.1		12.67
CSBP Agstar®	15.5	29.3		15.71
Summit Easycrop 2®	31	20.6		25.81
Summit Rapeseed 2®	33	27.5		28.30
Summit Topyield 3®	27.3	26.4		23.95
Summit Cereal®	18.5	25.2		17.31
Summit Rapeseed 1®	18.5	25.2		17.31
Summit Croprich®	18	32.1		17.96
Summit Sustain®	10.8	27.5		12.0
Summit Cropyield®	17.1	44.9		19.19
Summit DAPSZC®	17.1	41.9		18.75

*** Includes the energy consumed formanufacture, packaging and transportation of the fertilisers.**

3.2.8 Specific Energy Density Associated with the Use of Labour

The specific energy density associated with the use of labour is estimated from the monetary cost (salary) of labour using the monetary to energy conversion factor (Table 3-3), according to the method used in previous publications (Wu et al., 2008, Wu et al., 2006).

3.3 Energy Output Accounting

The energy output of the biodiesel production process comes from the biodiesel as the main product. Apart from this energy output, utilisation of by-products (rapeseed straw, rapeseed meal, and glycerol) contributes as energy credits that can be substituted for some of the energy requirements of the biodiesel production process. The methods used to account for the energy output from biodiesel and energy credits from utilisation of by-products are discussed in the following subsections.

3.3.1 Biodiesel Energy Output

As an alternative transport fuel, biodiesel energy output is usually accounted for using its net calorific value. The figures published for the net calorific value of rapeseed-based biodiesel in several publications are similar and are summarized in Table 3-7. A value of 37.3 MJ/kg is used in this study.

Table 3-7 Net calorific value of rapeseed-based biodiesel.

Net calorific value (MJ/kg)	Reference
37.1-37.3	(Batchelor et al., 1995)
37.3	(Stephenson et al., 2008)
37.1	(Culshaw and Butler, 1992)
38.5	(Bernesson et al., 2004)
37.2	(Kaltschmitt et al., 1997)
37.7	(Janulis, 2004)

3.3.2 Rapeseed Straw Energy Credit

The most commonly used method to account for straw utilisation, i.e. adding the gross energy content of the straw to the energy output contributed by biodiesel, can be misleading because the quality factor of a fuel in the form of straw is much lower than that of a liquid fuel such as biodiesel (Giampietro et al., 1997). In this study, energy credit is instead assigned to the straw for its utilisation as energy source to substitute process heat and electricity requirements in the rapeseed oil extraction and transesterification plants.

The amount of process heat that can be obtained from straw is calculated from the typical properties of the straw (Karaosmanoglu et al., 1999, Peterson and Hustrulid, 1998) according to a procedure developed previously (Lyons et al., 1985) and is found to be 11.12 MJ/kg straw. The amount of electrical energy that can be obtained from straw is also calculated using the same procedure, assuming an overall electricity generation efficiency of 33.6% (based on lower heating value) in a conceptual straw-fired steam cycle (Wu et al., 2006), and is found to be 4.41 MJ/kg straw (1.22 kWh/kg straw).

The energy credits assigned to the straw are equivalent to the primary energy requirements associated with generation of the displaced process heat and electricity, which can be calculated from their energy densities (subsections 3.2.2 and 3.2.3). Displacement of 11.12 MJ of process heat in the form of steam by utilisation of 1 kg of straw corresponds to an energy credit of 14.13 MJ/kg straw. The energy credit associated with displacement of 11.12 MJ of other forms of process heat by utilisation of 1 kg of straw is calculated from the efficiencies of the equipment generating the heat and of the fuel used by the equipment. Displacement of 1.22 kWh of electricity by utilisation of 1 kg of straw is equivalent to an energy credit of 13.61 MJ/kg straw.

3.3.3 Rapeseed Meal Energy Credit

Rapeseed meal utilisation considered in this study is its most common utilisation as animal/livestock feed (Bonnardeaux, 2007, Braid, 2007). In this case, it is misleading to add the energy content of the meal to the energy output contributed by biodiesel since the rapeseed meal is not utilised as fuel (Culshaw and Butler, 1992). A method to account for the contribution of rapeseed meal is to assign an energy credit to the meal which is equal to its replacement value, i.e. the energy value of animal feed that can be replaced by the meal (Culshaw and Butler, 1992, Ulgiati, 2001). A typical replacement value for an Australian layer chicken feed (Layer Crumble®), 6.98 MJ/kg (MilneAgrigroup, 2004), is used in this study as an energy credit for rapeseed meal utilisation.

3.3.4 Glycerol Energy Credit

When accounting for the energy credit contributed by glycerol, it should be taken into consideration that the glycerol market worldwide is at or approaching saturation (Culshaw and Butler, 1992). Therefore, there is likely to be an excess of glycerol in the market should a considerable amount of glycerol be produced by the transesterification process and an alternative use for the glycerol should be sought after.

A possible scenario for the use of glycerol is for co-firing with coal in a coal-fired power station (Stephenson et al., 2008). In this case, an energy credit is assigned to glycerol based on the primary energy requirement associated with generation of the displaced electricity (subsection 3.2.2) as a result of glycerol co-firing. With a lower heating value of 17 MJ/kg glycerol (Stephenson et al., 2008), the electricity produced from the combustion of glycerol is 5.95 MJ/kg glycerol (assuming 35% efficiency), which corresponds to an energy credit of 18.36 MJ/kg glycerol.

3.4 Output/Input Energy Ratio and Energy Productivity

Following the previously discussed methods used to account for the energy requirements and the energy output and energy credits, the output/input energy ratio (R) of the biodiesel production process is calculated as:

$$R = \frac{Energy\ output\ \ from\ biodiesel}{Total\ \ primary\ energy\ requirement\ of\ \ biodiesel\ \ production\ \ process}$$

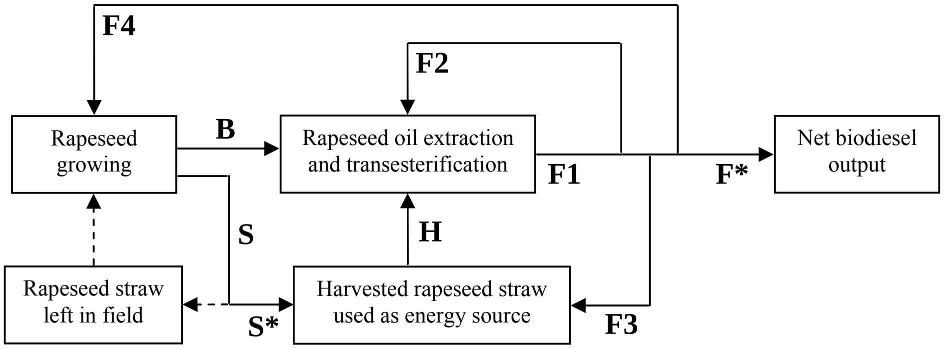
The energy productivity (E) will also be used as another indicator of energy performance of biodiesel production from rapeseed. The energy productivity has been defined in previous studies (Wu et al., 2008, Wu et al., 2006) as the total energy output per unit land area per annum. The energy productivity is accordingly defined in this study as the energy output from biodiesel that is obtained by processing rapeseed harvested from a unit of agricultural area (hectare) in a growing season:

$$E = \frac{Energy\ output\ \ from\ biodiesel}{Hectare\ \ per\ \ growing\ \ season}$$

The energy ratio will then be used to calculate the land, water, and labour requirements of the biodiesel production process, which will be compared to the actual land and fresh water availability and existing labour constraint in Western Australia, to indicate whether a large scale biodiesel production from rapeseed is feasible as an alternative transport fuel to fossil diesel in Western Australian transport sector. The method used to analyse the feasibility of the biodiesel production process will be discussed in the next section.

3.5 Feasibility Analysis (Net Energy Accounting)

The feasibility of a large scale biodiesel production that is necessary for a significant contribution to the Western Australian transport sector is analysed by comparing the land, water, and labour requirements of the production process to the actual land and water availability and existing labour constraint in Western Australia according to the net energy approach (Figure 3-2) suggested in previous studies (Giampietro and Ulgiati, 2005, Giampietro et al., 1997, Ulgiati, 2001). In the net energy approach, only part of the biodiesel produced (i.e. the net biodiesel output) is available as replacement for fossil diesel fuel. The rest of the biodiesel is invested back into the production process, creating an internal loop of energy requirement, so as to make the process not dependent on non-renewable fuels. This is deemed necessary since production of a large amount of biodiesel is likely to consume a large amount of non-renewable fuels and hence is still limited by the availability of non-renewable fuels.



B = Rapeseed processed for biodiesel production
S = Rapeseed straw
S* = Harvested rapeseed straw utilised as energy source in rapeseed processing
H = Energy requirements of rapeseed processing met by utilisation of rapeseed straw
F1 = Gross biodiesel production
F2 = Biodiesel equivalent for energy requirements of rapeseed processing that is not met by rapeseed straw
F3 = Biodiesel equivalent for energy requirements of harvesting and processing rapeseed straw
F4 = Biodiesel equivalent for energy requirements of rapeseed growing
F* = Net biodiesel output available as replacement for fossil diesel fuel = F1 – F2 – F3 – F4

Figure 3-2 The net energy approach showing internal loop of energy requirements in biodiesel production from rapeseed (adapted from Giampietro et al. (1997) and Giampietro and Ulgiati (2005))

From Figure 3-2 it can be seen that the output/input energy ratio (R) can be calculated as $R = \frac{F1}{F2 + F3 + F4}$. An obvious condition for the feasibility of the biodiesel production process is that R be greater than 1, otherwise there would be a net loss of energy in the production process.

Another significant condition for the feasibility of the biodiesel production process is that R must be sufficiently high to prevent an excessive demand of land, water, and labour per unit of net biodiesel produced so that the biodiesel production process will not be constrained by the availability of land, water, and labour in where the production process takes place (Giampietro and Ulgiati, 2005, Giampietro et al., 1997, Ulgiati, 2001). This condition is very important in determining the feasibility of the production process since it has been shown that the land, water, and labour requirements of the production process increase non-linearly as R decreases. For example, it was shown that when R equals 1.5, the ratio between net and gross output of biodiesel, which can be calculated as $\frac{F*}{F1} = \frac{R-1}{R}$, is 0.33, which means that a net supply of 1 L of biodiesel requires a gross production of 3 L of biodiesel. When R equals 1.2, however, F*/F1 equals 0.16 and hence a gross production of 6 L of biodiesel is required for every net litre of biodiesel produced. Hence, the land, water, and labour requirements of the biodiesel production process double when its energy ratio only decreases by 20%. Accordingly, the value of R evaluated in this study will be used to calculate the land, water, and labour requirements of the biodiesel production process, which will then be compared to the actual land and fresh water availability and existing labour constraint in Western Australia to evaluate its feasibility as an alternative to fossil diesel fuel consumption in Western Australian transport sector.

Chapter 4

Energy Balance & Feasibility Analyses of Biodiesel Production from Rapeseed

This chapter presents the overall energy balance analysis of the biodiesel production from rapeseed under typical Western Australian conditions. The chapter starts with a section on typical Western Australian agricultural field data and rapeseed oil extraction and transesterification process parameters, followed by the evaluation of the energy requirements and energy outputs of the production process according to the method described in the previous chapter. The energy ratio and energy productivity of the biodiesel production process will then be calculated and compared with those evaluated in past studies. The feasibility of a large scale biodiesel production from rapeseed as an alternative to fossil diesel consumption in Western Australian transport sector is then analysed according to its energy ratio and compared to that of a large scale ethanol production from mallee as an alternative to fossil petrol (gasoline) consumption in Western Australian transport sector.

4.1 Rapeseed Growing Field Data and Processing Parameters

The typical rapeseed growing field data and statistics and rapeseed processing (oil extraction and transesterification) parameters applicable to Western Australian conditions are described in the following subsections. The transport means and distances involved in the transport and/or distribution of rapeseed, rapeseed oil, biodiesel, and any utilised by-products will also be discussed.

4.1.1 Rapeseed Growing Field Data

The typical agricultural activities associated with growing triazine tolerant (TT) rapeseed in the Great Southern and Lakes District in Western Australia (Figure 4-1), along with the input requirements and typical rapeseed growing statistics, are shown in Table 4-1. The typical average rapeseed yield is 1.4 tonnes/ha with an average oil and moisture contents of 43% (wt) and <8.5% (wt), respectively, while the typical average rapeseed straw yield is 2.5 tonnes/ha.

Table 4-1 Typical activities associated with growing TT rapeseed (Carmody and Herbert, 2001, Duff et al., 2006, Knight, 2006).

Operation	Month	Input requirements
Pest control (pre-seeding knockdown).	Late spring	• A driver on a tractor (63 kW engine power) fitted with on-farm spray rig (boom spray). • Herbicides: 0.8 L/ha Glyphosate (360 g a.i./L), 0.02 kg/ha Lontrel (750 g a.i./kg), 0.025 L/ha Hammer (240 g a.i./L). • Insecticides: 0.3 L/ha Fastac (100 g a.i./L)
Fertiliser application (soil topdressing)	Jan	• A driver on a tractor (same as above) fitted with a solid fertiliser distributor. • Fertilisers: 85 kg/ha super phosphate.
Seed planting (with starter fertilisers).	Apr	• Seed: 2.9 kg/ha. • Seed dressing: 400 mL Maxim XL (35 g a.i./L) per 100 kg seed. • A driver on a tractor (same as above) fitted with a disc seeder or a knife-point-and-press-wheel machine and a liquid fertiliser injector. • Fertilisers: 45 kg/ha Agstar E, 85 kg/ha MacroPro Extra, 50 L/ha Flexi N.
Crop monitoring.	Apr-harvest	• Farmer using a diesel utility cab vehicle.
Post-seeding pre-emergent (PSPE) pest control.	Apr/May	• A driver on a tractor (same as above) fitted with on-farm spray rig (boom spray). • Herbicides: 2 kg/ha Atrazine (900 g a.i./kg).
Early post-emergent pest control.	May	• A driver on a tractor (same as above) fitted with on-farm spray rig (boom spray). • Herbicides: 0.07 L/ha Select (240 g a.i./L), 0.25 L/ha Targa (99.5 g a.i./L).
Later pest control to control insects & persistent weeds.	When needed.	• A driver on a tractor (same as above) fitted with on-farm spray rig (boom spray). • Insecticides: 2.1 L/ha Endosulfan (350 g a.i./L), 0.8 L/ha Chlorpyrifos (500 g a.i./L).
Split application of nitrogen fertiliser.	Jun	• A driver on a tractor (same as above) fitted with a liquid fertiliser distributor. • Fertilisers: 80 L/ha Flexi N.
Split application of nitrogen fertiliser.	Jul	• A driver on a tractor (same as above) fitted with a liquid fertiliser distributor. • Fertilisers: 50 L/ha Flexi N.
Swathing.	Sep/Oct	• A driver on a self-propelled harvester/swather (70 kW engine power), fitted with a swather front.

<table>
<tr><th>Operation</th><th>Month</th><th colspan="3">Input requirements</th></tr>
<tr><td>Harvesting.</td><td>Oct/Nov</td><td colspan="3">• A driver on a self-propelled harvester/swather (70 kW engine power).</td></tr>
<tr><td>Straw baling.</td><td>Oct/Nov</td><td colspan="3">• A driver on a tractor (same as above) fitted with a straw baler.</td></tr>
<tr><td>Rapeseed storage</td><td>After harvest</td><td colspan="3">• Grain silo equipped with aeration cooling system (0.4 kW fan power). Supervision of the fan motor ¼ of the time the fan is operated. The fan is operated 1/7 of the storage time.</td></tr>
<tr><td rowspan="6">Typical rapeseed growing statistics</td><td colspan="2">Seeding rate</td><td>2.9</td><td>kg/ha</td></tr>
<tr><td colspan="2">Plant density</td><td>70-80</td><td>Plants/m^2</td></tr>
<tr><td colspan="2">Average rapeseed yield</td><td>1.4</td><td>t/ha</td></tr>
<tr><td colspan="2">Average rapeseed oil content at harvest</td><td>43</td><td>%wt rapeseed</td></tr>
<tr><td colspan="2">Average rapeseed moisture content at harvest</td><td><8.5</td><td>%wt rapeseed</td></tr>
<tr><td colspan="2">Average straw yield</td><td>2.5</td><td>t/ha</td></tr>
</table>

4.1.2 Rapeseed Oil Extraction Process Parameters

The typical process parameters of a commercial rapeseed oil extraction plant utilising the prepressing-extraction method (Figure 2-2), such as that operated by Riverland Oilseed Processors Pty. Ltd. in Pinjarra, Western Australia (RiverlandOilseeds, 2007b), are described in Table 4-2. The process parameters are for extracting fuel-grade rapeseed oil, as described in section 2.1.2, which requires less purification than food-grade rapeseed oil.

Table 4-2 Typical process parameters of a rapeseed oil extraction plant (Anjou, 1972, Cassells et al., n.d., Dorsa and Eickhoff, n.d., Juristowszky, 1983, Mag, 1990, Niewiadomski, 1990, Unger, 1990, Wettstrom, 1972)

Process stage	Process parameters
General	• Processing capacity: 340 tonnes rapeseed/day. • Plant's service life: 20 years. • Labour: 3 operators per shift, 3 shifts per day.
Rapeseed handling (storage, cleaning, and drying).	• Cleaning and then drying of rapeseed from 8%wt moisture content to 6%wt using diesel-fuelled continuous grain dryer (31% efficiency). • Heat requirement for drying rapeseed: 54.45 MJ/tonne rapeseed. • Electricity requirement: 13.64 kWh/tonne rapeseed.
Prepressing-extraction.	• Rapeseed crushing by roller mill prior to cooking in stack cooker and extraction in expeller press. Residual oil in expeller cake is then solvent extracted in a percolation extractor. Rapeseed cake from the solvent extractor is dried in a desolventiser-toaster and the rapeseed oil is separated from the solvent in an evaporator. • Solvent (hexane) requirement to replace lost solvent: 1.94 L/tonne rapeseed. • Cooling water requirement: 14.56 m^3/tonne rapeseed. • Steam requirement: 368.94 kg/tonne rapeseed. • Electricity requirement: 40.78 kWh/tonne rapeseed.

<table>
<tr><th>Process stage</th><th colspan="2">Process parameters</th></tr>
<tr><td>Crude rapeseed oil degumming</td><td colspan="2">• Degumming of crude rapeseed oil from the prepressing-extraction stage using water in a mixing tank (at ≈80^0C, 101.3 kPa), followed by vacuum drying (at 80^0C-90^0C) of the degummed rapeseed oil.
• Degumming water requirement: 8.33 kg/tonne rapeseed (2%wt of incoming crude rapeseed oil from prepressing-extraction stage).
• Steam requirement: 80.03 kg/tonne rapeseed.
• Electricity requirement: 1.69 kWh/tonne rapeseed.</td></tr>
<tr><td>Alkali refining.</td><td colspan="2">• Pre-treatment of the degummed rapeseed oil with phosphoric acid (ρ = 1.685 kg/L) in a mixing tank followed by treatment with NaOH (2-3.5 M) in a mixing tank to neutralise the phosphoric acid and free fatty acid in the degummed oil. The alkali refined oil is then water washed and vacuum dried.
• Phosphoric acid requirement: 0.88 L/tonne rapeseed (0.2%vol of incoming degummed rapeseed oil).
• NaOH requirement: 2.88 kg (mixed with 27.45 kg water)/tonne rapeseed.
• Washing water requirement: 40.34 kg/tonne rapeseed (10%wt of incoming degummed rapeseed oil).
• Steam requirement: 68.59 kg/tonne rapeseed.
• Electricity requirement: 2.65 kWh/tonne rapeseed.</td></tr>
<tr><td rowspan="4">Plant utility parameters</td><th colspan="2">Steam</th></tr>
<tr><td>Energy delivered by steam
Boiler make-up water rate</td><td>2 MJ/kg steam.
5% of total steam.</td></tr>
<tr><th colspan="2">Cooling water</th></tr>
<tr><td>Cooling tower make-up water rate</td><td>3% of total cooling water</td></tr>
</table>

4.1.3 Rapeseed Oil Transesterification Process Parameters

The typical process parameters of a commercial rapeseed oil transesterification plant utilising the homogeneous alkali-catalysed transesterification process (Figure 2-4), such as that operated by Australian Renewable Fuels Pty. Ltd. in Picton, Western Australia (ARF, 2008a), are described in Table 4-3.

Table 4-3 Typical process parameters of a vegetable oil transesterification plant (Chau et al., 2002).

Process stage	Process parameters
General	• Processing capacity: 50 ML (45600 tonnes) refined rapeseed oil/year. • Plant operating days: 340 days/year. • Plant's service life: 20 years. • Labour: 4 operators per shift, 3 shifts per day.
Catalyst (KOH) mixing with methanol & reaction with rapeseed oil	• Mixing of methanol and KOH in a mixer (40^0C, 101.3 kPa), followed by reaction with rapeseed oil in a CSTR reactor (60^0C, 101.3 kPa). • Rapeseed oil flow rate: 134.12 tonnes/day. • Methanol requirement: 215.89 kg/tonne rapeseed oil (6:1 molar ratio of methanol to triglyceride in rapeseed oil). • KOH requirement: 10 kg/tonne rapeseed oil (1%wt of incoming rapeseed oil). • Steam requirement: 1382.13 kg/tonne rapeseed oil. • Electricity requirement: 6.69 kWh/tonne rapeseed oil.

Process stage	Process parameters	
Crude separation of product stream from reactor.	• Gravity separation into crude biodiesel and crude glycerol streams in a gravity settler (55^{0}C, 23.6 kPa) • Electricity requirement: 0.09 kWh/tonne rapeseed oil.	
Biodiesel purification.	• Water washing of crude biodiesel in a perforated-plated washing column (60^{0}C, 1013 kPa) followed by drying of the washed biodiesel in a flash column (100^{0}C, 101.3 kPa). • Washing water requirement: 209.94 kg/tonne rapeseed oil (20%wt of crude biodiesel entering washing column). • Cooling water requirement: 668.75 kg/tonne rapeseed oil. • Steam requirement: 1772.45 kg/tonne rapeseed oil. • Electricity requirement: 1.11 kWh/tonne rapeseed oil.	
Glycerol purification.	• Removal of volatile impurities by flash evaporation in a flash column (120^{0}C, 101.3 kPa), followed by neutralisation of entrained catalyst using stoichiometric addition of H_2SO_4 in a mixer (30^{0}C, 101.3 kPa). Precipitated solid is then removed in a cyclone separator (60^{0}C, 101.3 kPa). • H_2SO_4 requirement: 5.40 kg/tonne rapeseed oil. • Cooling water requirement: 617.44 kg/tonne rapeseed oil. • Steam requirement: 830.20 kg/tonne rapeseed oil. • Electricity requirement: 1.57 kWh/tonne rapeseed oil.	
Methanol recovery.	• Methanol distillation in a packed column (64.1-101.8^{0}C, 101.3 kPa). • Cooling water requirement: 4285.17 kg/tonne rapeseed oil. • Steam requirement: 3341.44 kg/tonne rapeseed oil. • Electricity requirement: 0.21 kWh/tonne rapeseed oil.	
Wastewater treatment.	• Gravity separation of entrained oil followed by soap removal in an air flotation tank (35^{0}C, 101.3 kPa) using $Al_2(SO_4)_3$ as coagulating agent. The pH of the resulting waste water is controlled by addition of NaOH in a mixing tank (30^{0}C, 101.3 kPa), followed by biological treatment in a facultative lagoon in open atmosphere. • $Al_2(SO_4)_3$ requirement: 0.02 kg/tonne rapeseed oil. • NaOH requirement: 0.10 kg/tonne rapeseed oil. • Cooling water requirement: 701.39 kg/tonne rapeseed oil. • Electricity requirement: 0.83 kWh/tonne rapeseed oil.	
Plant utility parameters	**Steam**	
	From boiler	180^{0}C, 1000 kPa
	Returned to boiler	100^{0}C, 101.3 kPa
	Boiler make-up water rate	5% of total steam
	Cooling water	
	From cooling tower	30^{0}C, 101.3 kPa
	Returned to cooling tower	45^{0}C, 101.3 kPa
	Cooling tower make-up water rate	3% of total cooling water

4.1.4 Transport Means and Distances

The rapeseed, rapeseed oil, biodiesel and any utilised by-products of the biodiesel production process are considered in this study to be transported to their respective processing/utilisation sites using the most common type of articulated trucks/tankers for carrying freight in Australia, i.e. six-axle semi trailer powered by diesel engine and with an average payload of 27 tonnes (Affleck and Wright, 2002). The trucks/tankers are assumed to be fully loaded when they depart and empty when they return after delivery using the same route for the return journey as for the outgoing journey.

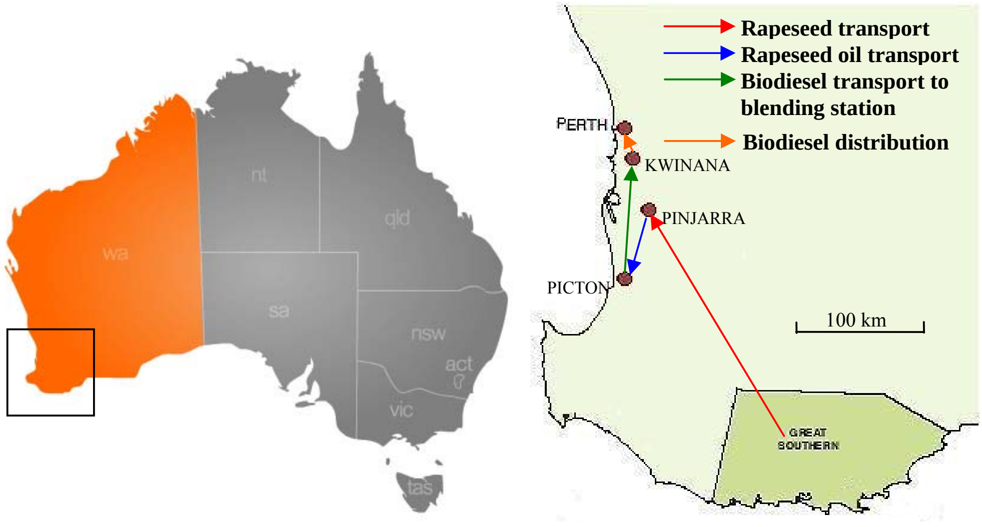


Figure 4-1 Transport of rapeseed, rapeseed oil, and biodiesel in the biodiesel production process chain considered in this study.

Transport of rapeseed, rapeseed oil, and biodiesel are shown in Figure 4-1. Harvested rapeseed is transported from the Great Southern and Lakes District using trucks over an average road distance of 217 km to an oil extraction plant located in Pinjarra, Western Australia, and operated by Riverland Oilseeds Pty. Ltd. (RiverlandOilseeds, 2007a). The rapeseed oil produced by the extraction plant is then transported using oil tankers over an approximate road distance of 93 km to an oil transesterification plant operated by Australian Renewable Fuels Pty. Ltd. (ARF, 2008b) and located in Picton, Western Australia. The biodiesel produced by the transesterification plant is then sent using oil tankers over an approximate road distance of 139 km to Kwinana in Western Australia, where the terminal operation site of Gull Petroleum is located (GullPetroleum, n.d.). There biodiesel is blended with conventional petroleum diesel to make B20 blend (20%vol biodiesel in petroleum diesel) before transported using oil tankers over an average road distance of 46 km to a Gull service station in Perth metropolitan area that sells the B20 blend (GullPetroleum, n.d.).

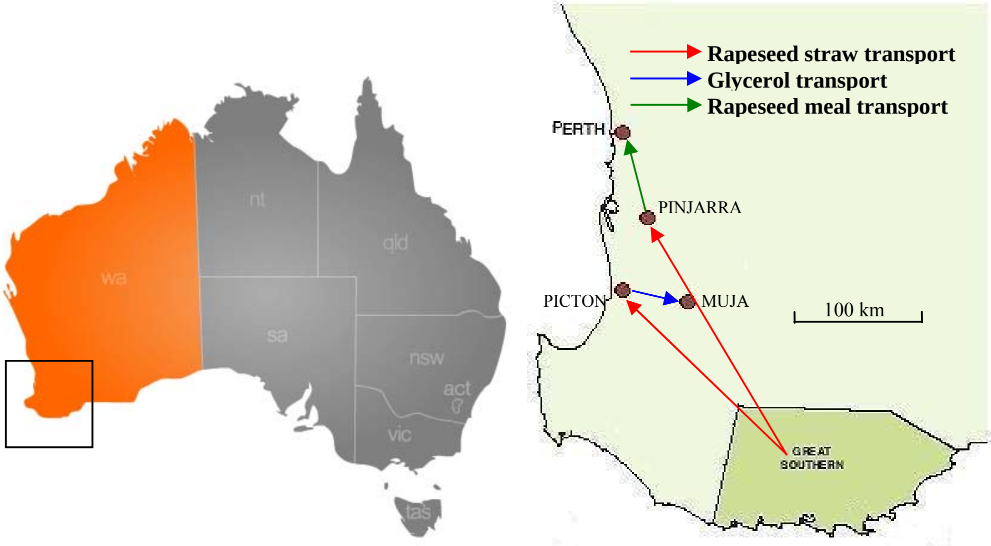


Figure 4-2 Transport of utilised by-products in the biodiesel production process considered in this study.

Figure 4-2 shows the transport of utilised by-products. Some of the rapeseed straw is utilised by the rapeseed oil extraction and transesterification plants as energy source to substitute the process heat (e.g. steam) and electricity required in the plants. The straw is transported from the Great Southern and Lakes District using trucks over average road distances of approximately 217 km and 204 km to Pinjarra and Picton, respectively. The rapeseed meal from the oil extraction plant that is utilised for layer chicken feed is transported from Pinjarra using trucks over an average road distance of approximately 125 km to a Western Australian poultry farm (Palmer, 2006). Utilised glycerol is transported from the oil transesterification plant in Picton using tankers over a road distance of approximately 71 km to Muja Power Station in Muja, Western Australia, for utilisation as co-firing fuel in the coal-fuelled power station.

4.2 Energy Balance Analysis of Biodiesel Production from Rapeseed in Western Australia

The energy requirements, energy output, energy productivity, and energy ratio of biodiesel production from rapeseed in Western Australia are evaluated according to the typical rapeseed growing field data and statistics, rapeseed processing parameters, and transport means and distances applicable to Western Australian conditions described previously (section 4.1).

4.2.1 Energy Requirements during Rapeseed Growing

a) Fuel consumption

Tractor fuel consumption per hectare during a particular field operation is estimated from the tractor engine power and efficiency and the typical engine loading and work rate (hour/ha) of the tractor while performing the task. Typical engine loadings and work rates of various tractor field operations are shown in Table 4-4 for a tractor with 63 kW engine power (35% engine efficiency). The total fuel consumption per hectare is calculated by adding the fuel consumption per hectare for each of the field operation performed by the tractor. It is noted (Leach, 1976) that the fuel input for each operation is more or less independent of the tractor power rating, given similar conditions. When performing a particular field operation, a large tractor applies the same total work effort per hectare as does a small tractor. The only difference is that the large tractor will complete the task in a shorter time. Also, the engine loadings and work rates are averages. Extreme soil, weather, and/or terrain conditions can give fuel input up to 50% higher or lower.

The amount of diesel fuel consumed by a combine harvester during swathing and harvesting operations is calculated in a similar manner to that of tractor fuel consumption. The typical engine loading and work rate of the combine harvester during these operations are also shown in Table 4-4.

Diesel fuel is also consumed during crop monitoring activities, in which a utility cab is used for on-farm travel. The typical on-farm transport vehicle fuel consumption in Western Australia is 0.08 L/ha (Short, 2007).

The diesel fuel consumptions (L/ha) associated with rapeseed growing activities (Table 4-1) are summarised in Table 4-5. A total of 40.73 L/ha of diesel fuel is consumed. Using the specific energy density of the diesel fuel (Table 3-1), this fuel consumption corresponds to a primary energy requirement of 1945.18 MJ/ha.

Table 4-4 Typical engine loadings and work rates of a 63 kW tractor during various agricultural field operations (Leach, 1976, Singh et al., 2008).

Operation	**Engine loading (%)**	**Work rate (hour/ha)**
Ploughing	50-75	0.50
Seed planting	50-75	0.29
Fertiliser application	25	0.29
Spraying	25	0.1
Combine harvester (70 kW)	85	1

Table 4-5 Fuel consumptions during rapeseed growing.

Field activities	**Fuel consumption (L/ha)**
Pre-seeding knockdown	0.42
Pre-seeding soil topdressing with fertiliser	1.22
Seed planting (with starter fertilisers)	3.65
Post-seeding pre-emergent pest control	0.42
Early post-emergent pest control	0.42
Later post-emergent pest control	0.42
First split application of fertiliser	1.22
Second split application of fertiliser	1.22
Swathing	15.84
Harvesting	15.84
Crop monitoring transport	0.08
Total	40.73

b) Electricity consumption

The harvested rapeseed is stored in grain silo that is fitted with an aeration cooling system to maintain the grain quality. The aeration cooling system utilises a fan which is driven by an electric motor. A typical aeration cooling fan motor has a power rating of 0.4 kW and runs continuously for the first 48 hours and then 1/7 of the rest of the storage period (Duff et al., 2006, Fusae, 2004a, Fusae, 2004b). When fitted to a 100 tonne silo which stores rapeseed for a period of two weeks, the electricity consumption of the fan motor is 0.50 kWh/ha, which corresponds to primary energy requirement of 5.55 MJ/ha.

c) Fertilisers and pesticides

The amount of fertilisers applied during rapeseed growing and the corresponding primary energy requirements are shown in Table 4-6. The rapeseed growing program also includes the application of pesticides (herbicide, insecticide, and fungicide) as pest control measures both pre-seeding (knockdown and seed dressing) and post-seeding (pre-emergent and post-emergent) (Knight, 2006). The amount of pesticides that are administered and the corresponding primary energy requirements are shown in Table 4-7.

Table 4-6 Primary energy requirements of the fertilisers applied during rapeseed growing (Knight, 2006).

Fertilisers	Usage (kg/ha)	Primary energy requirement (MJ/ha)
Single superphosphate	85	262.61
Agstar E	45	680.80
MacroPro Extra	85	1143.82
Flexi-N (liquid fertiliser)	237.6	5142.80
Total	452.6	7230.04

Table 4-7 Primary energy requirments of the pesticides applied during rapeseed growing (Knight, 2006).

	Usage (kg a.i./ha)	Primary energy requirement (MJ/ha)
Herbicides		
Atrazine	1.80	383.40
Glyphosate	0.29	137.38
Other	0.06	14.99
Insecticides		
Chlorpyrifos 500 g a.i./L	0.40	109.20
Other	0.77	205.07
Fungicides		
Maxim XL® (seed dressing)	0.0004	0.15
Total	3.32	850.19

d) Seed

Using a specific energy density of 41.27 MJ/kg seed (subsection 3.2.7), a seeding rate of 2.9 kg seed/ha (Table 4-1) corresponds to a primary energy requirement of 119.69 MJ/ha.

e) Field machineries, equipments, and transport vehicles

The primary energy requirements associated with the use of tractor and on-farm transport vehicle during rapeseed growing are evaluated from their fuel consumptions according to the method described previously (subsection 3.2.4). The primary energy requirements associated with the use of other agricultural field machineries and equipments (e.g. self-propelled harvester/swather, application equipments, tillage equipments etc.) are adapted from a previous publication (Table 3-2). These energy requirements are summarised in Table 4-8 and amount to a total of 1456.35 MJ/ha.

Table 4-8 Primary energy requirements associated with agricultural machineries, field equipments, and transport vehicles used during rapeseed growing (Leach, 1976).

Machinery/equipment/vehicle	Primary energy requirement (MJ/ha)
Seeding equipment (disc seeder)	158
Solid fertiliser distributor/applicator	45
Liquid fertiliser distributor/applicator	45
Boom sprayer for applying pesticides	34
Self-propelled harvester/swather	820
Tractor	171.40
Vehicle (for crop monitoring transport)	0.96
Storage and aeration system	182
Total	1456.35

f) Labour

The total labour time required during rapeseed growing process is 5.24 hours/ha, which includes the rate for machinery operations (including machinery repair time), crop monitoring time (including crop monitoring vehicle repair time), and storage supervision. Using a typical Australian agricultural labour cost of A$ 14/hr (Singh et al., 2008), the primary energy requirement associated with the use of labour during rapeseed growing is estimated to be 504.93 MJ/ha using the method described previously (subsection 3.2.8).

g) Summary of energy requirements during rapeseed growing

The total primary energy requirement of rapeseed growing is 12.11 GJ/ha (Table 4-9). Almost 60% of the total primary energy requirement is contributed by the use of fertilisers, mainly nitrogen fertilisers. Fuel consumption and the use of field machineries, equipments, and on-farm transport vehicles contribute to approximately 16% and 12% of the total primary energy requirement, respectively.

Table 4-9 Primary energy requirements during rapeseed growing.

	MJ/ha	**%**
Fuel	1945.18	16.06
Electricity	5.55	0.05
Seed	119.69	0.99
Fertilisers	7230.04	59.69
Pesticides	850.19	7.02
Field machineries, equipments & vehicles	1456.35	12.02
Labour	504.93	4.17
Total	12111.93	100

4.2.2 Energy Requirements during Rapeseed Oil Extraction

a) Process heat

The rapeseed delivered to the oil extraction plant is cleaned and dried from a moisture content of 8 wt% to 6 wt% in the rapeseed handling stage prior to further processing, requiring 54.45 MJ of heat for drying 1 tonne of rapeseed (Table 4-2). The drying is performed by a typical diesel-fuelled continuous grain dryer with an efficiency of 31%, requiring 4.55 L of diesel fuel per tonne rapeseed, which corresponds to a primary energy requirement of 217.11 MJ/tonne rapeseed.

Other process heat requirements in the rapeseed oil extraction plant are supplied by steam produced by the plant's utility boiler, which delivers 2 MJ/kg steam (Table 4-2), corresponding to a primary energy requirement of 2.54 MJ/kg steam (subsection 3.2.3). The total steam requirement of the oil extraction plant is 517.56 kg steam/tonne rapeseed (Table 4-2), which corresponds to a primary energy requirement of 1313.90 MJ/tonne rapeseed.

The total primary energy requirement for process heat during rapeseed oil extraction is 1531.01 MJ/tonne rapeseed, approximately 61% of which is contributed by the prepressing-extraction stage due to the considerable amount of steam that is needed during cooking and solvent extraction.

b) Electricity consumption

A typical continuous grain dryer utilises a fan which is driven by an electric motor. The fan motor typically consumes 3.94 kWh of electricity/tonne of grain dried by 1 % moisture content (Leach, 1976). Besides the drier fan motor, a typical grain cleaner in the rapeseed handling stage typically consumes 3.98 kWh of electricity/tonne rapeseed (Sheehan et al., 1998). With a further electricity consumption of approximately 2 kWh/tonne rapeseed for grain storage (Leach, 1976), the total electricity requirement in the rapeseed handling section is 13.64 kWh/tonne rapeseed, which corresponds to a primary energy requirement of 151.56 MJ/tonne rapeseed.

The typical electricity consumption of the prepressing-extraction stage of the oil extraction plant is 40.78 kWh/tonne rapeseed (Niewiadomski, 1990), which corresponds to primary energy requirement of 452.98 MJ/tonne rapeseed.

Electricity consumption in the refining section of the oil extraction plant is 4.34 kWh/tonne rapeseed (Sheehan et al., 1998), which corresponds to a primary energy requirement of 48.21 MJ/tonne rapeseed.

The total primary energy requirement for electricity generation in the oil extraction plant is 652.75 MJ/tonne rapeseed. The expeller press in the prepressing-extraction stage requires considerable amount of electricity, leading to almost 70% contribution of this stage towards the total.

c) Chemicals

The typical hexane loss during solvent extraction is 1.94 L/tonne rapeseed (Niewiadomski, 1990). This amount hexane is provided to the solvent extractor and is equivalent to primary energy requirement of 66.18 MJ/tonne rapeseed.

Phosphoric acid and NaOH requirements in the alkali refining section are 1.49 and 2.88 kg/tonne rapeseed, respectively. These correspond to primary energy requirements of 19.28 and 121.97 MJ/tonne rapeseed for phosphoric acid and NaOH, respectively.

The total primary energy requirement associated with the use of chemicals in the oil extraction plant is 207.43 MJ/tonne rapeseed.

d) Process water

Process water is consumed in the oil extraction plant as make-up water for steam production, make-up water for cooling water, and also as degumming water and washing water in the refining stages. From the total steam and cooling water requirements and also the degumming water and washing water requirements of the oil extraction plant (Table 4-2), the total amount of process water required is 538.92 kg/tonne rapeseed, which corresponds to a primary energy requirement of 4.98 MJ/tonne rapeseed.

e) Construction of plant, equipments, and maintenance

With a total capital investment of approximately A$ 60.62 million (Niewiadomski, 1990, Peters and Timmerhaus, 1991), the primary energy requirement associated with plant construction is calculated to be 180.36 MJ/tonne rapeseed oil according to the method described previously (subsection 3.2.5). The primary energy requirement associated with plant maintenance is similarly calculated from the annual maintenance cost of the plant, which is estimated at A$ 0.37 million/year (Niewiadomski, 1990, Peters and Timmerhaus, 1991), and corresponds to a primary energy requirement of 22.18 MJ/tonne rapeseed oil, respectively.

f) Labour

The primary energy requirement associated with the use of 9 operators (3 operators on 3 different shifts) and a salary of A$ 60000 per operator per year in the oil extraction plant is estimated to be 32.13 MJ/tonne rapeseed according to the method described previously (subsection 3.2.8).

g) Summary of energy requirements during rapeseed oil extraction

The total primary energy requirement during rapeseed oil extraction is 2.63 GJ/tonne rapeseed (Table 4-10). Taking into account the typical rapeseed yield of 1.4 tonnes/ha (Table 4-1), the corresponding total primary energy requirement during the extraction of oil from 1 hectare of rapeseed is 3.68 GJ/ha. Almost 60% of the total primary energy requirement is contributed by the process heat requirement mainly in the prepressing-extraction stage, while electricity consumption (mainly by the expeller press) contributes to almost 25% of the total primary energy requirement.

Table 4-10 Primary energy requirements during rapeseed oil extraction.

	MJ/t rapeseed	MJ/ha	%
Process heat	1531.01	2143.42	58.19
Electricity	652.75	913.85	24.81
Chemicals	207.43	290.40	7.88
Process water	4.98	6.98	0.19
Construction of plant, equipments & maintenance	202.54	283.56	7.70
Labour	32.13	44.98	1.22
Total	2630.85	3683.19	100

4.2.3 Energy Requirements of Rapeseed Oil Transesterification

a) Process heat

Process heat requirements in the rapeseed oil transesterification plant are supplied by steam produced by the plant's utility boiler. Under the boiler operating parameters (Table 4-3), 102 kJ is delivered by 1 kg of steam, corresponding to a primary energy requirement of 0.13 MJ/kg steam (subsection 3.2.3).

A total of 7326.22 kg steam/tonne rapeseed oil is required by the various stages of the transesterification plant (Table 4-3), which corresponds to a primary energy requirement of 949.48 MJ/tonne rapeseed oil. The reboiler in the methanol recovery stage is the most heat intensive equipment, contributing approximately 45% of the total primary energy requirement associated with steam consumption.

b) Electricity consumption

The total electricity consumption is 10.49 kWh/tonne rapeseed oil (Table 4-3), which is calculated from the power ratings of the various equipments in the transesterification plant (Chau et al., 2002). This electricity consumption corresponds to a primary energy requirement of 116.57 MJ/tonne rapeseed oil.

c) Chemicals

A 6 to 1 molar ratio of methanol to the triglyceride in the rapeseed oil is used during reaction and the amount of KOH used to catalyse the reaction is 1%wt of the incoming rapeseed oil. In addition to methanol and KOH consumptions in the reaction stage, sulphuric acid is added stoichiometrically to the glycerol product stream after removal of volatile impurities to neutralise the basic catalyst (KOH) entrained in the stream. In the wastewater treatment stage, aluminium sulphate is used as the coagulating agent in the flotation tank and the pH of the effluent water is then adjusted by NaOH addition prior to biological treatment in the wastewater lagoon. The consumption of chemicals in the transesterification plant and the corresponding primary energy requirements are shown in Table 4-11.

Table 4-11 Primary energy requirements associated with consumption of chemicals in the rapeseed oil transesterification plant.

	kg/t rapeseed oil	**MJ/t rapeseed oil**
Methanol	115.18*	4568.91*
KOH	10	423.26
Sulphuric acid	5.40	14.14
$Al_2(SO_4)_3$	0.02	0.06
NaOH	0.10	4.37
	Total	5010.74

*** Excluding the methanol recycle stream from the methanol recovery section.**

d) Process water

Process water is required in the transesterification plant as make-up water for steam production, make-up water for cooling tower, and washing water in the biodiesel purification stage. From the total steam and cooling water requirements and also the washing water requirement of the transesterification plant (Table 4-3), the total process water requirement is calculated to be 764.43 kg/tonne rapeseed oil, which corresponds to a total primary energy requirement of 7.07 MJ/tonne rapeseed oil.

e) Construction of plant, equipments, and maintenance

With a total capital investment of approximately A$ 12.12 million (Chau et al., 2002), the primary energy requirement associated with plant construction is calculated to be 91.44 MJ/tonne rapeseed oil according to the method described previously (subsection 3.2.5). The primary energy requirement associated with plant maintenance is similarly calculated from the annual maintenance cost of the plant, which is estimated as 6% of the total capital investment (Peters and Timmerhaus, 1991), and is found to be 109.72 MJ/tonne rapeseed oil, respectively.

f) Labour

The primary energy requirement associated with the use of 12 operators (4 operators on 3 different shifts) and a salary of A$ 60000 per operator per year in the oil transesterification plant (Chau et al., 2002) is estimated to be 101.18 MJ/tonne rapeseed oil according to the method described previously (subsection 3.2.8).

g) Summary of energy requirements of rapeseed oil transesterification

The total primary energy requirement during rapeseed oil transesterification is 6.39 GJ/tonne rapeseed oil (Table 4-12). Taking into account the typical rapeseed oil yield of 394.44 kg/tonne rapeseed (Table 4-2) and the typical rapeseed yield of 1.4 tonnes/ha (Table 4-1), the corresponding total primary energy requirement during transesterification of rapeseed oil produced from 1 hectare of rapeseed is 3.53 GJ/ha. The major contributors to the total primary energy requirement are the consumption of chemicals (mainly methanol) and steam requirement of the plant. Together, they contribute to more than 90% of the total primary energy requirement of the transesterification plant.

Table 4-12 Primary energy requirements during rapeseed oil transesterification.

	MJ/t rapeseed oil	**MJ/ha**	**%**
Steam	949.48	524.32	14.87
Electricity	116.57	64.37	1.83
Chemicals	5010.74	2767.01	78.46
Process water	7.07	3.90	0.11
Construction of plant and equipments	91.44	50.49	1.43
Maintenance	109.72	60.59	1.72
Labour	101.18	55.87	1.58
Total	6386.20	3526.56	100

4.2.4 Energy Requirements during Transport

a) Fuel consumption

Vehicle fuel consumptions during rapeseed, rapeseed oil, and biodiesel transport are 55.6 L/100 km (Harper, 2007) and 27.9 L/100 km (Leach, 1976) for full and empty articulated trucks/trailers, respectively. Using these fuel consumptions and the distance for rapeseed transport (subsection 4.1.4), the amount of diesel fuel consumed in a round trip (outgoing and return journey) completed by a truck transporting rapeseed is 181.15 L. Considering an average payload of 27 tonnes per truck (subsection 4.1.4) and a rapeseed yield of 1.4 tonnes/ha (Table 4-1), the average amount of diesel fuel consumed during transport of rapeseed produced by 1 ha of agricultural area is 9.39 L/ha. The average amounts of diesel fuel consumed during transport of rapeseed oil and biodiesel produced from 1 ha of rapeseed are calculated in a similar way and are found to be 1.59 L/ha and 5.91 L/ha, respectively. The total diesel fuel consumption during transport is 16.89 L/ha, which corresponds to a primary energy requirement of 806.81 MJ/ha. Approximately 55% of this total primary energy requirement is contributed by rapeseed transport.

b) Manufacture and maintenance of transport vehicle

The primary energy requirement associated with manufacture and maintenance of transport vehicles is calculated from the fuel consumption during transport according to the method described previously (subsection 3.2.6) and is found to be 201.70 MJ/ha.

c) Labour

The approximate average travel times required for a round trip transport of rapeseed produced by 1 ha of agricultural area and of rapeseed oil and biodiesel produced from 1 ha of rapeseed are 0.30 hour/ha, 0.05 hour/ha, and 0.24 hour/ha, respectively. Using a typical driver cost of A$ 25/hr (Wu et al., 2008, Wu et al., 2006), the total primary energy requirement associated with the use of labour during transport is estimated to be 102.31 MJ/ha according to the method described previously (subsection 3.2.8).

d) Summary of energy requirements during transport

The total primary energy requirement during transport is 1.11 GJ/ha (Table 4-13). More than 70% of this total primary energy requirement is contributed by diesel fuel consumption during transport.

Table 4-13 Primary energy requirements during transport.

	MJ/ha	**%**
Fuel consumption	806.81	72.63
Manufacture & maintenance of transport vehicle	201.70	18.16
Labour	102.31	9.21
Total	1110.83	100

4.2.5 Additional Energy Requirements Associated with By-products Utilisation

Utilisation of by-products from the biodiesel production process incurs additional energy requirements (Giampietro et al., 1997, Ulgiati, 2001). Rapeseed straw utilisation requires additional energy for its collection, storage, transportation, and also for replacing soil nutrients withdrawn by the straw from, but no returned to, the soil due to its utilisation. Similarly, utilisation of rapeseed meal and glycerol also incurs additional energy requirements e.g. for transport to their utilisation sites. The additional energy requirements associated with utilisation of by-products are evaluated as follows.

a) Additional Energy Requirements during Rapeseed Growing

Fuel consumption

Fuel is consumed during straw baling operation in which the utilised rapeseed straw is picked up from ground and baled using tractor drawn straw baler. The tractor fuel consumption is calculated at 25% engine loading and 0.4 hour/ha work rate using the same method described previously (subsection 4.2.1a) and is found to be 1.68 L/ha, which corresponds to a primary energy requirement of 80.09 MJ/ha.

Fuel is also consumed during application of fertilisers to replace the soil nutrients withdrawn from but not returned to the soil by the rapeseed straw due to its withdrawal. It is assumed that the fertilisers are applied through a single fertiliser application operation similar to that during the rapeseed growing process with a fuel consumption of 1.22 L/ha (Table 4-5) and a corresponding primary energy requirement of 58.07 MJ/ha.

The total additional fuel consumption during rapeseed growing is 2.90 L/ha, which corresponds to a primary energy requirement of 138.16 MJ/ha.

Electricity consumption

The collected straw is stored in separate silos, but with the same storage system, capacity, and period as that for the rapeseed (subsection 4.2.1b), consuming an average of 0.09 kWh of electricity per hectare of straw collected, which corresponds to a primary energy requirement of 0.97 MJ/ha.

Fertilisers

Table 4-14 shows the primary energy requirements associated with additional fertilisers applied to replace major nutrients withdrawn from the soil due to straw utilisation.

Table 4-14 Primary energy requirements associated with additional fertilisers to replace major nutrients withdrawn from soil due to straw utilisation.

Nutrients	Content in straw (%wt, db)	Withdrawal (kg/ha)	Replacement fertilisers		
			Type	(kg/ha)	(MJ/ha)
N	0.75	1.61	Urea	2.96	121.30
P	0.13	0.28	DAP	1.39	26.81
K	0.79	1.70	Muriate of Potash	3.41	24.22
			Total	7.76	172.33

Field machineries and equipments

A tractor drawn straw baler is required to collect the rapeseed straw. The collected straw is then stored in aerated storage system equivalent to that for rapeseed storage. Tractor is also used during fertiliser application to replace the lost nutrient due to straw withdrawal. The primary energy requirements associated with the manufacture and repairs of these additional field machineries and equipments are shown in Table 4-15.

Table 4-15 Primary energy requirements associated with manufacture and repairs of field machineries and equipments for straw collection (Leach, 1976).

Machinery/equipment	Primary energy requirement (MJ/ha)
Straw baler	330
Tractor	55.26
Straw storage and aeration system	31.99
Total	417.25

Labour

The additional labour time required during rapeseed growing process is 0.89 hours/ha, which includes the rate for machinery operations (straw baling and fertiliser application, including machinery repair time) and storage supervision. Using a typical agricultural labour cost of A$ 14/hr (Singh et al., 2008), the primary energy requirement associated with additional use of labour during rapeseed growing is estimated to be 85.91 MJ/ha, according to the method described previously (subsection 3.2.8).

b) Additional Energy Requirements during Transport

In addition to the transport of rapeseed, rapeseed oil, and biodiesel, the utilised rapeseed straw, rapeseed meal, and glycerol need to be transported to the sites where they are utilised.

Fuel consumption

Using the transport distances for by-products (subsection 4.1.4) and the same vehicle fuel consumptions and method described previously (subsection 4.2.4a), the average amounts of diesel fuel consumed during round trip transport of rapeseed straw collected from 1 ha of agricultural area and of rapeseed meal and glycerol produced from 1 ha of rapeseed are calculated to be 1.63 L/ha, 3.0 L/ha, and 0.12 L/ha, respectively, which correspond to a total primary energy requirement of 226.96 MJ/ha.

Manufacture and maintenance of transport vehicles

The primary energy requirement associated with manufacture and maintenance of transport vehicle is calculated from the fuel consumption during transport of by-products according to the procedure described previously (subsection 3.2.6) and is found to be 56.74 MJ/ha.

Labour

The total average travel time required for a round trip transport of rapeseed straw collected from 1 ha of agricultural area and of rapeseed meal and glycerol produced from 1 ha of rapeseed is 0.16 hour/ha. Using a typical driver cost of A$ 25/hr (Wu et al., 2008, Wu et al., 2006), the total primary energy requirement associated with the use of labour during transport of by-products is estimated to be 28.24 MJ/ha according to the method described previously (subsection 3.2.8).

c) Other Additional Energy Requirements

It should also be noted that the removal of rapeseed straw from the agricultural land will increase and facilitate soil erosion by wind and water due to the loss of soil coverage that is usually provided by the straw when it is left on the ground (Pimentel et al., 1995). Increased soil erosion will incur further additional energy costs for the replacement of water and nutrients lost due to increased amount of runoff water and entrainment of nutrients in the eroded soil. Also, less than average rapeseed yield can be expected, since erosion will have adverse effects on the fertility and productivity of the agricultural land. This will, in turn, have an adverse effect on the overall energy balance analysis of the rapeseed-to-biodiesel conversion process system. In this study, however, these additional energy requirements and adverse effects are assumed to be minimised by utilising only some of the rapeseed straw as discussed previously.

The energy costs involved in preparing by-products prior to utilisation, e.g. those associated with drying and/or briquetting, etc., need to be considered (Giampietro et al., 1997). The losses in energy value of by-products due to changes in moisture content and decay during storage and transport should also be considered. However, it is assumed in this study that the by-products can be utilised as they are without any further preparation and that they maintain their quality during storage and transport.

d) Summary of Additional Energy Requirements

The total additional energy requirement associated with by-products utilisation is 1126.57 MJ/ha (Table 4-16).

Table 4-16 Additional primary energy requirements associated with by-products utilisation.

	MJ/ha
Fuel consumption	365.12
Electricity	0.97
Fertilisers	172.33
Field machineries & equipments	417.25
Transport vehicles	56.74
Labour	114.15
Total	1126.57

4.2.6 Energy Credits from Utilisation of By-products

The energy credits (subsections 3.3.2 - 3.3.4) that result from utilisation of by-products are summarised in Table 4-17. Utilisation of rapeseed straw and meal contributes to approximately 90% of the total energy credit.

Table 4-17 Energy credits from by-products utilisation.

By-products utilisation	**Amount utilised (kg/ha)**	**Energy credit**	
		(MJ/kg)	**(MJ/ha)**
Rapeseed straw			
Process heat (steam) replacement	167.30	14.13	2363.78
Process heat (drying) replacement	6.86	44.34	303.96
Electricity replacement	71.89	13.61	978.23
Rapeseed meal			
Animal feed	776.37	6.98	5419.07
Glycerol			
Electricity replacement (co-firing)	54.67	18.36	1003.76
		Total	**10068.78**

4.2.7 Energy Output from Biodiesel and Energy Productivity

The yield of biodiesel in the oil transesterification plant is 959.98 kg/tonne rapeseed oil (Table 4-3), corresponding to an overall biodiesel yield of 530.12 kg/ha (602.41

L/ha). Using a net calorific value of 37.3 MJ/kg biodiesel (subsection 3.3.1), the energy output from biodiesel is calculated to be 19.79 GJ/ha.

The energy productivity (E) of the biodiesel production process, as defined previously (section 3.4), is equivalent to the energy output from biodiesel, i.e. 19.79 GJ/ha per growing season.

4.2.8 Energy Ratio of Biodiesel Production from Rapeseed in Western Australia and Comparison with Other Regions in the World

Results of the overall energy balance and the energy ratio of biodiesel production from rapeseed in Western Australia evaluated in this study are summarised in Table 4-18. Breakdown of energy requirements without by-products utilisation (base case) in each stage of the production process is shown in Figure 4-3. Without by-products utilisation, the energy ratio (R_1) is less than 1, indicating that utilisation of by-products is necessary for the biodiesel production process to be energetically feasible. Utilisation of rapeseed straw and/or rapeseed meal contributes most to the improvement of energy ratio, with only marginal contribution from glycerol utilisation. The maximum energy ratio is obtained when all by-products are utilised (R_5 = 1.72). Correspondingly, the feasibility of a large scale biodiesel production from rapeseed as an alternative transport fuel to fossil diesel in Western Australian transport sector will be evaluated using R_5 in a later section (section 4.3).

Figure 4-3 indicates that almost 60% of total energy requirement is due to rapeseed growing. Rapeseed processing (oil extraction and transesterification) contributes to approximately 35% of the total energy requirement, while transport activities constitute the remaining 5%. Table 4-18 further indicates that the single largest contributor (more than 35%) to the total energy requirement is the use of fertilisers, mainly nitrogen fertilisers, which are applied during rapeseed growing. Consumption of process chemicals is another significant energy consumer, contributing to almost 15% of the total energy requirement, which is mostly due to the energy required to manufacture the large excess of methanol used during transesterification reaction (Table 4-12). Fuel consumption, especially during field machinery operations in the rapeseed growing stage, and process heat requirement, especially during rapeseed oil extraction, are also significant consumers of energy, giving a combined contribution of approximately 25% to the total energy requirement.

The energy ratio and energy productivity evaluated in this study are also compared to those obtained in other countries/regions in the world in Table 4-19. The energy ratios without by-products utilisation (R_1) and energy productivities obtained in other regions are higher than that evaluated in this study for Western Australian conditions, which can generally be attributed to the higher rapeseed yields per hectare in other regions than in Western Australia. Also, improvement of the base case energy ratio from by-products utilisation evaluated in other studies is more significant due to assumption of utilisation of by-products as fuels and addition of their energy contents to the biodiesel energy output. However, the improvement obtained in this utilisation scenario can be misleading due to the difference between energy quality of by-products to that of biodiesel (Giampietro et al., 1997). More common utilisation scenarios for by-products are considered in this study and energy credits are assigned accordingly (sections 3.3.2 - 3.3.4), resulting in more moderate and conservative improvement.

Reduction in the previously mentioned main energy input contributors and increase in rapeseed yield will provide a basis for development of possible key strategies to improve the energy ratio and energy productivity of biodiesel production from rapeseed in WA, which will be later discussed in this study (section 4.4).

Table 4-18 Overall energy balance analysis of biodiesel production from rapeseed in Western Australia.

Energy input	**MJ/ha**	**MJ/L**	**%**
Base case (no by-products utilisation)			
Fuel	2751.99	4.57	13.47
Process heat	2667.73	4.43	13.06
Electricity	983.77	1.63	4.81
Agrochemicals (pesticides)	850.19	1.41	4.16
Fertilisers	7230.04	12.00	35.38
Process chemicals	3057.41	5.08	14.98
Process water	10.88	0.02	0.06
Machineries, equipments & vehicles	2052.69	3.41	10.05
Seed	119.69	0.20	0.59
Labour	708.10	1.18	3.48
Total base case energy requirement	**20432.51**	**33.92**	**100**
Additional			
Fuel	365.12	0.61	32.41
Electricity	0.97	0.002	0.09
Fertilisers	172.33	0.29	15.30
Machineries, equipments & vehicles	473.99	0.79	42.07
Labour	114.15	0.19	10.13
Total additional energy requirement	**1126.57**	**1.87**	**100**
Energy credit			
Rapeseed straw	3645.97	6.05	36.21
Rapeseed meal	5419.07	8.99	53.82
Glycerol	1003.76	1.67	9.97
Energy output			
Biodiesel	**19792.34**	**32.86**	
Energy Ratio (R) = Energy output/(Energy input – Energy credit)			
Base case (R_1)	0.97		
Base case + straw (R_2)	1.12		
Base case + meal (R_3)	1.30		
Base case + meal & glycerol (R_4)	1.39		
Base case + straw, meal & glycerol (R_5)	1.72		

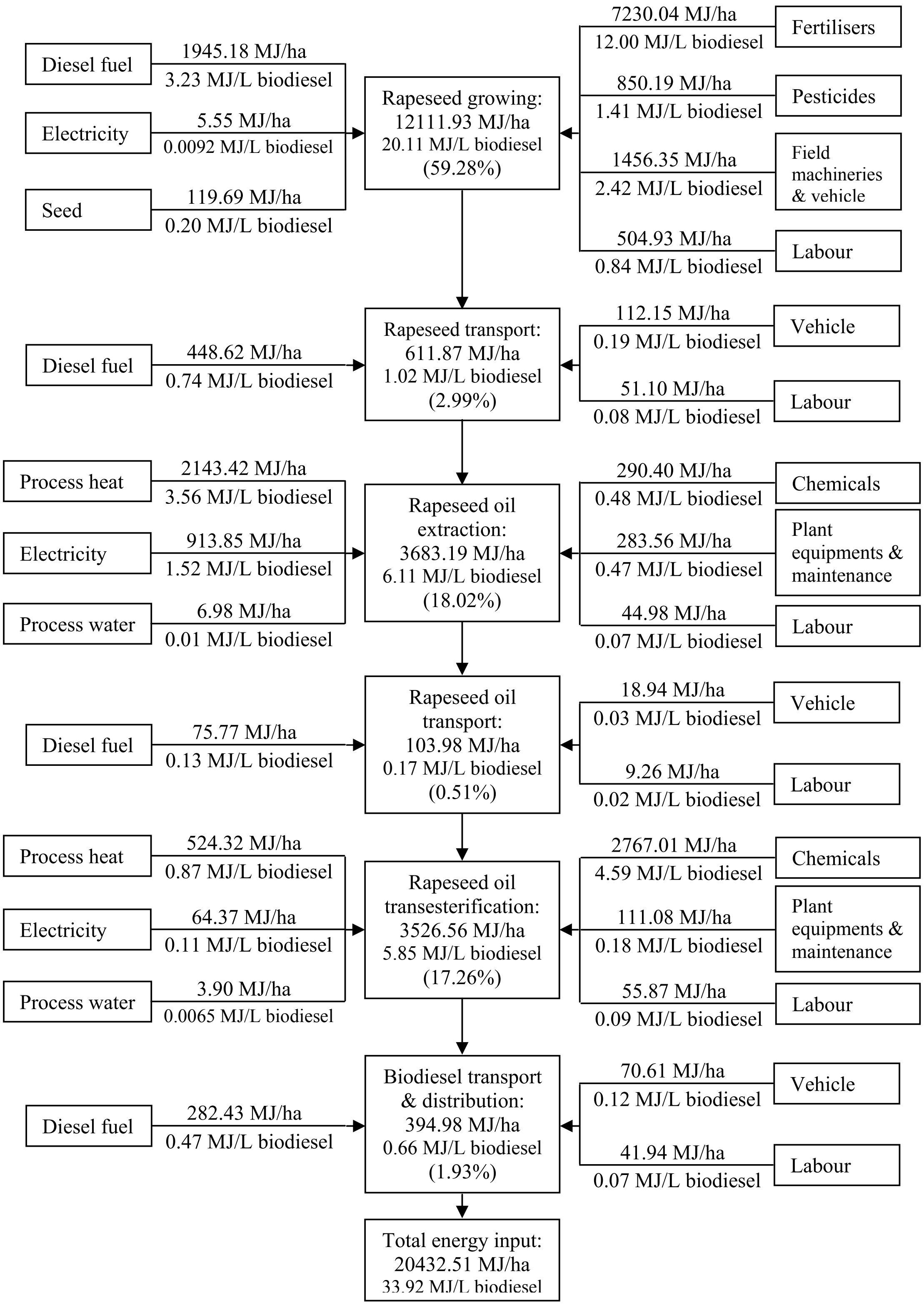


Figure 4-3 Breakdown of base case energy requirements in each stage of biodiesel production from rapeseed in Western Australia.

Table 4-19 Comparison of energy ratios and energy productivities of biodiesel production from rapeseed in different regions of the world.

References	Country	R_1[a]	R_2[b]	R_3[c]	R_4[d]	R_5[e]	E (GJ/ha)	Comments
Culshaw & Butler (1992)	UK	1.35	2.50	2.55	2.62	3.77	43.93	Typical UK conditions. Yields: rapeseed = 3.2 t/ha, straw = 2.5 t/ha, meal = 1.86 t/ha, glycerol = 0.14 t/ha, biodiesel = 1.18 t/ha. Energy values of by-products are added to that of biodiesel.
	Austria, Switzerland, Italy, France	1.3-2.1			2-3			No conditions specified. Energy values of by-products are added to that of biodiesel.
Richards (2000)	UK	1.78	3.67	1.82		3.71	54.35	Typical UK conditions. Yields: rapeseed = 4.08 t/ha, straw = 4 t/ha, meal = 2.37 t/ha, biodiesel = 1.51 t/ha. Meal utilisation as fertiliser. Straw utilisation in heat/electricity generating plant. Meal energy credit and energy value of straw are added to energy value of biodiesel.
Mortimer & Elsayed (2006)	UK	1.51					59.16	Typical conditions in North East of England. Average nitrogen fertiliser application rate = 184 kg/ha. Yields: rapeseed = 4 t/ha, biodiesel = 1.59 t/ha.
Batchelor et al. (1995)	UK	0.67-2.23	1.98-7.47	0.88-3.83	0.91-3.95	2.22-9.18	36.3-63.04	A range of conditions in Scotland. Yields: rapeseed = 2.8-4.2 t/ha, straw = 5.2-8.4 t/ha, meal, biodiesel: 1.08-1.73 t/ha, unspecified meal and glycerol yields. Energy values of by-products are added to that of biodiesel

References	Country	R_1^a	R_2^b	R_3^c	R_4^d	R_5^e	E (GJ/ha)	Comments
Kaltschmitt et al. (1997)	Germany	1.8					42.53	Typical conditions in Germany. Yields: biodiesel = 1.14 t/ha. Unspecified rapeseed yield.
Bernesson et al. (2004)	Sweden	1.76-2.46					27.99-40.34	Typical conditions in central Sweden. Energy ratio and productivity values for small, medium, and large scales of biodiesel production from rapeseed cultivated by common agricultural practice for all scales. Yields: rapeseed = 2.67 t/ha, biodiesel = 0.73-1.05 t/ha.
Janulis (2004)	Lithuania	1.04-1.59			1.76-2.68	3.80-5.81	37.7	Typical conditions in Lithuania. Energy ratio and productivity values for a range of rapeseed yields. Yields: rapeseed = 2-3.5 t/ha, straw = 6 t/ha, meal = 1.5 t/t biodiesel, glycerol = 0.1 t/t biodiesel. Energy values of by-products are added to that of biodiesel.
This study	Australia	0.96	1.11	1.29	1.38	1.70	19.79	Typical Western Australian conditions. Yields: rapeseed = 1.4 t/ha, straw = 2.5 t/ha, meal = 0.78 t/ha, glycerol = 54.67 kg/ha, biodiesel = 0.53 t/ha. Utilisation of some of straw as energy source to substitute process heat & electricity in processing plants. Meal is utilised as animal feed and glycerol for co-firing in power station. Energy credits for by-products utilisation are substituted for some of the energy requirements.

a No by-products utilisation (base case). b With utilisation of rapeseed straw. c With utilisation of rapeseed meal. d With utilisation of rapeseed meal & glycerol. e With utilisation of rapeseed straw, meal, & glycerol.

4.3 Feasibility Analysis of Biodiesel Production from Rapeseed in Western Australia.

A large scale biodiesel production in Western Australia that can contribute to 10-20% or more of the total diesel fuel consumption would be necessary to play a significant role in ensuring energy security in the Western Australian transport sector (O'Connell et al., 2007). In this study, the feasibility of a large scale biodiesel production from rapeseed capable of replacing at least 10% of the 48.8 PJ of fossil diesel fuel consumed in Western Australian transport sector in 2006 – 2007 (ABARE, 2008a) is discussed by comparing the land, water, and labour requirements of the production process evaluated using the net energy approach to the actual land and water availability and existing labour constraint in the energy sector in Western Australia, as suggested previously (Giampietro and Ulgiati, 2005, Giampietro et al., 1997, Ulgiati, 2001).

4.3.1 Net Biodiesel Production

Using the net energy approach (Figure 3-2), the ratio of net to gross output of biodiesel (F*/F) associated with an energy ratio of 1.72 (R_5 in Table 4-18) is calculated to be 0.42, which means that to deliver 1 net MJ of biodiesel that can be used as an alternative transport fuel to fossil diesel, 2.38 MJ of biodiesel must be produced by the biodiesel production process. The amount of biodiesel that must be produced annually to deliver the net biodiesel that is usable for replacement of at least 10% of the total diesel fuel consumption in Western Australian transport sector is shown in Table 4-20.

Table 4-20 Annual biodiesel production requirement for replacement of diesel fuel in Western Australian transport sector.

% replacement	Net biodiesel (PJ/year)*	Biodiesel requirement (PJ/year)
10	4.88	11.63
20	9.76	23.27
30	14.64	34.90
50	24.40	58.17
100	48.80	116.34

*** Based on a total of 48.8 PJ of diesel fuel consumed in Western Australian transport sector in 2006-2007 (ABARE, 2008a).**

4.3.2 Land, Water, and Labour Requirements and Feasibility of Large Scale Biodiesel Production from Rapeseed in Western Australia.

The associated land, water, and labour requirements of the biodiesel production process to produce the required amount of biodiesel are evaluated and compared in Table 4-24 to the actual land and water availability in Western Australia and labour constraint in the energy sector that produces fossil diesel fuel for Western Australian transport sector (Table 4-23). In addition, Table 4-24 also compares the requirements of the biodiesel production process to those of ethanol production from mallee in Western Australia, which will be discussed later (subsection 4.3.4), to compare the feasibilities of both production processes.

Table 4-24 shows that to produce enough net biodiesel to replace 10-20% of the total diesel fuel consumption in Western Australian transport sector, suggested previously (O'Connell et al., 2007) as being necessary for biodiesel to play significant role in ensuring energy security, approximately 5-10% of total land area that is being used for production of all crops in Western Australia must be dedicated to rapeseed growing. The demanding nature of this land requirement is apparent when compared to the land area that is being used for growing oilseeds. Arable land that is approximately 1.5 to 3 times larger than the area currently in use for growing oilseeds is required to produce enough net biodiesel to achieve 10-20% replacement of diesel fuel. This means that even if the current rapeseed production over the same area of land that has already been dedicated for rapeseed growing is increased by at least 1.5 to 3 times using a new agricultural practice that is more productive than the typical current agricultural practice to avoid competition for arable land use with production of other crops, there would be not enough rapeseed for other purposes than producing biodiesel since all harvested rapeseed is consumed by the biodiesel production process. More arable land has to be provided to grow rapeseed for other purposes (e.g. production of edible oil), which is likely to compete with land requirement for production of other crops.

The net biodiesel throughput per hour of labour (Table 4-24) in the biodiesel production process is another limiting parameter to the realisation of a large scale biodiesel production from rapeseed in Western Australia. Giampietro et al. (1997) has shown that one critical condition for any biofuel production process to be a feasible alternative to the production of fossil fuel in a society is that the net biofuel energy throughput per hour of labour in the biofuel production process must match the energy throughput per hour of labour in the energy sector that produces and supplies fossil fuel to the society. Table 4-24 shows that the net biodiesel energy throughput per hour of labour in the biodiesel production process considered in this study is 1.24 net GJ/hour, which is slightly lower than the diesel fuel energy throughput of 1.31 GJ/hour achieved in Western Australian energy sector that supplies diesel fuel to the transport sector. The amount of net biodiesel produced is not enough to support the transport activities that are currently supported by diesel fuel produced in Western Australian energy sector.

The above land and labour requirements would be the main constraints to the feasibility of a large scale biodiesel production from rapeseed in Western Australia, although its water requirement seems not to be a limiting parameter. Table 4-24 shows that 10-20% replacement of diesel fuel results in consumption of less than 0.01% of typical total annual water resource availability. This water consumption also represents only less than 1% of typical annual water consumption by all economic sectors in Western Australia. However, it should be pointed out that the amount of total annual water resource is highly dependent on the amount of rainfall and since one of the key features of Australia’s rainfall is the variability from year to year and season to season, many parts of Australia may experience below average rainfall and shortage of water during drought (Pink, 2008c).

4.3.3 Importance of By-Products Utilisation

Table 4-18 shows that the energy ratio obtained without by-products utilisation is less than 1, rendering the biodiesel production process energetically unfeasible. Utilisation of by-products, therefore, is a necessary condition for the biodiesel to be a feasible replacement for fossil diesel fuel in Western Australian transport sector. The feasibility of the biodiesel production process is correspondingly evaluated in this study using the maximum energy ratio which is obtained when all by-products are utilised.

Caution should be exercised, however, when analysing the feasibility of biodiesel production from rapeseed even when the by-products are utilised for various purposes. It is assumed in this study that all of the rapeseed meal and glycerol can be utilised. It has been pointed out (Giampietro et al., 1997, Ulgiati, 2001) however, that care should be taken as to how much of these by-products can actually be utilised, since a large-scale production of biodiesel will result in a large amount of by-products that it will be impossible to utilise all of them.

The amount of rapeseed meal that would be produced annually by 10-20% replacement of diesel fuel in Western Australian transport sector is approximately 0.46-0.93 million tonnes. This amount of rapeseed meal in Western Australia alone is approximately 45-85% the typical Australian total annual protein meal consumption from all oilseed crops (Table 4-21). Unless an alternative utilisation of rapeseed meal is found, there would likely be an excess of rapeseed meal which would likely be considered as waste (Giampietro et al., 1997), whose disposal would incur further energy costs which must be incorporated into the energy balance analysis. These additional energy costs would likely decrease the energy ratio and the ratio of net to gross biodiesel output and hence increase the land, water, and labour requirements of the biodiesel production process which would negatively affect its feasibility as an alternative to fossil diesel production.

The corresponding amount of glycerol that would be produced annually by the biodiesel production process is 0.03-0.07 million tonnes, which is approximately 3.5-7 times the Australian glycerol market of 9000 tonnes (Ellis, 2008). Unless an alternative utilisation of glycerol is found, the excess glycerol would incur additional energy requirements associated with its disposal and cause similar decrease in the energy ratio and negative effect on the feasibility of the biodiesel production process as that caused by an excess of rapeseed meal.

Table 4-21 Australian oilseed protein meal consumption (Mailer, 2004).

Oilseed meal	**Consumption (tonnes)**			
	1999/00	**2000/01**	**2001/02**	**2002/03**
Rapeseed meal	222000	172000	239000	224000
Soybean meal*****	75000	195000	270000	375000
Sunflower seed meal	70000	42000	0	13000
Cotton seed meal	254000	285000	190000	175000
Palm kernel meal*****	17000	20000	92000	121000
Cotton seed whole	240000	260000	200000	140000
Rapeseed whole	n/a	n/a	n/a	25000
Total	878000	974000	991000	1073000

***Includes imports.**

4.3.4 Comparison with feasibility of large scale ethanol production from Mallee in Western Australia

The feasibility of large scale biodiesel production from rapeseed is compared with the feasibility of large scale ethanol production from mallee in Western Australia. The comparison is deemed necessary since both biofuels are produced for similar purposes (alternative transport fuels) and therefore an assessment is needed to decide which fuel is more feasible to produce, since their productions are in competition for limited resources, e.g. arable land. It is also noteworthy that ethanol production from mallee has not yet been developed to an operational stage and the comparison made in this study is theoretical.

a) Process Chain of Ethanol Production from Mallee

The process chain of ethanol production from mallee in Western Australia (Figure 4-4) has been discussed in Wu et al. (2006 & 2008). Briefly, mallee eucalypts have been developed as woody crops to tackle dryland salinity problem in the low to medium rainfall (300 – 600 mm mean annual rainfall) Western Australian wheat belt. The mallee trees are planted in an alley farming system for a 50-year production period which consists of an initial 5-year period from seed/seedling to first harvest, followed by 15 three-year coppice-to-harvest cycles. At the end of the first 5-year period, and also at the end of each 3-year period, mallee biomass products, which consist of leaf, bark, and wood, are harvested and transported to a conceptual ethanol generation plant for conversion into ethanol through the NREL lignocellulosic process described in detail in Aden et al. (2002).

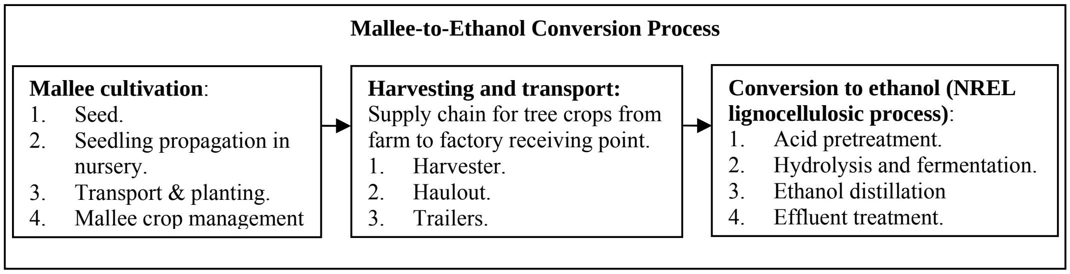


Figure 4-4 Process chain of ethanol production from mallee.

b) Energy Ratio, Energy Productivity, and Net Ethanol Production

The energy ratio and energy productivity of ethanol production from mallee in Western Australia have been previously evaluated by Wu et al. (2006) to be 5.95 and 80.0 GJ/ha/year, respectively. Using the net energy approach (Figure 3-2), the ratio of net to gross output of ethanol (F*/F) associated with an energy ratio of 5.95 is calculated to be 0.83, which means that to deliver 1 net MJ of ethanol that can be used as an alternative transport fuel to fossil petrol, 1.20 MJ of ethanol must be produced by the ethanol production process.

As aforementioned, a large scale ethanol production in Western Australia that can contribute to at least 10% of the total petrol fuel consumption would be necessary to play a significant role in ensuring energy security in the Western Australian transport sector (O'Connell et al., 2007). Total petrol fuel consumption in Western Australian transport sector in 2006-2007 was 64.5 PJ (ABARE, 2008a). The amount of ethanol that must be produced annually to deliver the net ethanol that is usable for replacement of at least 10% of the total petrol fuel consumption in Western Australian transport sector is shown in Table 4-22.

Table 4-22 Annual ethanol production requirement for replacement of petrol fuel in Western Australian transport sector.

% replacement	Net ethanol (PJ/year)*	Ethanol requirement (PJ/year)
10	6.45	7.75
20	12.90	15.51
30	19.35	23.26
50	32.25	38.77
100	64.50	77.53

*** Based on a total of 64.5 PJ of petrol fuel consumed in Western Australian transport sector in 2006-2007 (ABARE, 2008a).**

c) Land, Water, and Labour Requirements and Feasibility of Large Scale Ethanol Production from Mallee in Western Australia

The associated land, water, and labour requirements of the ethanol production process to produce the required amount of ethanol are evaluated and compared in Table 4-24 to the actual land and water availability in Western Australia and labour constraint in the energy sector that produces petrol fuel for Western Australian transport sector (Table 4-23). In addition, Table 4-24 also compares the requirements of the ethanol production process to those of the biodiesel production process, discussed previously (subsection 4.3.2), to compare the feasibilities of both production processes.

Table 4-24 shows that to make the necessary 10-20% replacement of the total petrol fuel consumption in Western Australian transport sector, approximately 0.80-1.60%

of total land area that is being used for production of all crops in Western Australia must be dedicated to mallee production. In contrast to the demanding nature of the land requirement of the biodiesel production process, the land requirement of the ethanol production process translates into only approximately 2.40-4.80% of the area currently in use for growing wheat in Western Australia. A model-based prediction (Cooper et al., 2005, as cited by Wu et al., 2008) has indicated that mallee crop, with an average yield of 93 green tonnes per hectare per harvest cycle, grown on a planted area of 3.7% of all land sown for wheat in Western Australian wheatbelt to tackle dryland salinity problem, would be economically competitive. The current mallee yield used by Wu et al. (2006) in their study of energy balance of ethanol production from mallee is 60 green tonnes per hectare per harvest cycle. Although, at the yield level studied, such mallee crop cultivation practice would probably not be competitive economically, it is shown in this study that approximately 15% of the total petrol fuel consumption in Western Australian transport sector can be replaced by ethanol produced from the mallee, indicating its potential to play a significant role in future energy security in Western Australian transport sector.

From the point of view of its labour requirement and the corresponding net energy throughput, the net ethanol throughput per hour of labour in the ethanol production process (10.22 net GJ/hour) is higher than the petrol fuel energy throughput of 1.74 GJ/hour of labour achieved in Western Australian energy sector that supplies petrol fuel to the transport sector. Contrary to the biodiesel production process, a large scale ethanol production from mallee would therefore be capable to deliver net ethanol at a rate fast enough to maintain the transport activities that are currently supported by petrol fuel produced in Western Australian energy sector.

The model-based prediction (Cooper et al., 2005) also highlighted the dependence of mallee yield on the availability of sufficient water, which, in turn, is dependent on the amount of rainfall. Therefore, despite the much lower water requirement of the ethanol production process compared to that of biodiesel production process (Table 4-24), the feasibility of a large scale ethanol production from mallee in Western Australia is dependent on the amount of rainfall, which varies from year to year and season to season, causing many parts of Australia to experience below average rainfall and shortage of water during drought (Pink, 2008c).

Table 4-23 Land and water availability and labour constraint in the energy sector that produces fossil fuels for the transport sector in Western Australia.

Land for crop production	
Total cropland area (10^6 ha)[a]	12.09
Total area sown for oilseeds (10^6 ha)[a]	0.41
Total area sown for wheat (10^6 ha)[a]	4.04
Water resource	
Typical water resource availability (GL/year)[b]	49094
Typical use by agricultural sector (GL/year)[b]	535
Typical use by all sector (GL/year)[b]	1495
Labour hours & energy throughput in the energy sector	
Worked labour hours (10^6 hours/year)[c]	37.14
Diesel throughput (GJ/worked labour hour)[d]	1.31
Petrol throughput (GJ/worked labour hour)[e]	1.74

[a] Data for the period 2006 – 2007 (Pink, 2008a, Pink, 2008b). [b] Latest available data (2004 – 2005) on typical annual water resource availability and consumption (Pink, 2008c). [c] Approximately 1.08 million people were employed in all industrial divisions in WA in end of 2006 with an average of 34.4 hours worked per person per week, approximately 1.92% of which was spent in WA energy sector (Linacre, 2007). [d] Calculated by dividing the 48.8 PJ of diesel fuel consumption in WA transport sector in 2006-2007 (ABARE, 2008a) by the total annual worked hours in the energy sector. [e] Calculated by dividing the 64.5 PJ of petrol fuel consumption in WA transport sector in 2006-2007 (ABARE, 2008a) by the total annual worked hours in the energy sector.

Table 4-24 Comparison of land, water, and labour requirements of biofuel production processes to the land & water availability and labour constraint in the energy sector

Replacement (%)	**10**		**20**		**30**		**50**		**100**	
	Biodiesel	**Ethanol**	**Biodiesel**	**Ethanol**	**Biodiesel**	**Ethanol**	**Biodiesel**	**Ethanol**	**Biodiesel**	**Ethanol**
Land requirement										
(10^6 ha)[a]	0.59	0.10	1.18	0.19	1.76	0.29	2.94	0.48	5.88	0.97
(ha/L net biofuel)	3.96×10^{-3}	3.53×10^{-4}	3.96×10^{-3}	3.53×10^{-4}	3.96×10^{-3}	3.53×10^{-4}	3.96×10^{-3}	3.53×10^{-4}	3.96×10^{-3}	3.53×10^{-4}
As % of cropland area	4.86	0.80	9.72	1.60	14.58	2.40	24.30	4.01	48.61	8.01
As % of area sown for oilseeds/wheat[b]	143.37[b]	2.40[b]	286.74[b]	4.80[b]	430.10[b]	7.20[b]	716.84[b]	11.99[b]	1433.68[b]	23.99[b]
Water requirement										
(GL/year)[c]	0.86	2.29	1.73	4.58	2.59	6.88	4.32	11.46	8.65	22.92
(L water/L net biofuel)	5.82	8.34	5.82	8.34	5.82	8.34	5.82	8.34	5.82	8.34
As % of available water resource	<0.01	<0.01	<0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.05
As % of typical use by all economic sector	0.06	0.15	0.12	0.31	0.17	0.46	0.29	0.77	0.58	1.53
Labour requirement										
(labour hours/ha)[d]	6.69	6.51	6.69	6.51	6.69	6.51	6.69	6.51	6.69	6.51
Net biofuel throughput (net GJ/hour)[e]	1.24	10.22	1.24	10.22	1.24	10.22	1.24	10.22	1.24	10.22
Diesel throughput in energy sector (GJ/hour)[f]	1.31	n/a	1.31	n/a	1.31	n/a	1.31	n/a	1.31	n/a
Petrol throughput in energy sector (GJ/hour)[f]	n/a	1.74	n/a	1.74	n/a	1.74	n/a	1.74	n/a	1.74

[a] Calculated by dividing the biofuel production requirement (Table 4-20 & Table 4-22) by the biofuel energy output or energy productivity (Table 4-18 & section 4.3.4b). [b] The land requirement of biodiesel production is compared to total area sown for oilseeds, while that of ethanol production to total area sown for wheat. [c] Water requirement of biodiesel production is calculated from the total process water requirement (subsections 4.2.2d and 4.2.3d), assuming 80% water supply efficiency (Ulgiati, 2001). Water requirement of ethanol production process is calculated from make-up water requirement of 186649 kg/hour (Aden et al., 2002) and feedstock throughput of 151.52 t mallee/hour (Wu et al., 2006) in the ethanol conversion plant and from the total amount of mallee that must be processed annually, which is calculated from the annual ethanol production requirement, energy content of mallee of 10737.6 MJ/t and 38.8% energy efficiency of ethanol conversion plant (Wu et al., 2006) [d] Labour requirement of biodiesel production process is calculated from labour hour requirements during rapeseed growing and processing and transport activities calculated in the energy balance analysis in this study. Labour requirement of ethanol production process is calculated from the labour requirement during mallee crop management, harvest, and transport reported by Wu et al. (2008) and during conversion to ethanol (calculated from feedstock throughput, mallee yield of 60 t/ha (Wu et al., 2006), and 20 operators divided in 3 shifts (Aden et al., 2002)) [e] Calculated by dividing the net biofuel output per hectare by its labour hour requirement per hectare. [f] Value from Table 4-23.

4.4 Strategies for Biofuels in Western Australia

4.4.1 Biodiesel Production Strategies in Western Australia

The results of energy balance and feasibility analysis in this study have indicated that the wide implementation of biodiesel production from rapeseed in Western Australia, such as that to replace a significant fraction of diesel fuel consumed in the Western Australian transport sector, is unsustainable. Future implementation of rapeseed-based biodiesel production in Western Australia should therefore be directed at smaller and more specific targets. Implementation within these targets should then be supported by development of key strategies aimed at increasing rapeseed yield and reducing some of the previously mentioned main energy input contributors (e.g. fertiliser use during rapeseed cultivation, fuel use during field machinery operation, and methanol consumption during rapeseed processing) to improve the energy ratio and energy productivity of the whole production process.

a) Rapeseed growing strategies

A sensitivity analysis (Table 4-25) studying the effect of changing rapeseed yield and main energy input items one at a time on the energy ratio and energy productivity of the biodiesel production process considered in this study indicates that the most significant improvement of energy ratio, and also an increase in energy productivity, is associated with an increase of rapeseed yield per hectare. Development and adoption of a higher yielding rapeseed variety that is suitable for growing under typical Western Australian conditions and for industrial production of biodiesel through a plant breeding program in the agricultural sector would therefore be a key strategy towards a sustainable biodiesel production from rapeseed in Western Australia.

Table 4-25 Effect of changing rapeseed yield and main energy input items on energy ratio (R) and energy productivity (E).

Parameters	**Typical values**[a]	**Change**[b]	**R and E after change in typical values**					
			R_1[c]	**R_2**[c]	**R_3**[c]	**R_4**[c]	**R_5**[c]	**E**[c]
Rapeseed yield	1.40 kg/ha	+40%	1.17 (+21.30%)	1.41 (+27.00%)	1.67 (+30.78%)	1.84 (+33.64%)	2.53 (+48.47%)	28274.77 (+42.86%)
		-40%	0.67 (-30.51%)	0.72 (-34.71%)	0.81 (-37.05%)	0.85 (-38.62%)	0.94 (-44.94%)	11309.91 (-42.86%)
N-fertiliser use	237.6 kg/ha	+40%	0.88 (-9.10%)	0.99 (-10.34%)	1.14 (-11.83%)	1.21 (-12.55%)	1.45 (-15.05%)	-
		-40%	1.07 (+11.12%)	1.25 (+13.04%)	1.49 (+15.49%)	1.61 (+16.75%)	2.07 (+21.53%)	-
Methanol use during transesterification	63.60 kg/ha	+40%	0.92 (-4.68%)	1.05 (-5.36%)	1.21 (-6.18%)	1.29 (-6.58%)	1.57 (-8.00%)	-
		-40%	1.01 (+5.17%)	1.18 (+6.00%)	1.38 (+7.05%)	1.49 (+7.58%)	1.87 (+9.52%)	-
Fuel use during rapeseed growing	40.73 L/ha	+40%	0.92 (-3.96%)	1.06 (-4.70%)	1.22 (-5.23%)	1.30 (-5.58%)	1.58 (-7.04%)	-
		-40%	1.00 (+4.30%)	1.17 (+5.19%)	1.37 (+5.85%)	1.47 (+6.28%)	1.84 (+8.19%)	-

[a] Values used in the energy balance analysis in this study. [b] % increase or decrease in typical values. [c] Values in the brackets are the % change of R and E with respect to their original values in Table 4-18.

Table 4-25 also indicates that significant improvement of energy ratio is also associated with reduction in the amount of fertiliser used per hectare during rapeseed growing. In developing a strategy to improve the energy ratio through reduction of fertiliser use, it should be noted that a relationship between the amount of fertilisers applied and rapeseed yield exists (Mortimer and Elsayed, 2006) and that an understanding of this relationship under typical Western Australian condition to achieve the optimum rapeseed yield is very important to minimise the amount of fertilisers applied during rapeseed cultivation. Accordingly, the fertiliser application regime should be optimised through understanding of the nutrient requirement of the rapeseed variety grown and of the specific soil conditions in the agricultural region where the variety is grown. Particularly, soil tests should be conducted to reproduce the soil water chemistry as an indication of the quantity of nutrients available for plant uptake (Pittaway, 2002) so that the application of fertiliser can be optimised by balancing the nutrient uptake by fertiliser inputs.

Alternatively, a potential reduction in the amount of energy-intensive inorganic nitrogen fertilisers that need to be applied during rapeseed growing may be achieved by integration of bio-fertilisation (ACIAR, 2000) in the fertiliser application regime, i.e. by inoculating the rapeseed plant with culture of microbes selected for their nitrogen-fixing ability. Application of bio-fertilisation technique to another crop with reduced amount of inorganic nitrogen fertilisers has also been associated with an increased yield (ACIAR, 2000). Adoption of a suitable bio-fertilisation technique for rapeseed growing under typical Western Australian conditions may therefore offer significant improvement of the overall energy ratio of the biodiesel production process.

Since fuel consumption during rapeseed growing is one of the main energy input contributors and the majority of the fuel is consumed during rapeseed swathing and harvest (Table 4-1), further improvement of energy ratio that is associated with reduction of fuel use during rapeseed growing (Table 4-25) can be achieved by general improvement in fuel efficiency of machinery operations, particularly that of self-propelled harvester and swather.

b) Rapeseed processing strategies

Utilisation of rapeseed straw as energy source to substitute process heat and electricity requirements in the rapeseed oil extraction and transesterification plants has been shown in this study to increase the energy ratio from ~0.96 (R_1) to ~1.11 (R_2) when only straw is utilised and to ~1.70 (R_5) when rapeseed meal and glycerol by-products are also utilised for other purposes (Table 4-18).

Table 4-25 indicates process improvement to reduce the amount of large excess of methanol required during transesterification reaction can further increase the energy ratios. Also, since the large energy consumption associated with the use of methanol is due to the energy required during its manufacture, the use of an alternative type of alcohol, e.g. bio-ethanol, manufactured from renewable raw materials through an appropriately selected less energy-intensive technology, to replace methanol, may offer further improvement to the energy ratio of the whole biodiesel production process.

4.4.2 Biofuel production strategies in Western Australia

Comparison between the feasibilities of the two biofuel production processes considered in this study indicates that one option for a large scale biofuel production to play a significant role in future energy security in Western Australian transport sector would be based on ethanol production from mallee grown in Western Australian wheatbelt to replace a fraction of petrol fuel consumed in Western Australian transport sector.

a) Mallee growing strategies

As aforementioned (subsection 4.3.4), mallee yield per hectare, which is a crucial parameter in determining the energy ratio and energy productivity, and hence the feasibility of a large scale ethanol production process, is dependent on the availability of sufficient water (Cooper et al., 2005), which, in turn, is dependent on the amount of rainfall. Due to the variability of Australian rainfall causing water shortage during below average rainfall periods (Pink, 2008c), drought management to provide consistent water supply is a vital strategy towards the realisation of a sustainable ethanol production from mallee in Western Australia. Application of active water harvesting practice combined with better site selection and layout to optimise water capture during mallee growing (Bartle et al., 2008) can offer opportunities to maintain sufficient water supply during drought periods.

b) Mallee processing strategies

During mallee conversion into ethanol, a large amount of process heat is consumed in the process of purification (distillation and dehydration) of ethanol (Aden et al., 2002, Wu et al., 2006). In addition to the utilisation of the lignin fraction of mallee biomass as energy source to fulfil some of these energy requirements, additional energy can be obtained from utilisation of wheat straw. Integration of mallee and wheat harvest and transport logistics in the wheatbelt to include the harvest and transport of some of the wheat straw to the ethanol plant to be utilised as energy source may offer further improvement to the overall energy ratio of the ethanol production process.

Chapter 5

Conclusions and Recommendations

5.1 Conclusions

- Energy balance analysis of biodiesel production from rapeseed in Western Australia has been conducted, considering the typical Western Australian rapeseed growing practices and rapeseed processing parameters. Specifically, the energy ratio and the energy productivity associated with the biodiesel production process have been calculated and the feasibility of a large scale production to replace fossil diesel consumption in Western Australian transport sector analysed based on its land, water, and labour requirements evaluated from its energy ratio using the net energy approach.

- When the by-products of the biodiesel production process are not utilised, the energy ratio is found to be 0.96, indicating a net loss of energy in the production process. The highest energy ratio (1.70) is achieved when all by-products (rapeseed straw, rapeseed meal, and glycerol) were utilised, giving substitution energy credits in the overall energy balance of the production process. The energy productivity of the production process is calculated from the biodiesel energy output and is found to be 19.79 GJ/hectare per rapeseed growing season.

- Feasibility analysis using net energy approach shows that the land and labour requirements of a large scale biodiesel production from rapeseed to produce enough net biodiesel to make 10-20% replacement of the total diesel fuel consumption in Western Australian transport sector are likely to be the major constraints due to the severe competition for arable land with production of other crops and the insufficient net biodiesel production rate to maintain the transport activities that are currently supported by diesel fuel produced in Western Australian energy sector.

- A large scale ethanol production from mallee grown in Western Australian wheatbelt to tackle dryland salinity problem, on the other hand, has a potential to deliver enough net ethanol to replace approximately 15% of the total petrol fuel consumption in Western Australian transport sector. Its feasibility, however, is dependent on the use of widely spaced narrow belts to intercept sufficient water to maintain the mallee yield level considered in this study.

- Implementation of rapeseed-based biodiesel in Western Australia should therefore be directed at smaller and more specific targets, supported by development of key strategies aimed at increasing rapeseed yield and reducing main energy input contributors, especially the fertiliser requirements during rapeseed cultivation, to improve the energy ratio and energy productivity of the whole production process.

- A large scale ethanol production from mallee provides an option for a large scale biofuel production to play a significant role in future energy security in Western Australian transport sector, which should be supported by efficient water-use design strategies to maintain consistent water supply during drought periods.

5.2 Recommendations

- The relationship between rapeseed yield and fertiliser application rate during rapeseed growing warrant further studies since their optimisation would offer significant improvements to the overall energy ratio and energy productivity of biodiesel production from rapeseed and hence its realisation within specific targets with suitable production scale in Western Australia.

- The effect of arable land use for mallee growing within Western Australian wheatbelt on wheat production requires further studies to ascertain as to how large an ethanol production scale can be realised without causing negative impacts on wheat production, which is a principal agricultural commodity in Western Australia.

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